Prepared in cooperation with the
BUREAU OF RECLAMATION

Changes in Streamflow and Summary of Major-Ion Chemistry and Loads in the North Fork Red River Basin Upstream from Lake Altus, Northwestern Texas and Western Oklahoma, 1945–1999

Water-Resources Investigations Report 03–4086

Photograph of Lake Altus dam taken by S. Jerrod Smith.

U.S. Department of the Interior
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CONVERSION FACTORS, ABBREVIATIONS, AND HORIZONTAL DATUM

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter
inch (in)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	4,047	square meter
square mile (mi^2)	2.590	square kilometer
	Volume	
cubic foot (ft^3)	0.02832	cubic meter
acre-foot (acre-ft)	1,233	cubic meter
	Flow rate	
gallon per day (gal/d)	0.003785	cubic meter per day
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
	Mass	
ton per day (ton/d)	0.9072	metric ton per day
ton per year (ton/yr)	0.9072	metric ton per year
ton per year per square mile [(ton/yr)/mi^2]	0.3503	metric ton per year per square kilometer

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

Changes in Streamflow and Summary of Major-Ion Chemistry and Loads in the North Fork Red River Basin Upstream from Lake Altus, Northwestern Texas and Western Oklahoma, 1945–1999

By S. Jerrod Smith and Kenneth L. Wahl

ABSTRACT

Upstream from Lake Altus, the North Fork Red River drains an area of 2,515 square miles. The quantity and quality of surface water are major concerns at Lake Altus, and water-resource managers and consumers need historical information to make informed decisions about future development. The Lugert-Altus Irrigation District relies on withdrawals from the lake to sustain nearly 46,000 acres of agricultural land.

Kendall's tau tests of precipitation data indicated no statistically significant trend over the entire 100 years of available record. However, a significant increase in precipitation occurred in the last 51 years. Four streamflow-gaging stations with more than 10 years of record were maintained in the basin. These stations recorded no significant trends in annual streamflow volume. Two stations, however, had significant increasing trends in the base-flow index, and three had significant decreasing trends in annual peak flows.

Major-ion chemistry in the North Fork Red River is closely related to the chemical composition of the underlying bedrock. Two main lithologies are represented in the basin upstream from Lake Altus. In the upper reaches, young and poorly consolidated sediments include a range of sizes from coarse gravel to silt and clay. Near-surface horizons commonly are cemented as calcium carbonate caliche. Finer-grained gypsiferous sandstones and shales dominate the lower reaches of the basin. A distinct increase in dissolved solids, specifically sodium, chloride, calcium, and sulfate, occurs as the river flows over rocks that contain substantial quantities of gypsum, anhydrite, and dolomite. These natural salts are the major dissolved constituents in the North Fork Red River.

INTRODUCTION

The quantity and quality of surface water are major concerns at Lake Altus, and water-resource managers and consumers need historical information to make informed decisions about future development. To address these concerns, the U.S. Geological Survey, in cooperation with the Bureau of Reclamation, conducted a study of historic streamflow conditions, major-ion chemistry, and loads in the North Fork Red River basin upstream from Lake Altus, Oklahoma.

The North Fork Red River drains an area of about 4,828 square miles before joining the Red River at the southern border of Oklahoma. Three important tributaries of the North Fork Red River—McClellan Creek, Sweetwater Creek, and the Elm Fork—join the river along a 220-mile total length. One large impoundment, Lake Altus, is located about 73.4 miles upstream from the junction with the Red River. The Bureau of Reclamation began construction of the Lake Altus dam in 1941 as part of the W.C. Austin Project. Storage operations began in 1946, and the project was completed in 1948 (Oklahoma Water Resources Board, 1990). The purposes of the W.C. Austin project were flood control, water supply for the city of Altus, and irrigation. In 2002, the Lugert-Altus Irrigation District relied on withdrawals from the lake to sustain nearly 46,000 acres of agricultural land (A. Ensley, Lugert-Altus Irrigation District, oral commun., 2002).

For the portion of the North Fork Red River basin upstream from Lake Altus, consumptive water use in 1995 was estimated at 108 million gallons per day (R.L. Tortorelli, USGS, written commun., 2001). Ground-water supplied the majority of that amount. The western half of the basin, because of greater irrigation requirements, withdrew more than twice as much water as the eastern half. Withdrawals in the western half were predominantly supplied by ground water (94 percent) while the eastern half relied on surface water (72 percent). Irrigated agriculture was the greatest consumer of water resources in the basin in 1995, accounting for 82 percent of total withdrawals, 79 percent of ground-water withdrawals, and 89 percent of surface water withdrawals (R.L. Tortorelli, USGS, written commun., 2001).

Purpose and Scope

This report summarizes a study of historic streamflow conditions and surface-water quality in the North Fork Red River basin upstream from Lake Altus, Oklahoma. The primary goals of this report are to 1) present statistical trends in streamflow, 2) summarize major-ion chemistry, and 3) summarize annual dissolved and suspended loads and yields. This report also presents statistical trends in annual precipitation from water years 1896 to 1995.

Description of the Study Area

The study area was the portion of the North Fork Red River basin upstream from the dam at Lake Altus (fig. 1). The study area extends 147 miles from the High Plains headwaters at Amarillo, Texas, to the westernmost exposure of the Wichita Uplift near Lugert, Oklahoma (Johnson and others, 1972). The study area covered four counties in Texas (Carson, Gray, Potter, and Wheeler) and five counties in Oklahoma (Beckham, Greer, Kiowa, Roger Mills, and Washita) (fig. 1). About two thirds of the study area is in the Texas Panhandle. The study area covered 2,515 square miles, of which 399 square miles were non-contributing (Blazs and others, 2001).

Climate

The semiarid climate in the North Fork Red River basin is caused by the position of the basin on the leeward side of the Rocky Mountains. Mean annual precipitation increases steadily to the east as the effect of the mountains decreases. The basin headwaters receive about 17 inches of mean annual precipitation, and the basin outlet receives about 26 inches (Daly and others, 1994). In Oklahoma Climate Division 4 (fig. 2) most rainfall occurs from spring and early summer storms, usually peaking in May (fig. 3). Storms tend to move rapidly, but can cause intense localized flooding. Warm and humid conditions are typical of Oklahoma and Texas in summer, but sometimes there are prolonged periods of drought. Most thunderstorms that occur in the summer are too localized to produce substantial runoff (Cooter, 1991).

A fall peak in precipitation occurs in September (fig. 3). The least precipitation occurs during the winter months and commonly is a combination of rain, ice, and snow. About 95 percent of annual precipitation is lost to evapotranspiration (Pettyjohn and others, 1983, p. 23). Mean annual runoff for 1951-80 is less than 2.5 percent of the mean annual precipitation, ranging from 0.2 to 1 inch per year across the study area (Gebert and others, 1987).

Geologic Setting

The North Fork Red River basin lies on the southern limb of a broad syncline that abuts the Wichita Uplift in the study area. The bedrock in the westernmost third of the study area is the Ogallala Formation of Tertiary age (fig. 4) consisting mostly of clay to gravel-sized unconsolidated sediment with intermittent layers of calcium carbonate caliche (fig. 5). In northwestern Texas, the Ogallala Formation is usually blanketed with the Quaternary-age Blackwater Draw Formation[1] (Texas Bureau of Economic Geology, 1992). A large number of small playa lakes are scattered throughout the extent of this formation that resulted from the scouring action of winds and dissolution of soluble layers of underlying bedrock

[1]Geologic names and stratigraphic ages in this report are accepted by the Texas Bureau of Economic Geology or the Oklahoma Geological Survey and are not necessarily the same as those used by the U.S. Geological Survey.

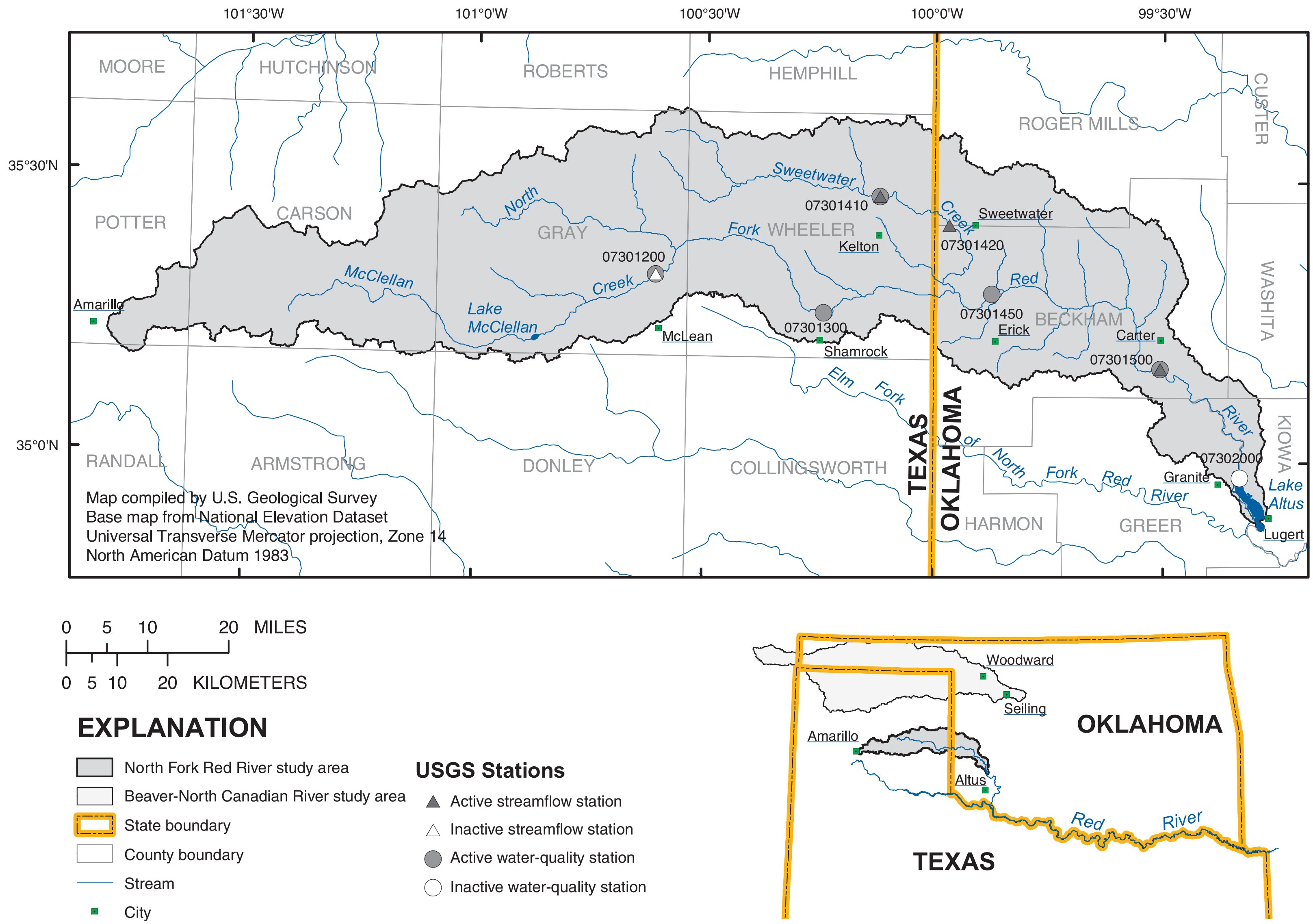


Figure 1. North Fork Red River basin upstream from Lake Altus with streamflow-gaging stations and water-quality monitoring stations.

(Oklahoma Water Resources Board, 1990, p. 52). High rates of evaporation in the Texas Panhandle concentrate salts in these lakes, which eventually leach to ground water. Natural springs and seeps are common at the base of the Ogallala Formation (Marine, 1963, p. 4). In northwestern Texas, the Ogallala Formation, Blackwater Draw Formation, and overlying alluvial deposits form the High Plains Aquifer.

The bedrock in the eastern two-thirds of the basin consists of Permian age, gypsiferous shale and sandstone (figs. 4 and 5). Beds of gypsum, anhydrite, and dolomite are common among the Permian age shales (Scott and Ham, 1957). In the Blaine Formation of Permian age, some individual beds of gypsum are more than 25 feet thick in outcrops (Scott and Ham, 1957, p. 28). Terrace and dune-sand deposits of Quaternary age overlie a substantial portion of the lower basin (fig. 4).

Background and Previous Studies

High-salinity surface water is a major concern in southwestern Oklahoma. Natural salts are the major dissolved constituents in surface water and excessive salt concentrations can limit the uses of the water. In tributaries below Lake Altus, such as the Elm Fork of North Fork Red River (fig. 1), water commonly contains such large concentrations of salts that it is unusable for most purposes. For this reason, the lake was impounded just a few miles upstream from the Elm Fork and North Fork Red River junction to store the relatively fresh water from the upstream portion of the basin (Oklahoma Water Resources Board, 1990, p. 34). In terms of geologic sources, the greatest contributors of dissolved solids in southwestern Oklahoma are halite (sodium chloride) and gypsum/anhydrite (calcium sulfate). In the North Fork Red River basin, these salts occur naturally throughout much of the Permian-age units (fig. 5). Dolomite (calcium-magnesium carbonate) also is present in these units.

The Beaver-North Canadian River study area (fig. 1) is similar in climate and geologic setting to the North Fork Red River study area. Wahl and Tortorelli (1997) examined changes in streamflow characteristics of the Beaver-North Canadian River and determined that annual streamflow volume and annual peak discharges had been decreasing, especially at gaging stations underlain by the Ogallala Formation. Wahl and Tortorelli (1997, p. 48) attributed decreases in peak discharges to streambed infiltration, channel storage, and the increasing number of stock ponds in the basin. Annual base-flow volumes also decreased significantly at some upstream stations, but remained constant or increased at downstream stations. The ratio of annual base flow to annual streamflow (the base-flow index) increased at all but one of the stations. The base-flow index increased downstream and was most pronounced at the more downstream stations near Woodward and Seiling (fig. 1). Citing Wahl and Wahl (1988), the authors related these changes in streamflow to withdrawals of ground water from the High Plains Aquifer.

DATA ANALYZED

Climatic Data

Precipitation data were analyzed with Kendall's tau procedure as part of an examination of streamflow trends in the basin. At the time of the study described in this report, the U. S. Historical Climatology Network (HCN) precipitation database was available for water years 1896 through 1995 (Easterling and others, 1996; Karl and others, 1990). Because the streamflow data analyzed in this report began in 1945, the subset of data from 1945 to 1995, and the entire record of precipitation data were summarized for Oklahoma Climate Division 4 (fig. 2) and analyzed for temporal trends. The precipitation record is most accurate for the more humid, eastern portion of the basin.

