science for a changing world

Prepared in cooperation with the Oklahoma Water Resources Board

Trends in Base Flow, Total Flow, and Base-Flow Index of Selected Streams in and near Oklahoma through 2008

Scientific Investigations Report 2010–5104

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

Cover: This is a downstream photograph of the streamflow-gaging station at North Fork Red River near Carter, Oklahoma, and was taken by Martin Schneider, U.S. Geological Survey.

Trends in Base Flow, Total Flow, and Base-Flow Index of Selected Streams in and near Oklahoma through 2008

By Rachel A. Esralew and Jason M. Lewis

Prepared in cooperation with the Oklahoma Water Resources Board

Scientific Investigations Report 2010–5104

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

This and other USGS information products are available at http://store.usgs.gov/
U.S. Geological Survey
Box 25286, Denver Federal Center
Denver, CO 80225

To learn about the USGS and its information products visit http://www.usgs.gov/
1-888-ASK-USGS

Suggested citation:
Esralew, R.A., and Lewis, J.M., 2010, Trends in base flow, total flow, and base-flow index of selected streams in and near Oklahoma through 2008: U.S. Geological Survey Scientific Investigations Report 2010–5104, 143 p.

Contents

Figures

Tables

Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

Altitude, as used in this report, refers to distance above the vertical datum.

Trends in Base Flow, Total Flow, and Base-Flow Index of Selected Streams in Oklahoma through 2008

By Rachel A. Esralew and Jason M. Lewis

Abstract

The U.S. Geological Survey, in cooperation with the Oklahoma Water Resources Board, investigated trends in base flow, total flow, and base-flow index of selected streams in Oklahoma and evaluated possible causes for trends. Thirty-seven streamflow-gaging stations that had unregulated or moderately regulated streamflow were selected for trend analysis.

Statistical evaluation of trends in annual and seasonal (winter-spring and summer-autumn) base flow, total flow, and base-flow index at 37 selected streamflow-gaging stations in Oklahoma was performed by using a Kendall's tau trend test. This trend analysis also was performed for annual and seasonal precipitation for nine climate divisions in the study area, annual peak flows, the number of days where flow was zero or less than 1 cubic foot per second (both annually and seasonally), and annual winter groundwater levels for 35 shallow wells near the analyzed stations. Precipitation-adjusted trends using LOESS regressions and Kendall's tau were computed for annual and seasonal base-flow and total-flow volumes in order to identify the presence of underlying trends in streamflow that are not associated with annual or seasonal variations in precipitation.

In general, upward trends in precipitation were detected for climate divisions in north-central Oklahoma and south-central and southeastern Kansas. More climate divisions had statistically significant upward trends in total precipitation for annual water years than in winter-spring or summer-autumn water years.

Significant trends in annual or seasonal base-flow volume were detected for 22 stations, 19 of which had trends that were upward in direction. Significant trends in annual or seasonal total-flow volume were detected for 14 stations, 9 of which had trends that were upward in direction. Most stations that had significant upward trends in annual or seasonal total-flow volume also had significant upward trends in base-flow volume for the same period. Precipitation adjustment changed the results (significant only or significance and direction) of significant annual or seasonal trends in unadjusted base-flow volume for 12 stations and in unadjusted total-flow volume for 13 stations.

Significant trends in annual or seasonal base-flow index were detected for 25 stations, 23 of which had trends that were upward in direction. Eighteen stations that had significant upward trends in annual or seasonal base-flow index also had significant upward trends in base-flow volume and no significant downward trends in total-flow volume during the same period, which indicated that upward trends in base-flow index were likely driven by increases in base flow at these stations.

Trend results were highly variable throughout the State. However, some recurring patterns in locations of stations with similar trend results were detected. In general, significant downward trends in base-flow and total-flow volumes were detected for the three stations in the Oklahoma Panhandle. Significant upward trends in annual or seasonal base-flow volume before and after precipitation adjustment were detected for 12 stations in southwestern and central Oklahoma. In eastern Oklahoma, significant upward trends in annual or seasonal base-flow volume were only detected for 4 stations, and significant upward trends in annual or seasonal total-flow volume were only detected for 1 station. After precipitation adjustment no stations in this region had significant upward trends in either parameter, one station had significant downward trends in annual base-flow volume, and one station had significant downward trends in winter-spring total-flow volume.