Hydrologic Data

Five continuous-stage gages were installed in the North Fork Red River study area between 1945 and 1999. Four of the five stations had a period of record exceeding 10 years and were used to discern hydrologic trends (table 1). Streamflow in lower McClellan Creek has been regulated since the late 1940s by Lake McClellan, which lies about 20 river miles upstream from station 07301200 (fig. 1). All streamflow data for station 07301200 on McClellan Creek were collected after the impoundment of Lake McClellan. That streamflow-gaging station was discontinued after water year 1980 but was maintained

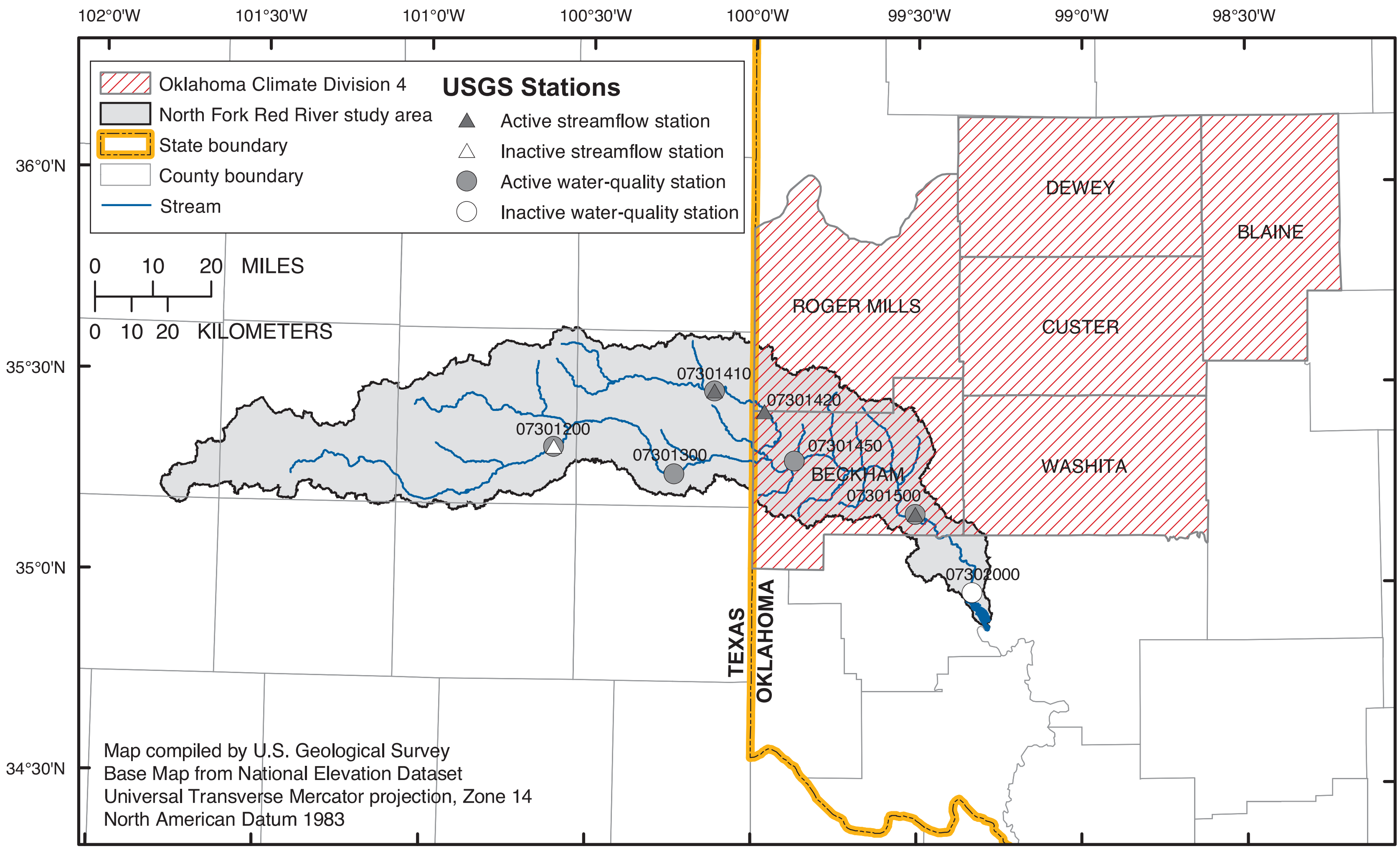


Figure 2. Oklahoma Climate Division 4 and the North Fork Red River study area.

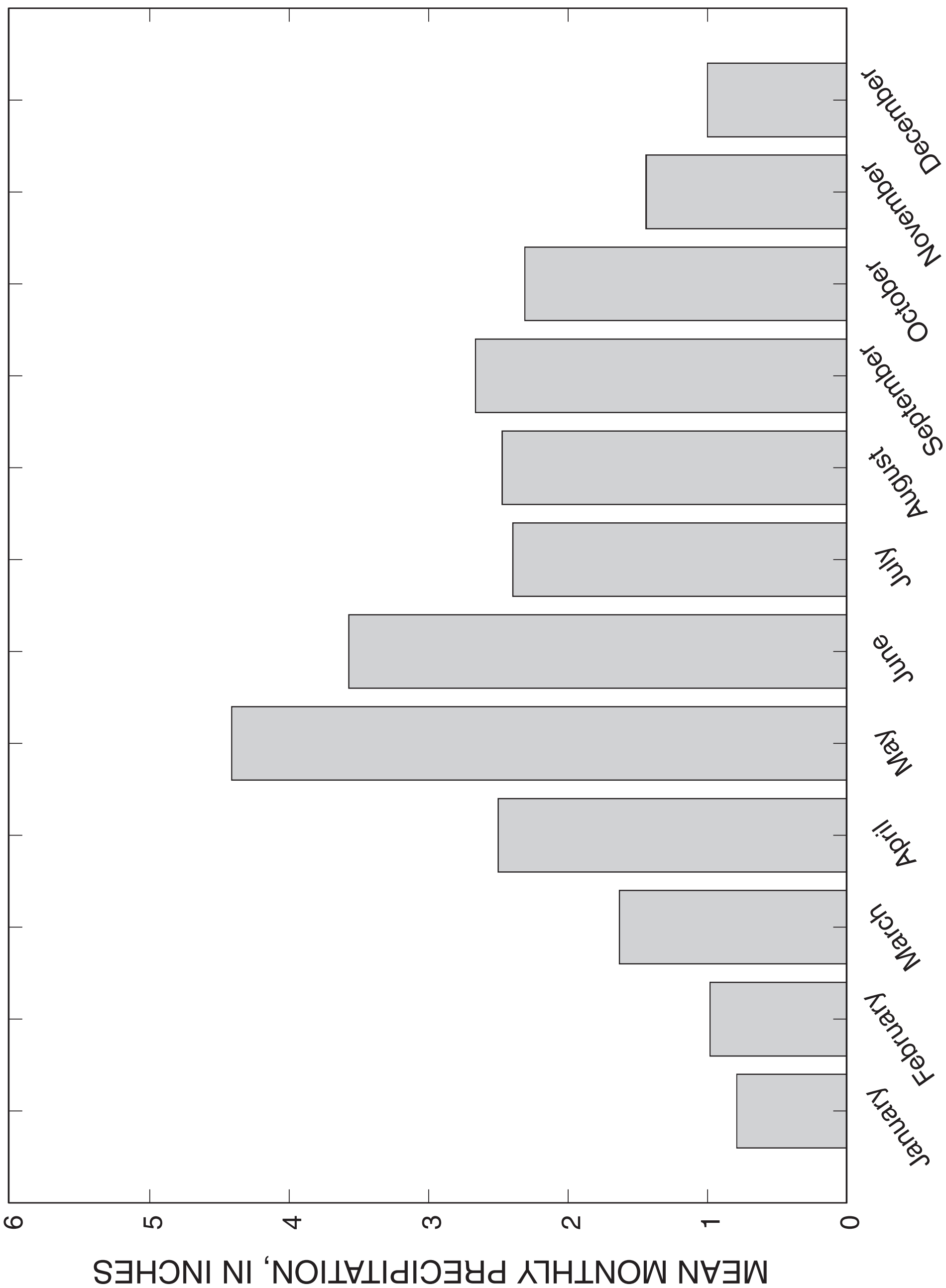
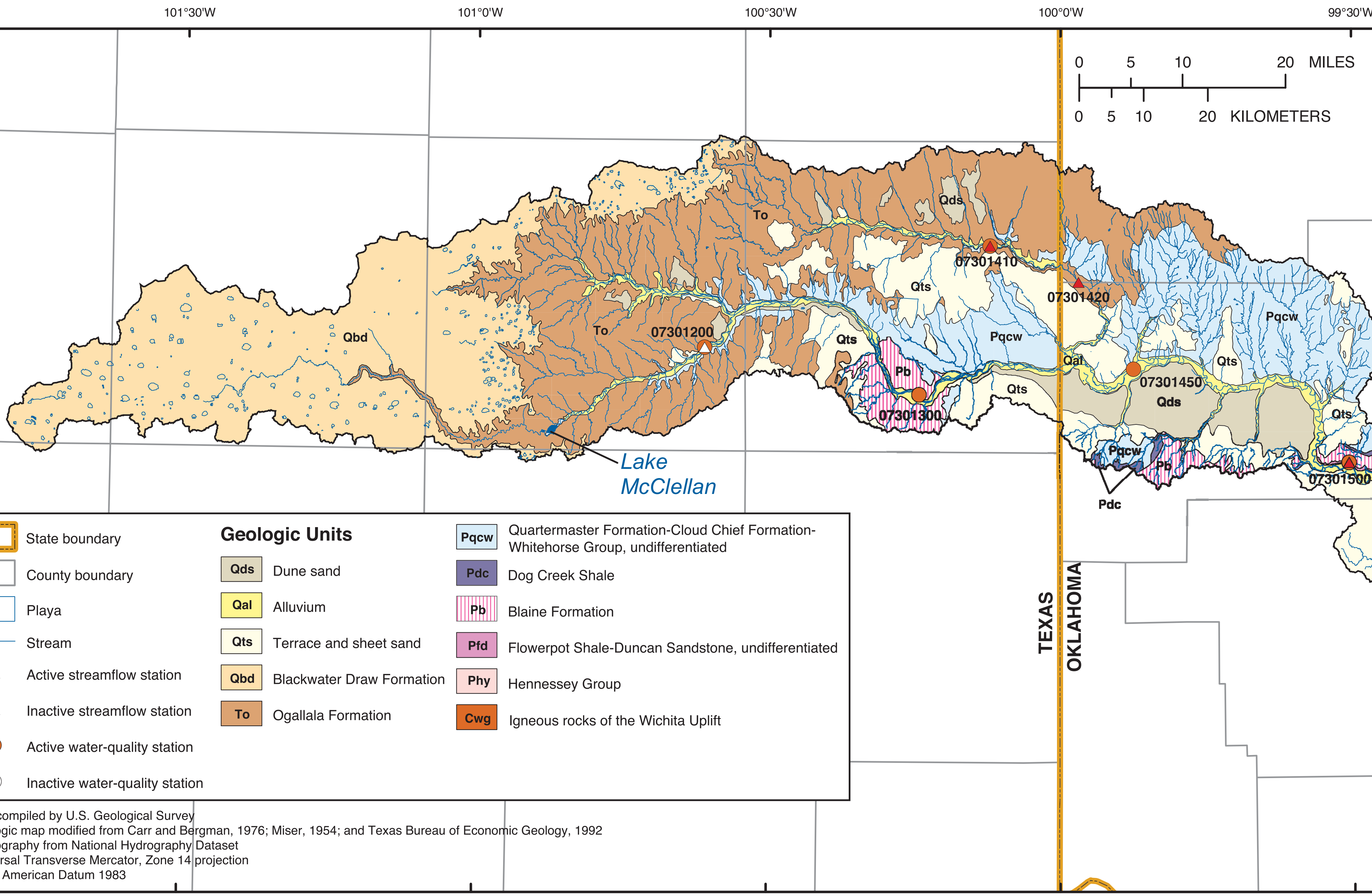


Figure 3. Mean monthly precipitation for Oklahoma Climate Division 4, water years 1896-1995.



ology of the North Fork Red River study area with streamflow-gaging stations and water-quality monitoring stations.

System	Group	Formation	Thickness (feet)	Physical character
Quaternary		alluvium, dune sand, sheet sand, and terrace	0-170	Silt, sand and clay deposits from the North Fork Red River and tributaries
		Blackwater Draw Formation	0-100	Wind-deposited sand and silt on the Ogallala Formation in Texas
Tertiary		Ogallala Formation	0-600	Light tan to salmon, mostly unconsolidated clay, silt, sand and gravel with near-surface zones of caliche
Permian		Quartermaster Formation	0-400	Reddish-brown fine-grained sandstone, siltstone, and silty shale weakly cemented by iron oxide, calcium carbonate, and calcium sulfate
		Cloud Chief Formation	0-400	Reddish-brown to orange-brown shale interbedded with siltstone and sandstone; some dolomite and much gypsum in lower part
	Whitehorse Group	Rush Springs Sandstone Marlow Formation	0-390	Red to pink, massive, very-fine grained, gypsiferous sandstone
	El Reno Group	Dog Creek Shale	0-80	Red, brown, and green gypsiferous shales with several beds of siltstone, sandstone, and dolomite; occasionally contains large dolomite concretions
		Blaine Formation	0-140	Beds of white massive gypsum and thin beds of gray medium-grained dolomite or dolomitic limestone separated by well defined red and green shale units
		Flowerpot Shale	0-150	Red-maroon blocky shales with thin beds of gypsum and dolomite
		Duncan Sandstone	0-40	Grayish-brown to buff, indurated, highly cross-bedded, ripple-marked, nonfossiliferous, silty to very fine dolomitic sandstone with interbedded shale
	Hennessey Group	—	0-500	Red to buff nonfossiliferous shale with calcareous fine-grained sandstone stringers and calcium sulfate concretions
Cambrian	—	—	—	Igneous rocks of the Wichita Uplift

Figure 5. Subsurface-geologic and major time-stratigraphic units in the North Fork Red River basin (Scott and Ham, 1957; Carr and Bergman, 1976; and Luckey and Becker, 1999).

Table 1. Summary of streamflow record for gaging stations with greater than 10 years of record in the North Fork Red River study area

Station number	Station name	Period of record tested (complete water year)	Years of record tested	Mean-annual streamflow (acre-feet)
07301200	McClellan Creek near McLean, Texas[1]	1968-1980	13	14,544
07301410	Sweetwater Creek near Kelton, Texas	1963-1999	37	10,150
07301420	Sweetwater Creek near Sweetwater, Oklahoma	1987-1999	13	19,214
07301500	North Fork Red River near Carter, Oklahoma	1945-1962, 1965-1999	53	98,398

[1]Streamflow on McClellan Creek near McLean, Texas, is regulated by Lake McClellan about 20 miles upstream

as a high-flow station, recording annual peaks between 1987-93 and 1995-97. The other three stations with 10 or more years of streamflow record were operational as continuous-stage gages at the time of this report (2003).

Major-Ion and Load Data

Elevated dissolved solids content in surface water is commonly the result of natural dissolution of earth materials. Common minerals such as halite (NaCl), gypsum ($CaSO_4 * 2H_2O$), calcite ($CaCO_3$), and dolomite ($CaMg(CO_3)_2$) are among the most soluble minerals. For the North Fork Red River basin, these four common minerals typically account for 95 percent or more of the dissolved solids. Mine waste, oilfield brines, agricultural products, and industrial chemicals can introduce other ions to surface water.

The U.S. Geological Survey National Water Information System (NWIS) database was queried for data on major-ion chemistry at five stations in the basin (table 2). Chemical data were reduced to only those samples that reported all major ions (calcium, magnesium, sodium, bicarbonate, sulfate, and chloride; potassium was optional). Bicarbonate concentration was assumed to be equal to acid-neutralizing capacity reported as bicarbonate. Anion-cation balances were performed to validate the dissolved-ion data. Only samples with a balance less than 5 percent were used in the analysis. There are not enough available data to support an analysis of temporal trends in major-ion concentrations in the basin, so this report focused on spatial differences in water quality between the five stations.

Suspended-sediment data also were available at discontinued surface-water station 07302000 (North Fork Red River near Granite, OK). This station recorded 12 water years (1904-08, 1938-44) of discharge data until the completion of the Lake Altus dam. Those data provide an estimate of suspended-sediment loads being supplied to Lake Altus.

METHODS OF ANALYSIS

Kendall's Tau and Kendall Slope Estimator

Kendall's tau (Kendall, 1938, 1975) is a rank-based statistic that tests for the presence of trends. It is generally insensitive to outlying values and can be applied even when some values in a series are missing (Wahl and Tortorelli, 1997, p. 9). The value of the tau statistic is a number between 1 and -1; endpoints that reflect positive and negative trends, respectively. In this report, a probability (p) value was reported with each tau statistic, and a 95 percent confidence level ($p = 0.05$) indicated a significant trend. When a trend was significant, the Kendall slope (Sen, 1968) was calculated to estimate the general slope of the trend.

Table 2. Summary of major-ion data for water-quality stations in the North Fork Red River study area

[Numbers in parentheses indicate the cation or anion proportion of the constituent. meq/L, milliequivalents per liter; %, percent]

Station number	Station name	Period of record used in analysis (water year)	Number of samples used in analysis	Mean cation concentrations			Mean anion concentrations		
				Calcium, dissolved (meq/L)	Magnesium, dissolved (meq/L)	Sodium and potassium, dissolved (meq/L)	Bicarbonate, dissolved (meq/L)	Sulfate, dissolved (meq/L)	Chloride, dissolved (meq/L)
07301200	McClellan Creek near McLean, TX	1965-1969, 1974-1980	67	3.51 (32.6%)	1.63 (15.1%)	5.64 (52.3%)	3.54 (32.9%)	2.60 (24.2%)	4.62 (42.9%)
07301300	North Fork Red River near Shamrock, TX	1964-1969, 1974-1980	69	14.4 (53.4%)	3.73 (13.8%)	8.82 (32.7%)	2.48 (9.23%)	14.0 (52.1%)	10.4 (38.7%)
07301410	Sweetwater Creek near Kelton, TX	1964-1968, 1974-1980	77	5.26 (51.9%)	2.09 (20.6%)	2.79 (27.5%)	4.35 (43.2%)	4.54 (45.1%)	1.17 (11.6%)
07301450	North Fork Red River near Erick, OK	1960-1962	18	10.3 (38.4%)	6.05 (22.5%)	10.5 (39.1%)	3.20 (11.9%)	15.4 (57.4%)	8.23 (30.7%)
07301500	North Fork Red River near Carter, OK	1960-1961, 1973-1976	102	11.0 (38.8%)	6.34 (22.4%)	11.0 (38.8%)	3.21 (11.4%)	15.3 (54.3%)	9.69 (34.4%)

Locally-weighted scatterplot smoothing (Cleveland and McGill, 1984; Cleveland, 1985), or LOWESS, was used to dampen variability and illustrate trends. LOWESS is preferable to a moving average, especially when the period of record is small, because every data point has an influence on the smoothing curve. The magnitude of influence, or weight, of a single point on any part of the curve decreases with distance.

Base-Flow Determination

Values of base flow were derived using BFI (Base Flow Index), a FORTRAN program developed by Wahl and Wahl (1988, 1995) derived from a procedure proposed by the Institute of Hydrology (1980a, 1980b). This program divides the water year into N-day periods based on the length of a typical hydrograph recession. After the minimum streamflow in each N-day period is identified, adjacent minimums are compared to establish turning points on a base-flow hydrograph. When these points are connected on semi-logarithmic paper, the area beneath the base-flow hydrograph is an estimate of the base-flow volume (Wahl and Tortorelli, 1997, p. 12). The two stations on Sweetwater Creek (07301410 and 07301420) used N=3; the other two stations (07301200 and 07301500) used N=5.

Stiff and Piper Diagrams

Stiff (1951) diagrams were used to illustrate average major-ion concentrations at each water-quality station. In these diagrams, milliequivalent concentrations are plotted horizontally from a vertical zero axis with cations on the left and anions on the right. Another type of diagram was used to illustrate differences in major-ion compositions between stations. In Piper (1944) diagrams, anion and cation compositions are plotted on separate ternary diagrams, and the positions are projected into a quadrilinear, diamond-shaped grid. Locations of the points on the diagram reveal the general water composition, imply a source, and illustrate mixing trends.

Constituent Load and Yield Computation

Sulfate, chloride, and dissolved solid loads were calculated at each station having at least 10 years of discharge record. Only daily discharge record has adequate resolution to make annual load estimates in streams of variable streamflow. However, constituent concentration data are collected periodically, not continuously. Because dissolved-constituent concentrations are correlated with discharge, estimated continuous water-quality estimates can be generated at each streamflow-gaging station. For this report, concentrations of sulfate, chloride, and dissolved solids were estimated for each day of the water year using linear or logarithmic regressions of constituent concentrations compared to instantaneous discharge. Daily dissolved loads of each constituent, in tons per day, were estimated using equation 1:

$$\text{Daily Load} = 0.0027Qa \qquad (1)$$

where Q is mean daily discharge in cubic feet per second, a is the regression-estimated mean daily concentration of the dissolved constituent in milligrams per liter (table 3), and 0.0027 is a conversion factor in units of liter*second*tons per milligram*day*foot^3. Values for each day of the water year were added to estimate the annual dissolved load for each station. The annual dissolved load was divided by the drainage area upstream from each station to obtain estimates of annual dissolved constituent yields. Suspended sediment was analyzed in a similar procedure.

The station near Sweetwater, Oklahoma, (07301420) did not have water-quality data for sulfate, chloride, and dissolved solids, but did have measurements of specific conductance. For each measurement of specific conductance at station 07301420, sulfate, chloride, and dissolved solids concentrations were estimated by using linear regression equations (table 3) derived from measurements of specific conductance and constituent concentrations at the station near Kelton (07301410). Subsequently, another regression was performed between the conductance-estimated concentrations and instantaneous discharge measured at station 07301420 (table 3). Only a few small tributaries join Sweetwater Creek in the 15 miles between station 07301410 near Kelton, Texas, and station 07301420 near Sweetwater, Oklahoma.

PRECIPITATION TRENDS

The precipitation record for Oklahoma Climate Division 4 was tested as an annual series (1 value per year for 1896-1995) using the Kendall's tau test. The test of the annual series resulted in a tau of 0.12, indicating a small increasing trend (table 4). However, the test of the entire precipitation record was not significant at a 95 percent level of confidence (p = 0.07).

The amount of annual precipitation in Oklahoma Climate Division 4 varied between 42 and 15 inches over 100 years. However, the LOWESS curve remained fairly constant at about 27 inches per year until 1945, after which it steadily increased (fig. 6). Based on this inflection point, the data were split into pre-1945 (49 years) and post-1945 (51 years) subsets. The Kendall's tau test on the 1896-1944 subset of the data indicated an insignificant decreasing trend with a tau of -0.04 and a p-value of 0.70 (table 4). The 1945-1995 trend was positive and significant with a tau of 0.23 and a p-value of 0.02 (table 4). The Kendall slope for this 51-year subset was 0.14 inch per year (table 4).

STREAMFLOW TRENDS

Streamflow characteristics were examined at each of the four streamflow-gaging stations having a period of record exceeding 10 years (table 1, figs. 7-10). The data were summarized by water year before doing statistical analysis. Using the Kendall's tau test, four streamflow characteristics were tested for trends: annual streamflow volume, annual base-flow volume, base-flow index, and annual peak discharge (table 5).

Table 3. Regression equations used in the estimation of dissolved and suspended constituent loads

[R^2, coefficient of determination; Q, instantaneous discharge in cubic feet per second; SC, specific conductance in microSiemens per centimeter at 25 degrees Celcius; [SO_4^{-2}], sulfate concentration in milligrams per liter; [Cl^-], chloride concentration in milligrams per liter; [DS], dissolved solids concentration in milligrams per liter; [SS], suspended sediment concentration in milligrams per liter]

Station number	Constituent	Regression type	Regression equation	R^2
		Regressions of constituent concentrations and specific conductance		
07301420 (from data for station 07301410)	sulfate	linear	$[SO_4^{-2}] = 0.4942(SC) - 238.75$	0.8773
	chloride	linear	$[Cl^-] = 0.0540(SC) - 6.8684$	0.6300
	dissolved solids	linear	$[DS] = 0.7669(SC) - 98.971$	0.9840
		Regressions of constituent concentrations and instantaneous discharge		
07301200	sulfate	linear	$[SO_4^{-2}] = -0.6596(Q) + 132.82$	0.1301
	chloride	linear	$[Cl^-] = -1.8402(Q) + 190.71$	0.4185
	dissolved solids	linear	$[DS] = -3.2316(Q) + 691.92$	0.2396
07301410	sulfate	logarithmic	$[SO_4^{-2}] = -63.767\ln(Q) + 353.24$	0.8113
	chloride	logarithmic	$[Cl^-] = -6.2173\ln(Q) + 55.935$	0.6742
	dissolved solids	logarithmic	$[DS] = -90.357\ln(Q) + 810.50$	0.8164
07301420	sulfate	logarithmic	$[SO_4^{-2}] = -140.42\ln(Q) + 757.08$	0.7116
	chloride	logarithmic	$[Cl^-] = -14.856\ln(Q) + 100.67$	0.6381
	dissolved solids	logarithmic	$[DS] = -214.41\ln(Q) + 1{,}441.4$	0.7116
07301500	sulfate	logarithmic	$[SO_4^{-2}] = -57.706\ln(Q) + 942.37$	0.1562
	chloride	logarithmic	$[Cl^-] = -6.0272\ln(Q) + 368.06$	0.0063
	dissolved solids	logarithmic	$[DS] = -96.202\ln(Q) + 2{,}193.1$	0.0786
07302000	suspended sediment	logarithmic	$[SS] = 3{,}360.2\ln(Q) - 13{,}197$	0.5387

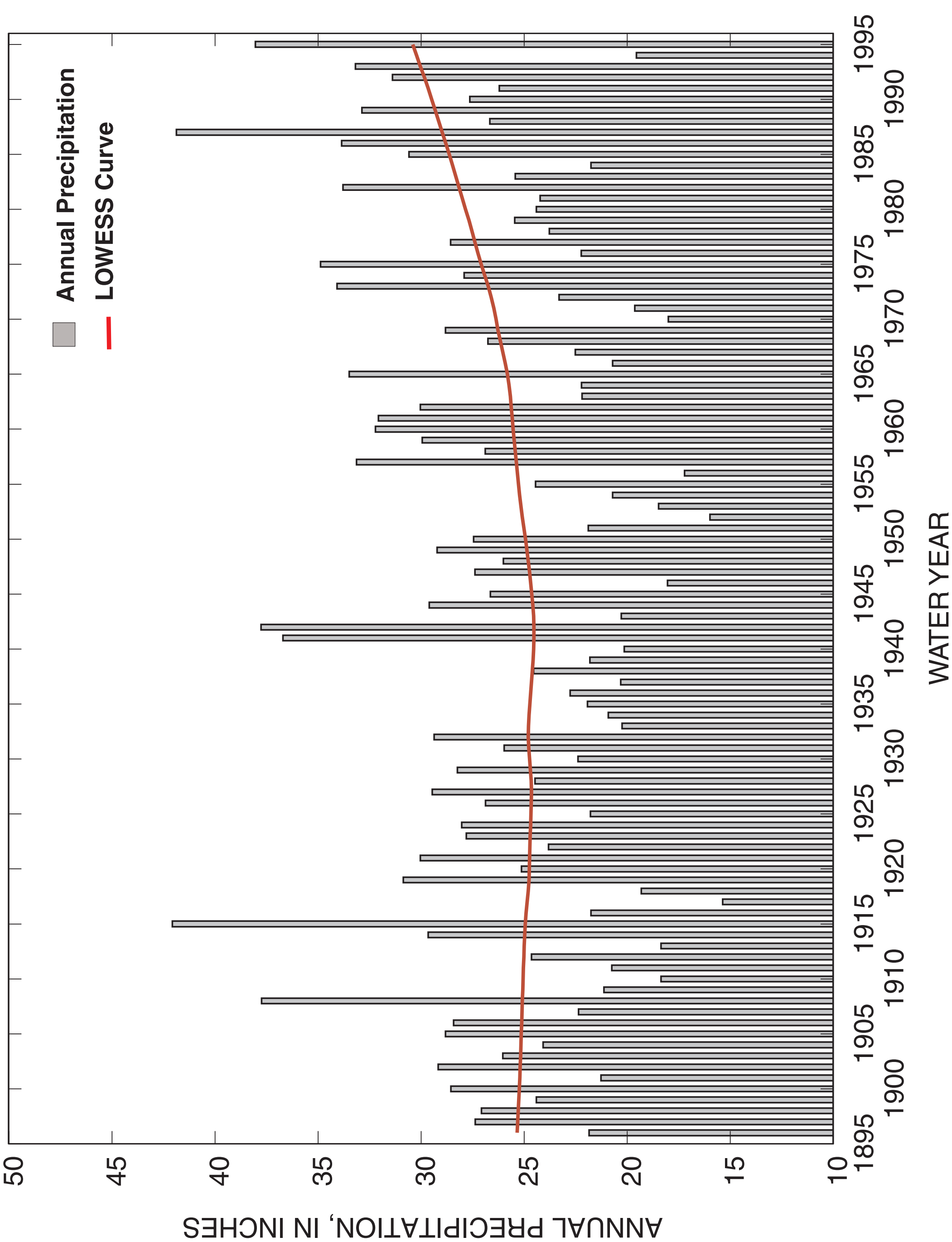


Figure 6. Annual precipitation for Oklahoma Climate Division 4, water years 1896–1995.

Table 4. Results of trend tests on precipitation data, Oklahoma Climate Division 4, 1896-1995

[shaded values are statistically significant at the p=0.05 level; --, no data]

Series, water years	Years of record tested	Kendall's tau	p-value for Kendall's tau	Mean annual precipitation (inches)	Trend slope (inches per year)
Annual, 1896-1995	100	0.12	0.07	26.13	--
Annual, 1896-1944	49	-0.04	0.70	25.51	--
Annual, 1945-1995	51	0.23	0.02	26.74	0.14

McClellan Creek near McLean, Texas (station 07301200)

Based on 13 years of record (1968-1980), the LOWESS curve and Kendall's tau (-0.36) for annual streamflow at station 07301200 indicated a decreasing streamflow trend (fig. 7, table 5), however, the trend is not significant (p = 0.10). That streamflow-gaging station was discontinued after water year 1980 but was maintained as a high-flow station, recording annual peaks between 1987-93 and 1995-97. Annual peak discharge for McClellan Creek near McLean (07301200) has a tau of -0.37, and the trend is significant (p = 0.02) over 23 years of discontinuous record (table 5). According to the Kendall slope estimator, annual peaks have decreased at an average rate of 120 cubic feet per second per year (table 5).