Increases in annual and seasonal precipitation, especially during a substantial wet period (1980-2000), may be one of the factors resulting in upward trends in base-flow volume and total-flow volume at many of the stations analyzed in this report. Eleven stations with significant upward trends in precipitation-adjusted annual and winter-spring base-flow volume were located in or near principal aquifers where many wells had significant upward trends in groundwater levels. Significant upward trends in annual or seasonal base-flow index were detected for all of these stations. Significant upward trends in base-flow volume and base-flow index for these stations may indicate increased recharge of underlying aquifers as a result of increases in precipitation, artificial recharge from irrigation returns, or changes in irrigation practices in the region. Downward trends in base-flow volume and total-flow volume in the Oklahoma Panhandle likely are caused by long-term

declines in groundwater levels and surface-water diversions for irrigation.

Introduction

Comprehensive planning for water-resources management, development, and use in Oklahoma can benefit from a description of temporal trends in streamflow and how these trends might vary throughout the State. Awareness of these trends can be useful to water-resources management agencies for drought monitoring and planning, water-supply permitting and allocation of beneficial water uses, maintenance of adequate streamflows for the protection of aquatic ecosystems, wastewater operations, and maintenance of streamflows for water-quality management.

Evidence indicates that the quantity of streamflow may be changing in the long-term for some streams in Oklahoma as a response to anthropogenic activities as well as changes in climate. For example, previous studies demonstrated that base flow and peak flow in some streams in the upper Beaver/North Canadian River Basin were decreasing as a result of depletion of groundwater and changes in land-use practices, especially since 1978 (Wahl and Tortorelli, 1997; Tortorelli and others 2005). In contrast, Smith and Wahl (2003) determined that the lower North Fork Red River had significant upward trends in base flow. Smith and Wahl (2003) reported that these trends may have been caused by changes in irrigation activities near the station or in the drainage basin. Previous studies also indicated that mean annual streamflow is increasing for many streams in Oklahoma, as much as 6.6 percent per year in the Washita River Basin, which may be a result of increases in precipitation (Tortorelli and others, 2005).

The most direct potential cause of long-term changes in streamflow is a change in precipitation, which is a function of variable climate conditions attributed, in part, to increasing global temperatures (Crawford and McManus, 2008). Previous studies have indicated that total precipitation in the United States has increased 10 percent during the 20th century from 1910 to 1995, and that during that time there was a statistically significant increase in the number of annual precipitation events (Karl and Knight, 1998). The same analysis revealed an increase in the intensity of some rainfall events. Oklahoma had an unprecedented wet period from the early 1980s to around 2000 (Oklahoma Water Resources Board, 2006; Garbrecht and Schneider, 2007). Increases in total precipitation may cause increases in streamflow as expressed by increases in annual and seasonal base-flow and total-flow volumes.

Despite the documented increase in streamflow from the early 1980s to 2000 for Oklahoma, precipitation and streamflow were highly variable in recent years. Water year 2006 (October 1, 2005, to September 30, 2006) was a year of extreme hydrologic drought and the driest year in the 2002-06 drought in Oklahoma (Tortorelli, 2009). In contrast with that drought, Oklahoma experienced one of the wettest years on record in water year 2007 for precipitation and streamflow (Arndt, 2007; Blazs and others, 2007).

Increased water demand as a result of population growth and development of agriculture in the State may reduce the variability of groundwater and surface-water resources through groundwater depletion and surface-water diversions for water supply. Depletion of groundwater and surface-water resources can reduce the magnitude of streamflow as well as extend the duration of periods of extreme low flow and periods of no streamflow, especially during dry years. In contrast, increases in groundwater levels and surface-water volumes may result from changes in land-management practices intended to reduce soil erosion and increase irrigation efficiency, such as no-till farming, micro-irrigation, and center-pivot irrigation (Beck and others, 1998, Luckey and Becker, 1999, Smith and Wahl, 2003, Tortorelli and others, 2005)

The rate and degree to which anthropogenic and climatic factors affect streamflow for drainage basins in the long-term can vary between drainage basins and across the State. Streamflow information collected at streamflow-gaging stations in Oklahoma can be used to statistically analyze, identify, and describe temporal trends in base flow and total flow.