Annual base flow at McClellan Creek has decreased at a rate of 166 acre-feet per year from 1968-1980. This decrease is possibly related to increases in irrigated agriculture in the Texas Panhandle. As a result of ground-water withdrawal, the saturated thickness of the High Plains Aquifer has declined more than 100 feet in some areas of the basin (Luckey and others, 1981; McGuire and Sharpe, 1997). Lowered water levels in the aquifer may have reduced the hydraulic gradient of ground water near the stream, in turn decreasing ground-water discharge to streams. The base-flow index, however, did not change significantly over the period of record from 1968 to 1980. During the 13 years of record, base flow accounted for a median of nearly 30 percent of the annual streamflow (table 5).

Sweetwater Creek near Kelton, Texas (station 07301410) and near Sweetwater, Oklahoma (station 07301420)

Sweetwater Creek near Kelton, Texas, (07301410) is similar to the station on McClellan Creek in terms of both geologic setting and median annual streamflow (fig. 4, table 5). Sweetwater Creek near Kelton had no significant trend in annual streamflow, but did have a significant decreasing trend in annual peak discharge over 37 years of record (table 5, fig. 8). The Kendall slope of the peak discharge trend is -11 cubic feet per second per year (table 5).

Unlike the station on McClellan Creek, there was not a significant decrease in annual base flow at Sweetwater Creek near Kelton (fig. 8, table 5). However, there was a significant increase in the base-flow index with a rise of 0.0044 (0.44 percent) per year (table 5). Most values of base-flow index for Sweetwater Creek near Kelton are greater than 0.5 and the median value is 0.667, indicating that most of the annual streamflow volume is base flow (fig. 8, table 5).

No significant trends in annual streamflow or base flow were evident at Sweetwater Creek near Sweetwater, Oklahoma, (07301420) (fig. 9, table 5). Base flow at the Sweetwater station supplied a median of 76.0 percent of the annual streamflow, slightly more

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Table 5. Results of trend tests on annual streamflow volume, annual base-flow volume, base-flow index, and annual peak discharge

[ft^3/s, cubic feet per second; shaded values are statistically significant at the p=0.05 level; --, no data]

Streamflow parameter	Period of record tested	Years of record tested	Kendall's tau	p-value for Kendall's tau	Median	Trend slope
07301200 McClellan Creek near McLean, Texas						
Annual Streamflow (acre-feet)	1968-1980	13	-0.36	0.10	11,820	--
Annual Base Flow (acre-feet)	1968-1980	13	-0.44	0.04	3,409	-166
Base-Flow Index	1968-1980	13	0.10	0.67	0.293	--
Annual Peak Discharge (ft^3/s)	1968-1980, 1987-1993, 1995-1997	23	-0.37	0.02	1,180	-120
07301410 Sweetwater Creek near Kelton, Texas						
Annual Streamflow (acre-feet)	1963-1999	37	0.02	0.90	9,681	--
Annual Base Flow (acre-feet)	1963-1999	37	0.16	0.17	6,532	--
Base-Flow Index	1963-1999	37	0.27	0.02	0.667	0.0044
Annual Peak Discharge (ft^3/s)	1962-1999	38	-0.37	0.00	390	-11
07301420 Sweetwater Creek near Sweetwater, Oklahoma						
Annual Streamflow (acre-feet)	1987-1999	13	0.00	1.00	17,780	--
Annual Base Flow (acre-feet)	1987-1999	13	0.00	1.00	13,040	--
Base-Flow Index	1987-1999	13	0.10	0.67	0.760	--
Annual Peak Discharge (ft^3/s)	1986-1999	14	0.14	0.51	265	--
07301500 North Fork Red River near Carter, Oklahoma						
Annual Streamflow (acre-feet)	1945-1962, 1965-1999	53	0.06	0.50	84,330	--
Annual Base Flow (acre-feet)	1945-1962, 1965-1999	53	0.40	0.00	23,190	713
Base-Flow Index	1945-1962, 1965-1999	53	0.53	0.00	0.300	0.0085
Annual Peak Discharge (ft^3/s)	1945-1999	55	-0.19	0.04	6,140	-86

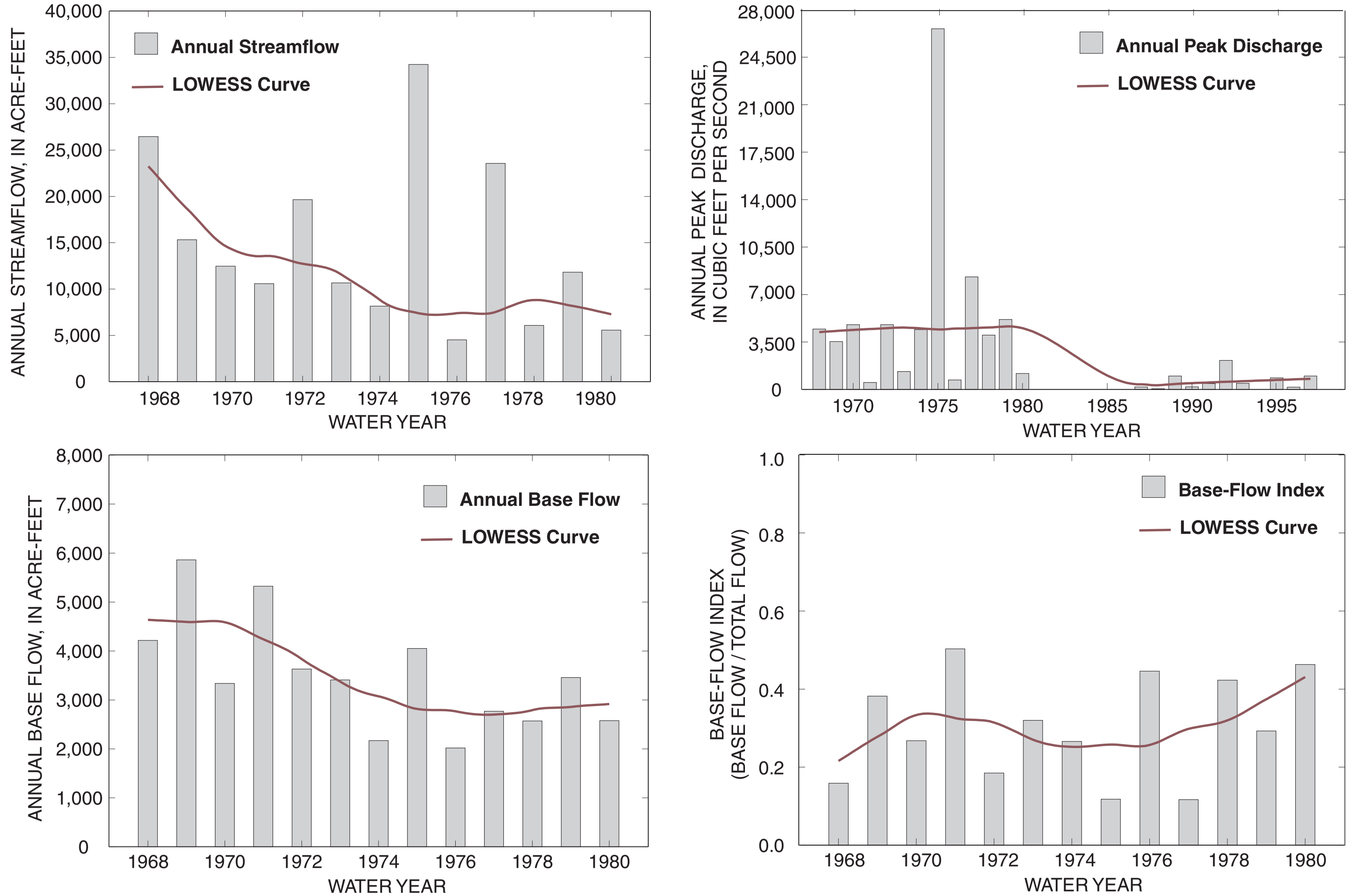


Figure 7. Annual streamflow, annual base flow, and base-flow index of McClellan Creek near McLean, Texas, (07301200) 1968–80, and annual peak discharge, 1968–80, 1987–93, and 1995–97.

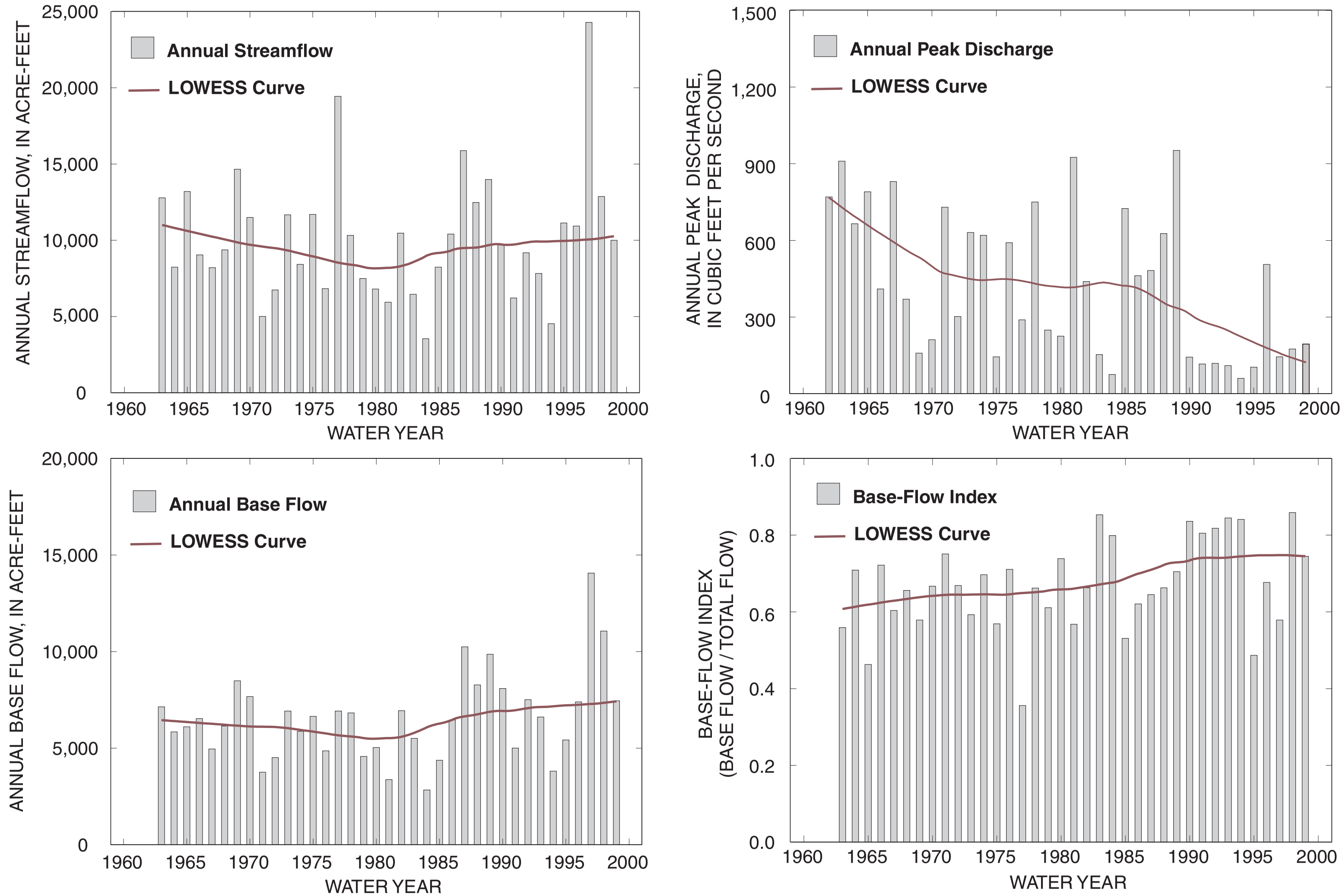


Figure 8. Annual streamflow, annual base flow, and base-flow index of Sweetwater Creek near Kelton, Texas, (07301410) 1963–99, and annual peak discharge, 1962–99.

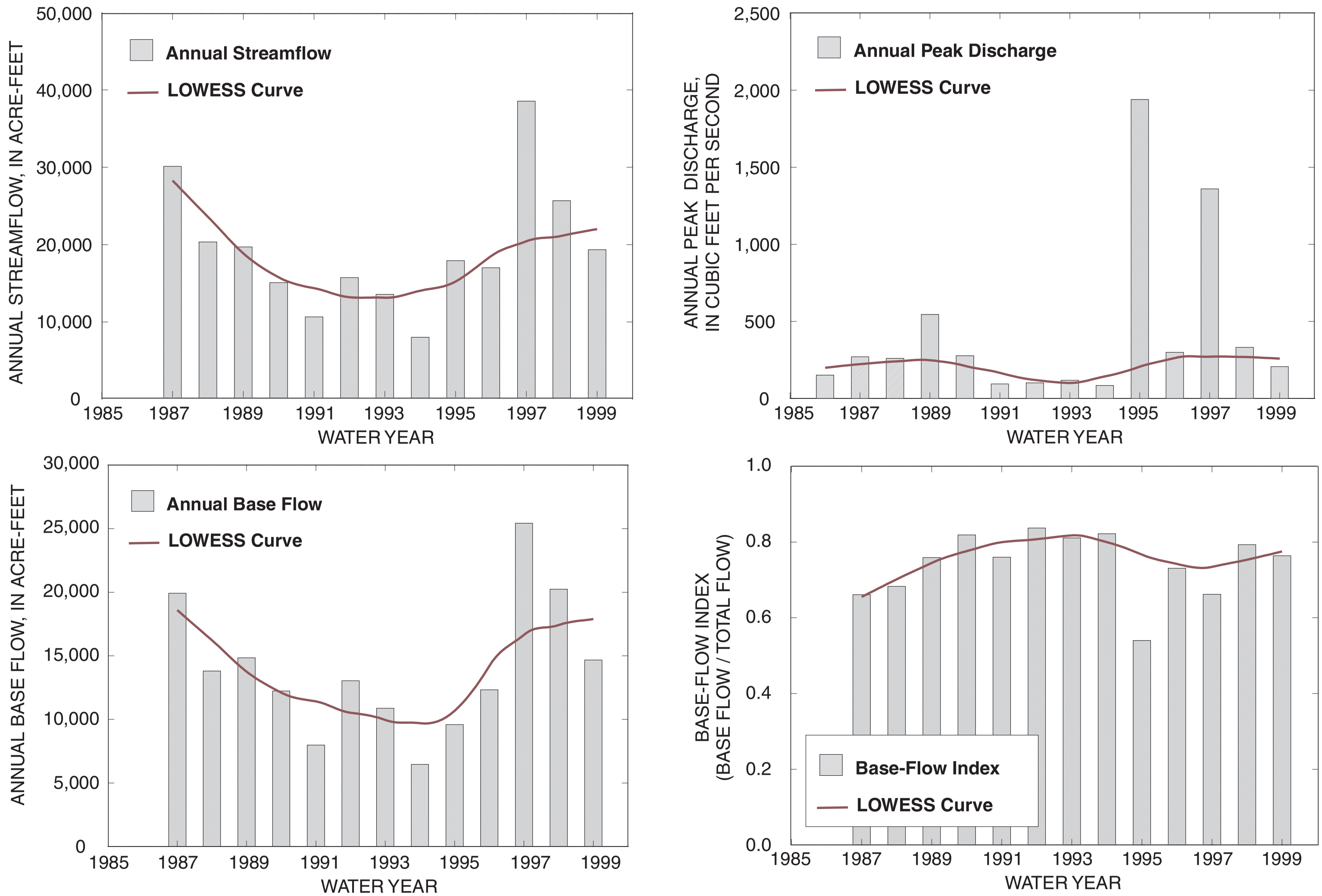


Figure 9. Annual streamflow, annual base flow, and base-flow index of Sweetwater Creek near Sweetwater, Oklahoma, (07301420) 1987–99, and annual peak discharge, 1986–99.

than the median base-flow contribution calculated at Kelton (66.7 percent) several miles upstream (table 5).

North Fork Red River near Carter, Oklahoma (station 07301500)

North Fork Red River near Carter, Oklahoma, (07301500) has the longest period of record—53 years between water years 1945 and 1999. The LOWESS curve for annual streamflow resembles a sinusoidal curve with a slight upturn in the last 15 years of record (fig. 10). The annual streamflow record had no statistically significant trend with a Kendall's tau value of 0.06 and a p-value of 0.50 (table 5).

Trends in the other three parameters are all significant at this station. The p-values for annual base flow and base-flow index were both 0.00 (table 5). Annual peaks significantly decreased over the period of record (table 5). The p-value for the test on peaks was 0.04, and the slope of the trend was -86 cubic feet per second per year, or just greater than 1 percent of the median per year (table 5).

The slope of the LOWESS curve for total annual base flow increased slightly in 1962 and increased again in 1978 (fig. 10). The Kendall slope estimator indicated the annual volume of base flow increased by an average 713 acre-feet each year (table 5). As a result of the greater contribution of base flow, the base-flow index also increased significantly at a rate of nearly 1 percent per year (table 5). For the first 10 years of record, base-flow index values were generally less than 0.2, or 20 percent of the annual streamflow (fig. 10). After 40 years of steady increase, the base-flow index at the station near Carter exceeded a value of 0.6, or 60 percent of the annual streamflow in 1992 (fig. 10). The 1992-1999 period marked a shift in the hydrology of the river from one dominated by surface runoff to one dominated by base flow.

Several possible explanations exist for the increased proportion of base flow in the North Fork Red River. An increase in the number of retention structures, such as stock ponds, would dampen storm peaks by decreasing the amount of runoff reaching the river. For several counties in the Texas and Oklahoma Panhandles, Wahl and Tortorelli (1997) reported an increase in the number of stock ponds from 100 to 1,000 between 1940 and 1990. More efficient irrigation techniques and farming practices also could play a role in increasing the base-flow index by retarding peak discharges and inducing more recharge. According to Luckey and Becker (1999, p. 56), dryland agriculture practices tend to enhance recharge from precipitation and decrease the amount of surface runoff. Artificial recharge or a reduction in the rate of ground-water extraction from aquifers could increase annual base flow and the base-flow index.

Comparison of Streamflow Trends between the North Fork Red River and Beaver-North Canadian River study areas

Four streamflow-gaging stations with more than 10 years of record were maintained in the basin from 1945 to 1999. These stations recorded no significant trends in annual streamflow volume (table 5). Base flow, however, decreased significantly at the most upstream station (07301200) and increased significantly at the most downstream station (07301500) (table 5). There was no significant change in base flow at two stations on Sweetwater Creek. Two of the streamflow stations had significant increasing trends in the base-flow index and three had significant decreasing trends in annual peak flows (table 5). The base-flow index increased at all four stations in the North Fork Red River basin as it did at most stations in the Beaver-North Canadian River basin (Wahl and Tortorelli, 1997). However, the increase in base-flow index was only statistically significant at Sweetwater Creek near Kelton (07301410) and North Fork Red River near Carter (07301500) (table 5). This increase in the base-flow index is most apparent in the downstream part of the North Fork Red River study area near Carter (07301500) as it was at the station near Woodward (fig. 1) in the downstream part of the Beaver-North Canadian River study area, located about 65 miles north of the North Fork Red River study area (Wahl and Tortorelli, 1997, p. 27).

Another characteristic shared by both study areas is a general decrease in peak discharge. For the three North Fork Red River study area stations with significant trends in peak discharge, the decrease is greatest at stations on or near the Ogallala Formation (fig. 4). Estimating the difference between the beginning and ending values of the LOWESS curve, the decreases are: 4,000 to 500 cubic feet per second (-88 percent) near McLean (fig. 7), 800 to 150 cubic feet per second (-81 percent) near Kelton (fig. 8), and 9,000 to 5,000 cubic feet per second (-44 percent) near

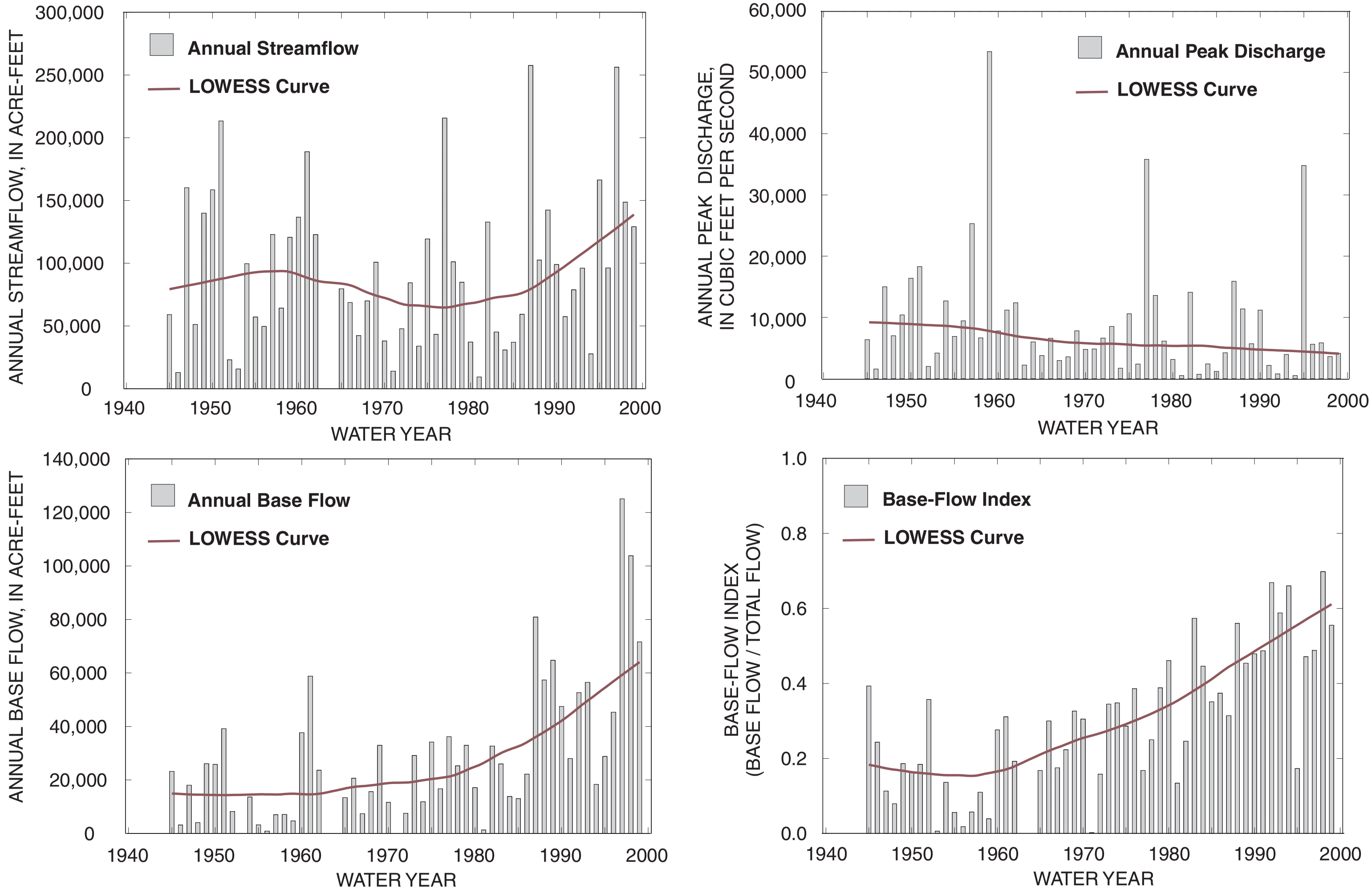


Figure 10. Annual streamflow, annual base flow, and base-flow index of the North Fork Red River near Carter, Oklahoma, (07301500) 1945–62, 1965–99, and annual peak discharge, 1945–99.

Carter (fig. 10). This pattern is similar to that reported by Wahl and Tortorelli (1997, p. 35) for the Beaver-North Canadian River study area. The stations near McLean and Kelton are located only a few miles downstream from the base of the Ogallala Formation of Tertiary age (fig. 4). In climate and geologic setting they are similar to the station near Woodward on the North Canadian River (fig. 1). The station near Carter (07301500) is geologically similar to the North Canadian station near Seiling (fig. 1).

In contrast to the Beaver-North Canadian River, most trends in streamflow are not as pronounced in the North Fork Red River upstream from Lake Altus. If these trends are a result of High Plains ground-water extraction as Wahl and Tortorelli (1997) suggest, it is logical that trends are less pronounced because the High Plains Aquifer underlies less than half of the North Fork Red River basin upstream from Lake Altus, whereas it underlies more than 90 percent of the portion of the Beaver-North Canadian basin studied by Wahl and Tortorelli (1997).

MAJOR-ION CHEMISTRY

Stiff diagrams

The two major tributaries of the North Fork Red River upstream from Lake Altus had somewhat different major-ion concentrations. The station on McClellan Creek near McLean (07301200) was the only one of the five water-quality stations that had greater concentrations of sodium and chloride than calcium and sulfate (fig. 11, table 2). The likely source of the sodium and chloride is water from salt springs that exist throughout the area near the base of the Ogallala Formation (fig. 4).

Compared to the McClellan Creek station, water quality at Sweetwater Creek near Kelton (07301410) was similar with respect to total dissolved-solids content, but calcium and sulfate were predominant constituents, not sodium and chloride (fig. 11, table 2). The primary source of calcium and sulfate in Sweetwater Creek is probably gypsum or anhydrite of the Quartermaster Formation and Whitehorse Group of Permian age (fig. 4, fig. 5). Of all five water-quality stations, the stations on McClellan Creek and Sweetwater Creek (07301200 and 07301410) had the greatest proportions of bicarbonate (fig. 11, table 2). Bicarbonate at these stations may be derived from the Ogallala Formation, which has multiple zones of calcium carbonate caliche (fig. 4, fig. 5).

For all three stations on the North Fork Red River, the Stiff (1951) diagrams were similar anvil or wide hourglass-shaped polygons (fig. 11). The bases of the polygons were slightly wider than the tops. This configuration indicates water rich in calcium sulfate with slightly smaller concentrations of sodium chloride (table 2). The calcium sulfate was almost certainly derived from Permian-age units, all of which are rich in gypsum and anhydrite (fig. 5). Mean major-ion concentrations in the North Fork Red River are established upstream from the Shamrock, Texas, station (07301300).

Concentrations of dissolved magnesium in the North Fork Red River increased in a downstream direction (fig. 12, table 2). An increase in magnesium can be caused by the dissolution of dolomite (which also is abundant in the Permian-age bedrock of the area) (Scott and Ham, 1957; Hem, 1989, p. 97). However, compared to station 07301300, stations 07301450 and 07301500 had decreases in calcium concentration that were almost identical in magnitude to increases in magnesium concentration (fig. 12, table 2). Therefore, dedolomitization, or dolomite dissolution paired with calcite precipitation, may be responsible for the elevated concentrations of magnesium in the downstream direction, according to the reaction:

$$CaMg(CO_3)_2 + Ca^{2+} \xrightarrow{\text{Gypsum Dissolution}} 2CaCO_3 + Mg^{2+}$$

The net result is a decreased concentration of dissolved calcium and an increased concentration of dissolved magnesium (Back and others, 1983).

Some water-quality stations had a change in chemical concentrations with discharge. For the station on McClellan Creek (07301200), the chemical concentrations remained fairly constant (table 6). The only difference was a 11.7 and 15.7 percent increase in dissolved sodium and dissolved chloride concentrations, respectively, during low discharge compared to high discharge (table 6). Several miles downstream on the North Fork Red River near Shamrock (07301300), the major-ion concentrations changed with streamflow (fig. 13, table 6). At discharges less than or equal to 10 cubic feet per second, dissolved sodium and chloride concentrations decreased by an average of 20.8 and 28.0 percent, respectively, compared to discharges greater than 10 cubic feet per second (table 6). In

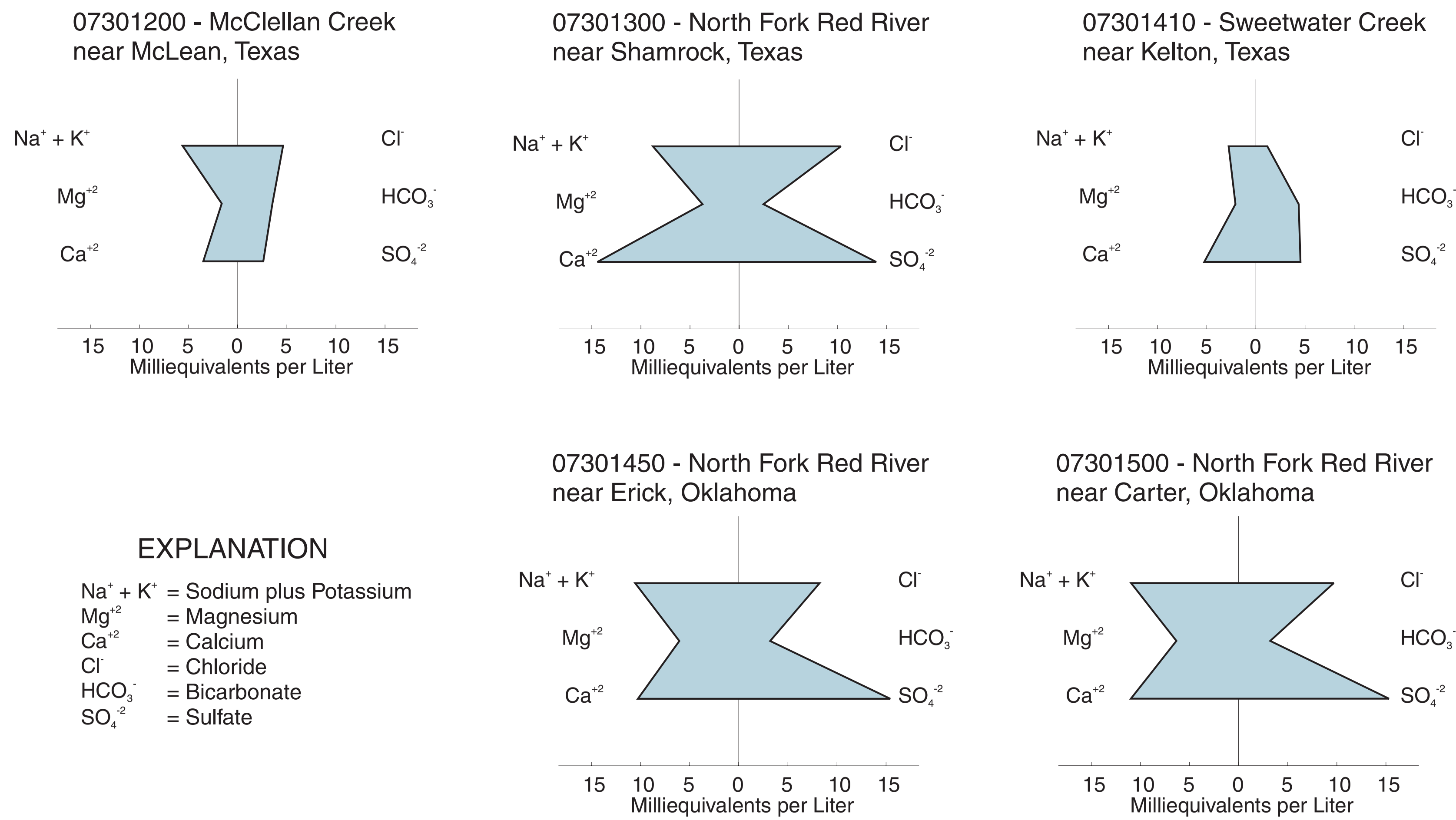


Figure 11. Mean major-ion concentrations at five water-quality stations in the North Fork Red River study area (periods of record in table 2).

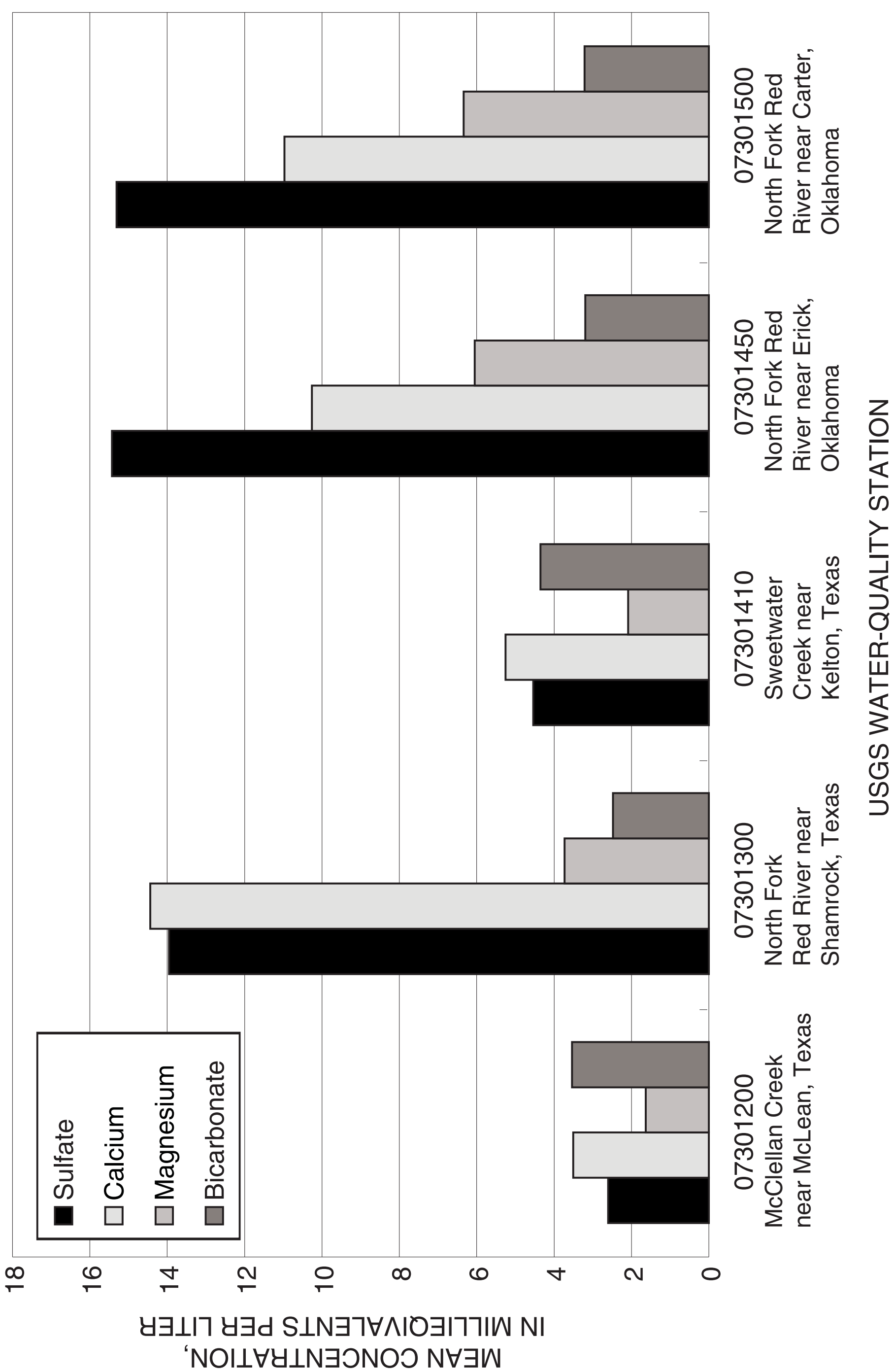
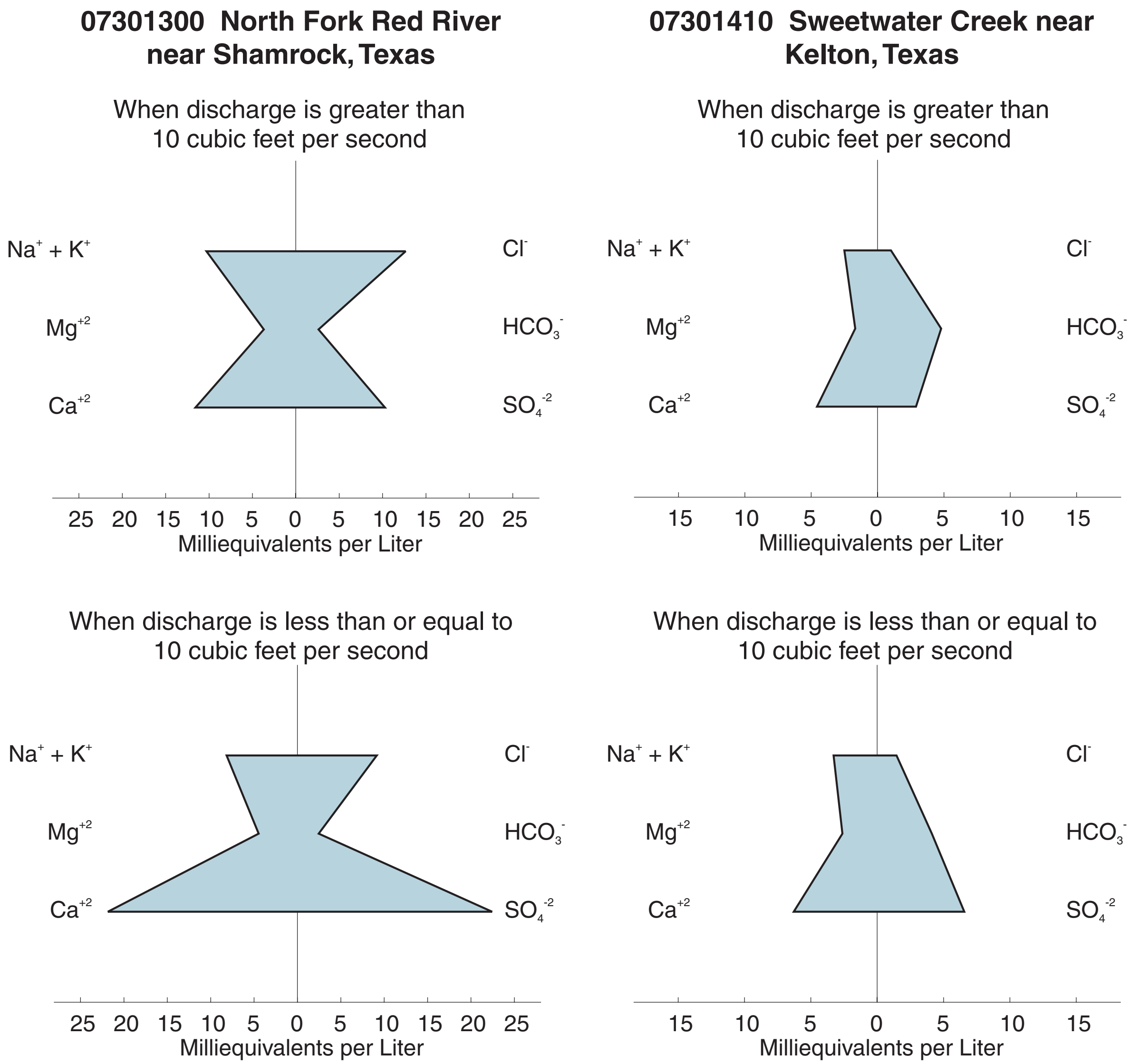


Figure 12. Mean concentrations of selected major ions in the North Fork Red River study area (periods of record in table 2).

Table 6. Changes in mean major-ion composition with discharge at water-quality stations in the North Fork Red River study area

[Numbers in parentheses indicate percent difference between high-flow and low-flow discharge ((concentration$_{lowflow}$-concentration$_{highflow}$)/concentration$_{highflow}$). ft^3/s, cubic feet per second; meq/L, milliequivalents per liter, >, greater than; ≤, less than or equal to; %, percent]

Station number	Station name	Period of record used in analysis (water year)	Discharge (ft^3/s)	Number of samples used in analysis	Mean cation concentrations			Mean anion concentrations		
					Calcium, dissolved (meq/L)	Magnesium, dissolved (meq/L)	Sodium and potassium, dissolved (meq/L)	Sulfate, dissolved (meq/L)	Chloride, dissolved (meq/L)	Bicarbonate, dissolved (meq/L)
07301200	McClellan Creek near McLean, TX	1965-1969, 1974-1980	High, > 10	27	3.58	1.60	5.31	2.57	4.27	3.64
			Low, ≤ 10	38	3.45 (-3.63%)	1.67 (4.38%)	5.93 (11.7%)	2.66 (3.50%)	4.94 (15.7%)	3.46 (-4.95%)
07301300	North Fork Red River near Shamrock, TX	1964-1969, 1974-1980	High, > 10	43	11.6	3.68	10.3	10.3	12.7	2.62
			Low, ≤ 10	23	21.8 (87.9%)	4.48 (21.7%)	8.16 (-20.8%)	22.4 (117%)	9.15 (-28.0%)	2.44 (-6.87%)
07301410	Sweetwater Creek near Kelton, TX	1964-1968, 1974-1980	High, > 10	38	4.56	1.68	2.50	2.90	1.01	4.79
			Low, ≤ 10	38	6.28 (37.7%)	2.62 (56.0%)	3.29 (31.6%)	6.56 (126%)	1.45 (43.6%)	4.12 (-14.0%)
07301450	North Fork Red River near Erick, OK	1960-1962	No discharge data available							
07301500	North Fork Red River near Carter, OK	1960-1961, 1973-1976	High, > 50	51	10.4	6.00	10.8	14.2	9.65	3.35
			Low, ≤ 50	51	11.5 (10.6%)	6.67 (11.2%)	11.1 (2.78%)	16.5 (16.2%)	9.72 (0.725%)	3.07 (-8.36%)



EXPLANATION

$Na^{+} + K^{+}$ = Sodium plus Potassium
Mg^{+2} = Magnesium
Ca^{+2} = Calcium
Cl^{-} = Chloride
HCO_3^{-} = Bicarbonate
SO_4^{-2} = Sulfate

Figure 13. Change in mean major-ion concentrations with discharge at two stations in the North Fork Red River study area (periods of record in table 2).

contrast, mean dissolved calcium and sulfate concentrations at low discharge were both about 22 milliequivalents per liter—nearly double the mean high-flow concentrations (table 6). These elevated concentrations of calcium and sulfate indicate the station is downstream from a calcium sulfate source. Small springs issuing from the gypsum-rich Blaine Formation (fig. 4) are probably the major contributor of the calcium and sulfate.

On Sweetwater Creek near Kelton (07301410), low-discharge concentrations of calcium, magnesium, sodium, sulfate, and chloride were greater than high-discharge concentrations (fig. 13, table 6). Dissolved calcium and sulfate concentrations increased by 37.7 percent and 126 percent, respectively (fig. 13, table 6). For bicarbonate, the concentration decreased 14 percent during low discharge compared to high discharge (table 6). The Sweetwater Creek station is the only one that had a more than 10 percent change in bicarbonate concentration with discharge (table 6).

The North Fork Red River station near Erick (07301450) was not analyzed for changes in water quality with streamflow because discharges were not reported. For the station on the North Fork Red River near Carter (07301500), the major-ion samples were grouped by discharges exceeding and not exceeding 50 cubic feet per second. Dissolved calcium, magnesium, and sulfate increased by 10.6, 11.2, and 16.2 percent, respectively, during low discharge (table 6). Concentrations of other ions were relatively unchanged, except for a small decrease in bicarbonate (-8.36 percent) (table 6).

Piper diagrams

Major-ion data from the five water-quality stations also were analyzed using Piper (1944) diagrams (figs. 14-18). The general location of the points on the diagram indicate the composition of the water and imply a source mineral. The spread of the points reflects the variability of water composition. When a linear pattern of variability occurs, the endpoints of the line may represent two distinct mineral sources indicating varying degrees of mixing.

Water-quality concentrations in samples from McClellan Creek near McLean (07301200, fig. 14) were similar in variability to those from the North Fork Red River near Erick (07301450, fig. 17) and Carter (07301500, fig. 18) but had a different composition (fig. 14). This configuration reflects a greater proportion of calcium carbonate in McClellan Creek. A weak mixing trend was indicated between sodium-chloride and calcium-magnesium-carbonate sources, but major-ion chemistry remained fairly constant at McClellan Creek near McLean.

The station on Sweetwater Creek near Kelton, Texas, (07301410, fig. 16), had a different mixing trend than the other four stations. Water-quality samples plotted in a linear pattern in the upper and left quadrants of the diamond that stretched from about 20 to 80 percent sulfate plus chloride (fig. 16). The trend line paralleled the Sulfate plus Chloride axis, with a nearly constant 75 percent calcium plus magnesium (fig. 16). The proportion of chloride was relatively constant at about 15 percent of all anions; proportions of bicarbonate and sulfate both ranged from about 10 to 80 percent of all anions (fig. 16). Sources of calcium sulfate and calcium carbonate were responsible for the changes in major-ion chemistry at Sweetwater Creek near Kelton.

The Piper diagram for the station near Shamrock (07301300, fig. 15) exhibits a well developed mixing trend with sodium chloride and calcium sulfate sources. Water-quality samples plotted in a linear pattern in the upper right quadrant of the diamond that stretched from about 50 to 95 percent calcium plus magnesium (fig. 15). Of the five active water-quality stations, station 07301300 near Shamrock, Texas, had the greatest percentage of calcium sulfate with 10 of the 69 samples exceeding 80 percent. It also was the only station underlain by bedrock of the Blaine Formation (fig. 4), which contains large quantities of bedded gypsum (Scott and Ham, 1957).

The stations near Erick (07301450, fig. 17) and Carter (07301500, fig. 18) on the North Fork Red River displayed similar characteristics. Water-quality samples from these two stations plotted as a cluster in the calcium-sulfate quadrant of the diamond that ranged from about 50 to 80 percent calcium plus magnesium (figs. 17-18). The station near Carter showed a weak mixing trend between calcium sulfate and calcium-magnesium carbonate (fig. 18).

CONSTITUENT LOAD AND YIELD ESTIMATES

Any attempt to control salinity in surface water requires knowledge of where the dissolved material

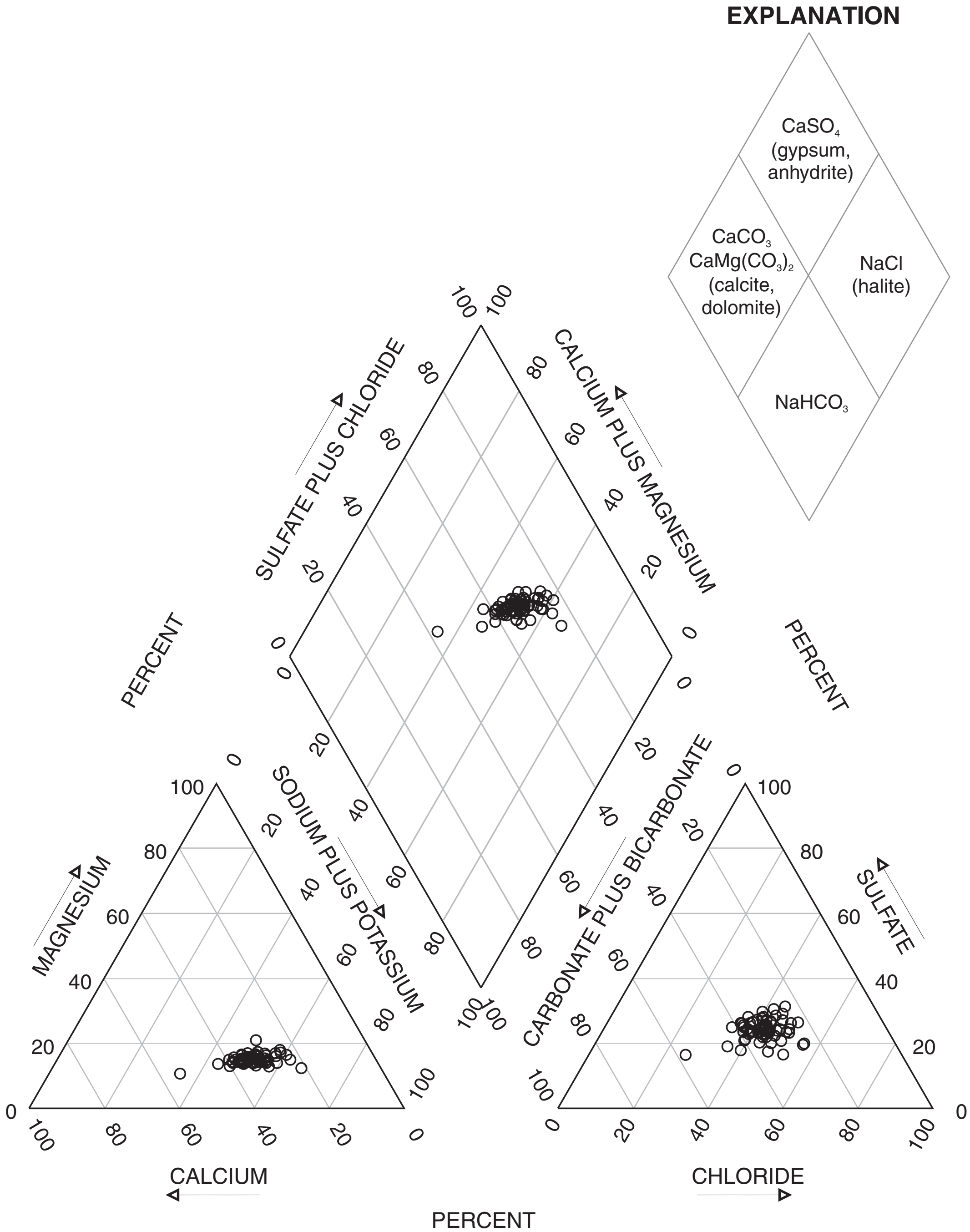


Figure 14. Major-ion water-quality data from McClellan Creek near McLean, Texas, (07301200), 1965–69 and 1974–80.

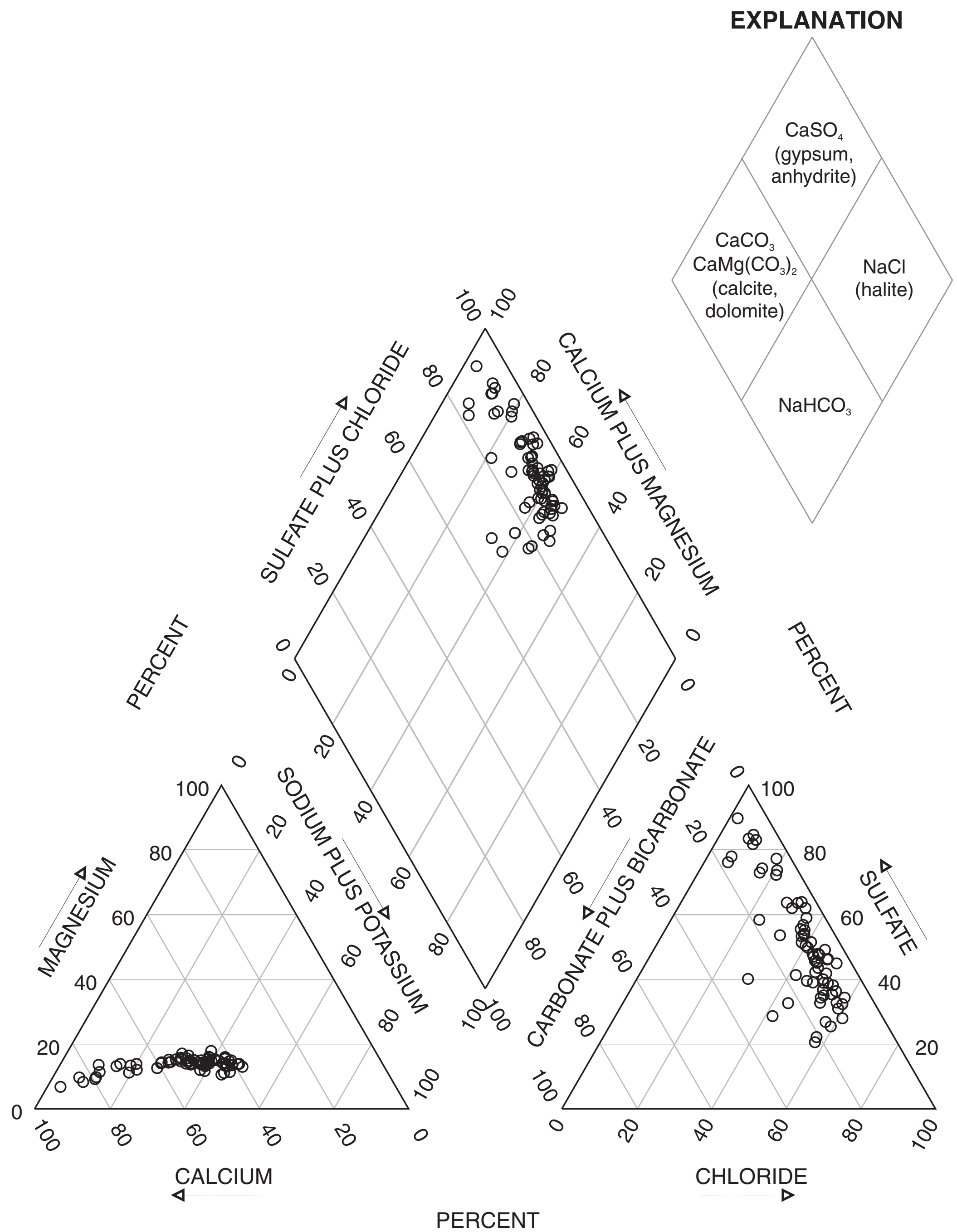


Figure 15. Major-ion water-quality data from the North Fork Red River near Shamrock, Texas, (07301300), 1964–69 and 1974–80.

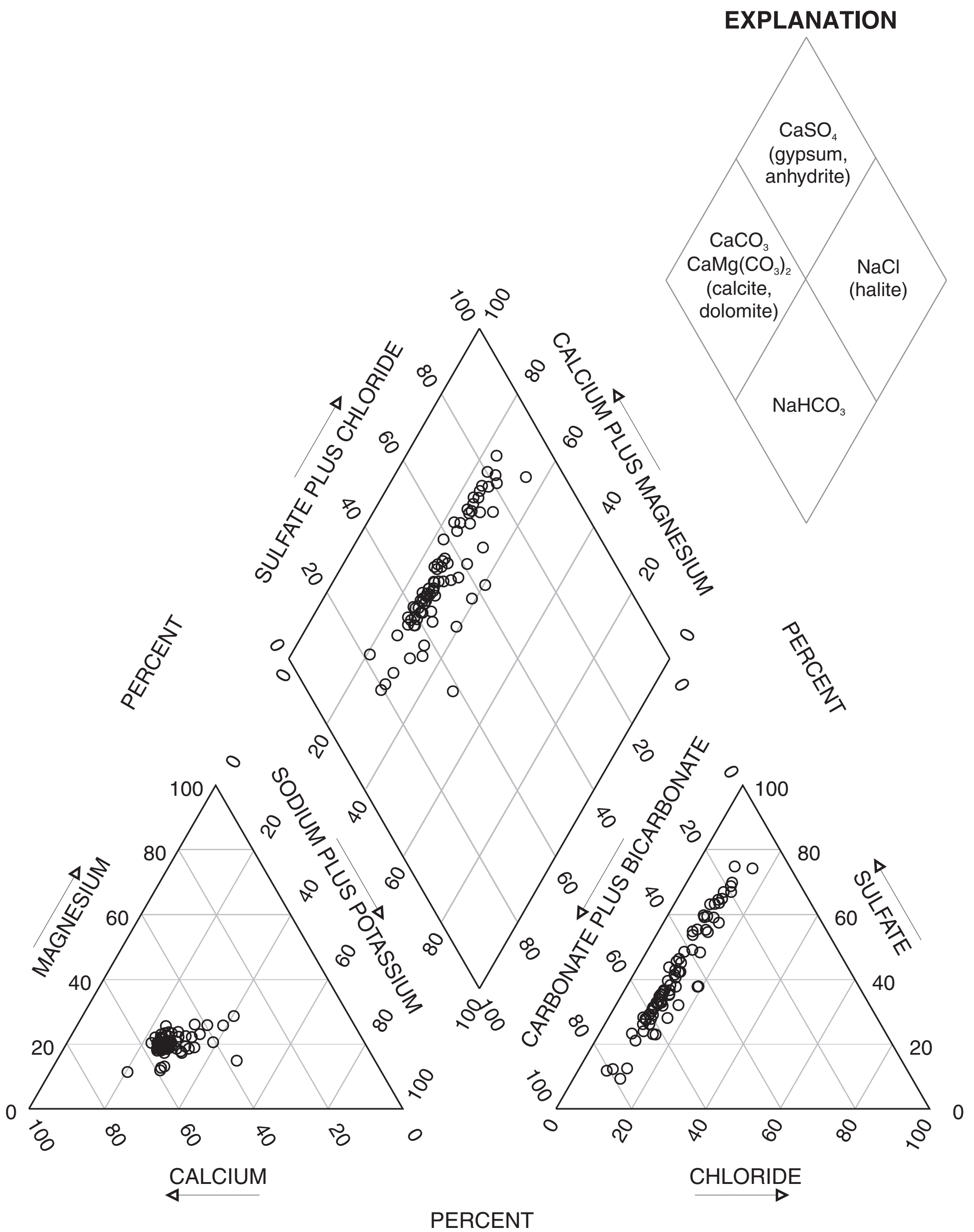


Figure 16. Major-ion water-quality data from Sweetwater Creek near Kelton, Texas, (07301410), 1964–68 and 1974–80

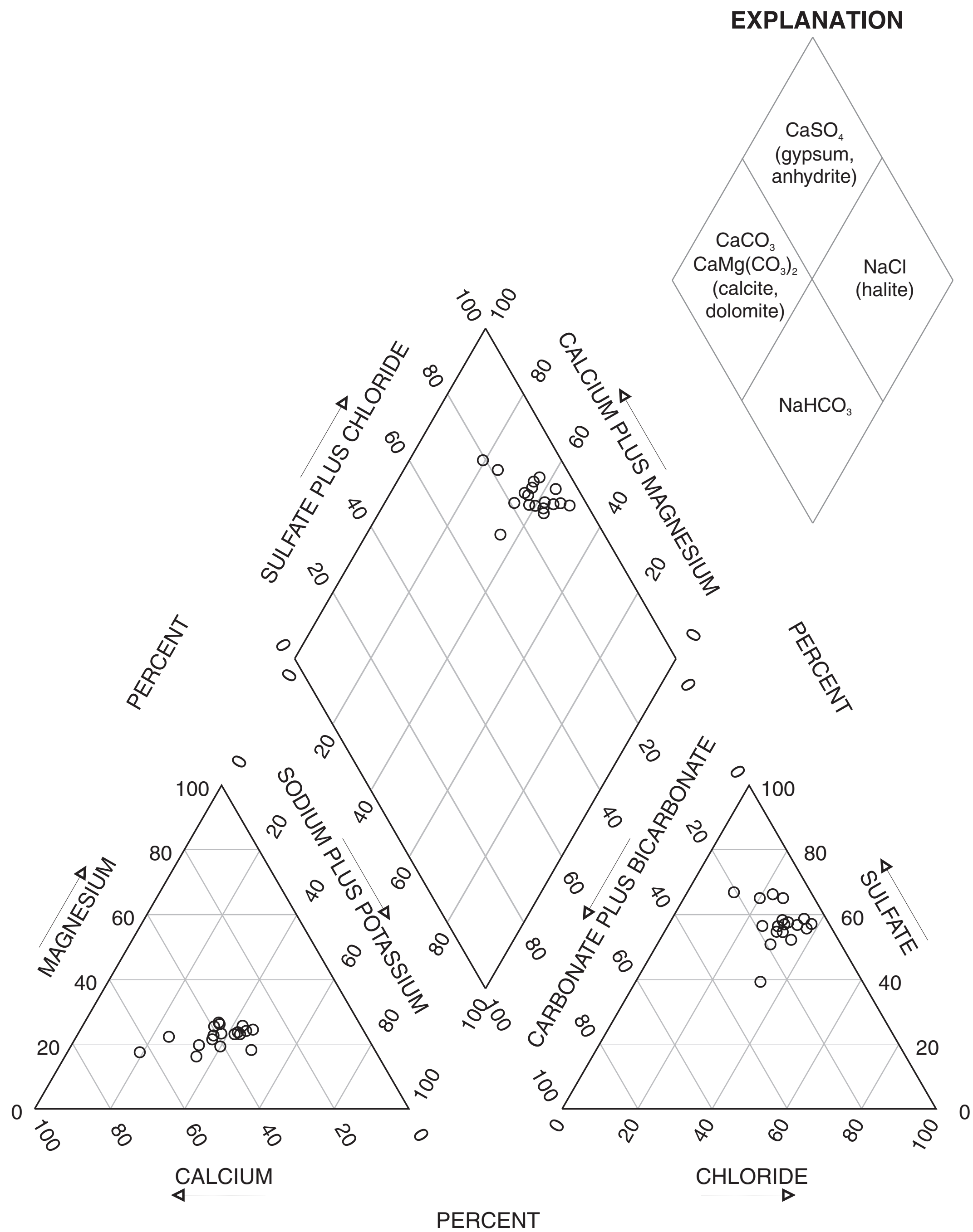


Figure 17. Major-ion water-quality data from the North Fork Red River near Erick, Oklahoma, (07301450), 1960–62.

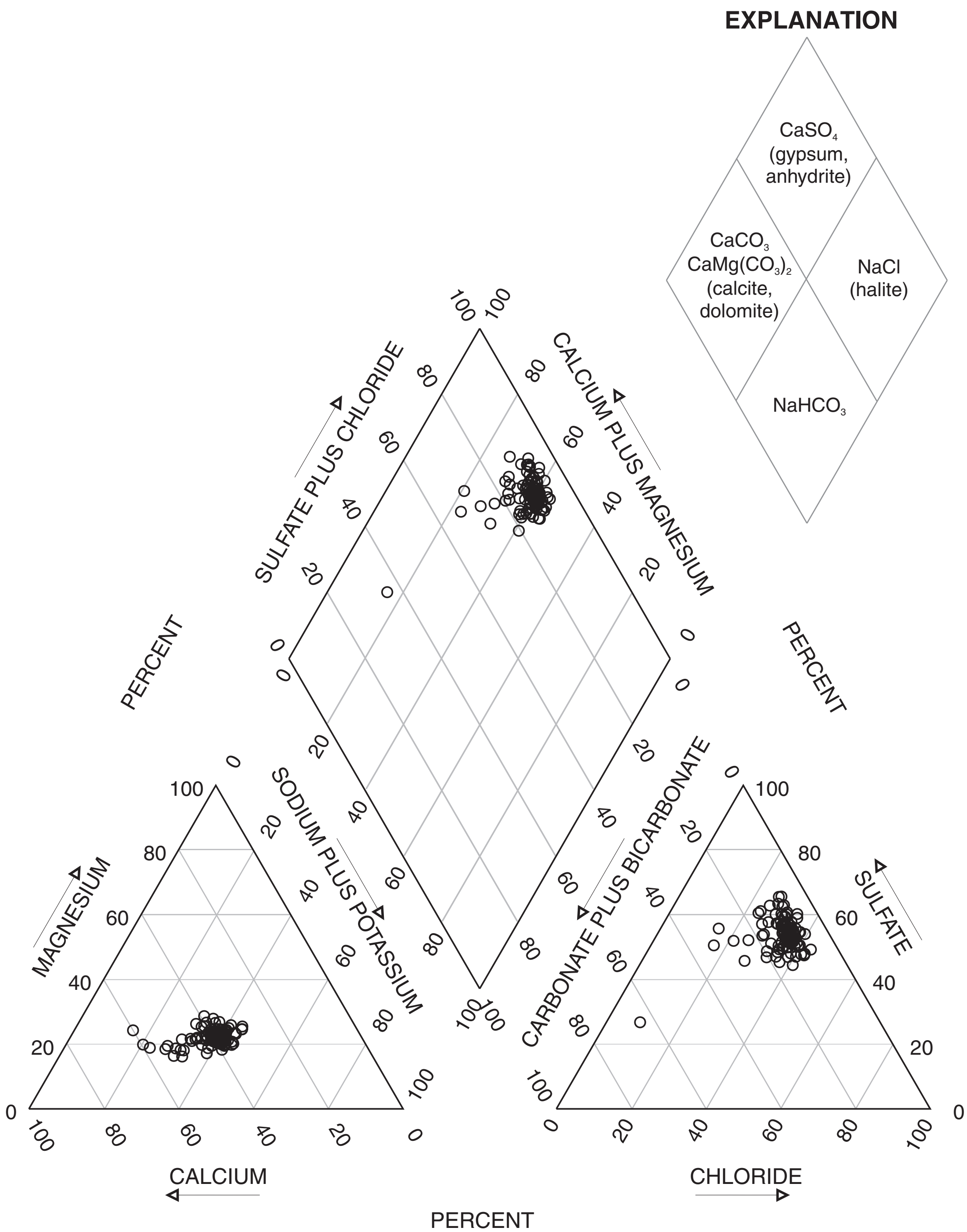


Figure 18. Major-ion water-quality data from the North Fork Red River near Carter, Oklahoma, (07301500), 1960–61 and 1973–76.

originates. Therefore, mean-annual loads and yields were estimated at each of the streamflow stations in the study area. At station 07301500 (North Fork Red River near Carter, OK), the active water-quality station nearest Lake Altus, the mean-annual dissolved load was estimated to be 187,768 tons per year (table 7). Of this total, 68,091 tons (36 percent) were sulfate and 39,296 tons (21 percent) were chloride (table 7).

Three other stations with estimates of mean-annual dissolved load are located on tributaries of the North Fork Red River. Station 07301200 is on McClellan Creek, the largest tributary by drainage area. Station 07301410 near Kelton, Texas, and station 07301420 near Sweetwater, Oklahoma, are both on Sweetwater Creek, separated by about 15 miles (fig. 1). Only a few small tributaries join Sweetwater Creek between the Kelton and Sweetwater stations.

Though similar in discharge, McClellan Creek and Sweetwater Creek had different load contributions to the North Fork Red River. McClellan Creek near McLean contributed an estimated 1,499 tons of chloride and slightly less sulfate annually (table 7). In contrast, Sweetwater Creek near Sweetwater contributed 1,183 tons of chloride and 6,241 tons of sulfate annual—-greater than five times more sulfate than chloride (table 7).

Upstream from the station near Sweetwater (07301420), Sweetwater Creek contributed 19.5 percent of the mean-annual streamflow and 8.9 percent of the mean-annual dissolved load in the North Fork Red River near Carter, Oklahoma, (07301500) (table 7). Together, McClellan Creek upstream from station 07301200 and Sweetwater Creek upstream from station 07301420 accounted for about 12.5 percent of the mean-annual dissolved load and 34.3 percent of the mean-annual streamflow at the station near Carter (07301500) (table 7). Most of the dissolved load at Carter may be derived from Permian-age evaporites of Wheeler County in Texas and Beckham County in Oklahoma (fig. 1, fig. 4).

Mean-annual dissolved constituent yields increased in a downstream direction for all three constituents (table 8), perhaps owing to the downstream reaches of the river flowing over more soluble bedrock. The mean-annual dissolved-solids yield for the station near Carter is 80.35 tons per year per square mile (table 8). Of this annual dissolved yield, 29.14 tons per year per square mile (36 percent) are sulfate and 16.81 tons per year per square mile (21 percent) are chloride (table 8).

The suspended sediment load for the North Fork Red River was measured at water-quality station 07302000 (North Fork Red River near Granite, Oklahoma) in water years 1904-08 and 1938-44, before the emplacement of Lake Altus. The station is no longer in service, but the station record still provides an estimate of sediment loads supplied to the lake. Using this U.S.

Table 7. Estimated mean-annual loads of sulfate, chloride, and dissolved solids in the North Fork Red River study area

Station number	Station name	Period of record (water year)	Mean-annual streamflow (acre-feet)	Sulfate (tons per year)	Chloride (tons per year)	Dissolved solids (tons per year)
07301200	McClellan Creek near McLean, TX	1968-1980	14,544	1,264	1,499	6,671
07301410	Sweetwater Creek near Kelton, TX	1963-1999	10,150	1,978	483	6,981
07301420	Sweetwater Creek near Sweetwater, OK	1987-1999	19,214	6,241	1,183	16,775
07301500	North Fork Red River near Carter, OK	1945-1962, 1965-1999	98,398	68,091	39,296	187,768

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Table 8. Estimated mean-annual yields of sulfate, chloride, and dissolved solids in the North Fork Red River study area

Station number	Station name	Period of record (water year)	Drainage area (square miles)	Sulfate (tons per year per square mile)	Chloride (tons per year per square mile)	Dissolved solids (tons per year per square mile)
07301200	McClellan Creek near McLean, Texas	1968-1980	759	1.67	1.97	8.79
07301410	Sweetwater Creek near Kelton, Texas	1963-1999	287	6.89	1.68	24.32
07301420	Sweetwater Creek near Sweetwater, Oklahoma	1987-1999	424	14.72	2.79	39.56
07301500	North Fork Red River near Carter, Oklahoma	1945-1962, 1965-1999	2,337	29.14	16.81	80.35

Geological Survey historical data, an average 1.6 million tons of suspended sediment were carried to the lake annually.

A Bureau of Reclamation sediment survey conducted at Lake Altus in 1967 reported a total suspended and bed-load sediment inflow of 1,430,720 tons per year between 1940 and 1967 (Lara, 1971, p. 11). A second independent estimate (Lara, 1971, p. 11) used a sediment rating curve and a flow-duration curve for the station near Carter (07301500). That estimate was augmented to include the drainage area between the station near Carter and the inflow to the lake and added 15 percent for the bed-load component for a total suspended and bed-load sediment discharge of 1,566,100 tons per year (Lara, 1971, p. 11). When reduced by 15 percent to remove the bed-load component, the estimates from Lara (1971) are 17 to 24 percent less than the load estimated in this report using historical, pre-lake data.

SUMMARY

The quantity and quality of surface water are major concerns at Lake Altus, and water-resource managers and consumers need historical information to make informed decisions about future development. This report summarizes a study of historical streamflow conditions and surface-water quality in the North Fork Red River basin upstream from Lake Altus, Oklahoma, from 1945 to 1999. The primary goals of this study were to 1) identify and interpret statistical trends in streamflow, 2) summarize major-ion chemistry, and 3) estimate annual suspended and dissolved loads and yields. As part of an examination of streamflow trends, 100 years of annual precipitation record were tested. Though no significant trend was observed in the test of the entire annual precipitation record, a significant trend was observed in the subset from 1945 to 1995. Over this 51-year period, annual precipitation increased by an average 0.14 inch per year.

Four streamflow parameters were examined at each of the four streamflow gages in the study area. These included annual streamflow volume, annual base-flow volume, base-flow index, and annual peak discharge. Annual streamflow did not change significantly at any of the four streamflow stations. Base flow, however, decreased significantly at the most upstream station (McClellan Creek near McLean, 07301200) and increased significantly at the most downstream station (North Fork Red River near Carter, 07301500). There was no significant change in base flow at two stations on Sweetwater Creek. The base-flow index increased at all four stations, but the increase was only statistically significant at Sweetwater Creek near Kelton (07301410) and North Fork

Red River near Carter (07301500). The annual peak discharge decreased significantly at three of the four streamflow-gaging stations. A study of the Beaver-North Canadian River reported similar decreases in annual peak discharge due to streambed infiltration, channel storage, and the increasing number of stock ponds in the basin.

High-salinity surface water is a major concern in southwestern Oklahoma because it limits the use of water. The greatest contributors of dissolved solids in the North Fork Red River are halite (sodium chloride) and gypsum/anhydrite (calcium sulfate), both of which occur naturally in the study area. Dolomite, another abundant mineral, can increase the amount of dissolved magnesium and decrease the amount of dissolved calcium in the river through the process of dedolomitization.

Major-ion water-quality data from five stations were analyzed using Stiff diagrams. The two major tributaries of the North Fork Red River upstream from Lake Altus had somewhat different compositions. McClellan Creek was dominated by sodium chloride, and Sweetwater Creek was dominated by calcium sulfate. Dissolved sodium chloride may discharge from salt springs at the base of the Ogallala Formation, which supplies base flow to McClellan Creek near McLean (07301200). The source of calcium sulfate in Sweetwater Creek is probably gypsum or anhydrite of the Quartermaster Formation and Whitehorse Group of Permian age. Concentrations of calcium and sulfate in Sweetwater Creek near Kelton (07301410) increased substantially during low discharge.

The Stiff diagrams for Shamrock (07301300), Erick (07301450), and Carter (07301500) are almost identical in shape. Therefore, major-ion chemistry in the river is established before it reaches the station near Shamrock, Texas. The major calcium sulfate source could be gypsum and anhydrite of the Blaine Formation of Permian age near Shamrock, Texas. Concentrations of calcium and sulfate at this station doubled during periods of low discharge, confirming that the station is near to a gypsum/anhydrite source. The major-ion chemistry at stations near Erick and Carter could be influenced by dedolomitization, with elevated concentrations of dissolved magnesium and sulfate and reduced concentrations of calcium.

In terms of annual loads, sulfate was the major dissolved constituent in the North Fork Red River. Near Carter, Oklahoma, (07301500), sulfate loads were nearly twice as great as chloride loads. Chloride, however, was sometimes the dominant loading constituent in headwater tributaries on the Ogallala Formation of Tertiary age. Upstream from Sweetwater, Oklahoma, Sweetwater Creek contributed 19.5 percent of the mean-annual streamflow and 8.9 percent of the mean-annual dissolved load in the North Fork Red River near Carter, Oklahoma. Together, Sweetwater Creek upstream from station 07301420 and McClellan Creek upstream from station 07301200 accounted for about 12.5 percent of the mean-annual dissolved load and 34.3 percent of the mean-annual streamflow at Carter (07301500).

From water years 1904-08 and 1938-44, before emplacement of the Lake Altus dam, suspended sediment discharge to Lake Altus was estimated to be 1.6 million tons per year. This estimate of annual suspended sediment discharge is greater than that inferred from a 1967 survey of Lake Altus suspended and bed-load sediment inflow.

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