Statistical trend analysis can be used to determine the probability that an upward or downward trend in streamflow has actually happened, and that a series of increases or decreases for any given set of years is not just because of random variability. In addition to statistical analysis, plotting results of temporal trends in streamflow can be useful in visualizing patterns and direction of trends. For example, a plot may show a change in the trend slope after a specific date, which statistical trend analysis might not easily convey. Mapping of statistical results of temporal trends in streamflow can help to reveal regional patterns in upward and downward trends across the State.

A simple observation of changes in base flow may not fully describe the complex nature of the streamflow regime and the potential response of streamflow to climate variability and anthropogenic activities. Analyzing the trend in the ratio of base flow to total flow, referred to as the base-flow index, can provide information about changes in the proportion of total flow that is derived from base flow. For example, if there are downward trends in base flow and total flow but an upward trend in the base-flow index, this might indicate that runoff is being depleted at a faster rate than base flow. Runoff depletion may be a response to a decrease in the frequency of storm events or an increase in the rate of direct surface-water withdrawals and diversions or a combination of both factors. This example of upward trends in base-flow index with downward trends in base-flow and total-flow volumes was observed for many stations in the Beaver/North Canadian River Basin from 1978 to 1994 as reported by Wahl and Tortorelli (1997).

Trend analysis of additional streamflow parameters, such as extreme high- and low-flow characteristics, including the number of days where extreme low-flow or zero-flow conditions are present, and changes in peak flow also are helpful for comprehensive water-resources management, especially for flood control, water supply permitting, and wastewater management (R.S. Fabian, Oklahoma Water Resources Board, written commun., September 2009). In addition, analysis of these parameters may help in identification of additional characteristics of the streamflow regime that might be changing because of climatic or anthropogenic influences.

Evaluation of changes in streamflow also can be enhanced by an analysis of possible causes of trends. Knowledge of possible causes of trends in streamflow can be useful for predicting whether the trend is likely to continue in the future. Spatial and temporal trends in annual precipitation and groundwater levels and an assessment of historical water use can be used to evaluate possible causes of increasing or decreasing streamflow.

The U.S. Geological Survey, in cooperation with the Oklahoma Water Resources Board, investigated trends in base flow, total flow, and base-flow index at selected streamflow-gaging stations in and near Oklahoma on an annual and seasonal basis. Also included are evaluation of trends in extreme low-flow days and peak flow to provide a comprehensive analysis of streamflow, and trends in precipitation and groundwater levels to evaluate potential causes of trends in streamflow.

Purpose and Scope

The purpose of this report is to describe trends in base flow, total flow, and base-flow index for selected streams in and near Oklahoma and to evaluate possible causes for observed trends. In addition, trends in annual and seasonal precipitation, annual peak flow, the annual and seasonal number of days where flow was zero or was less than 1 cubic foot per second (ft^3/s), and winter groundwater levels were assessed.

This report includes (1) a summary of data selected for trend analysis from streamflow-gaging stations with long-term streamflow record and the streamflow parameters that were analyzed; (2) a summary of the methods used to compute base-flow volume and evaluate trends; (3) documentation of whether statistically significant trends exist in annual and seasonal base-flow volume, total flow volume, base-flow index, annual peak flow, and the number of days where streamflow was zero or was less than 1 ft^3/s; and (4) an evaluation of possible causes of streamflow trends, including analysis of trends in precipitation and in streamflow adjusted for precipitation, in groundwater levels, and discussion of historic water-use activities and water-management practices that may affect observed streamflow trends.

Selection of Data for Analysis

Streamflow-Gaging Stations

The primary objectives of this report are to (1) determine if statistically significant trends in streamflow were observed for streamflow-gaging stations with long-term periods of record where base flow and total flow were not substantially affected by streamflow regulation (fig. 1) and (2) determine if spatial patterns for stations with significant trends were observable. Successful regional streamflow trend analysis in a large geographic area requires a large number of stations with a long period of record (Tortorelli, 2005). An attempt was made to select stations with a minimum length of continuous daily-mean streamflow record of at least 40 years that had streamflow data through water year 2008 without substantial record gaps and to select stations that had unregulated periods of record. For this report, streamflow at a station was considered regulated if 20 percent or more of the drainage basin upstream from the station was upstream from water-supply reservoirs or floodwater retarding (FWR) structures, which was the criterion for regulation used in previous studies in Oklahoma (Tortorelli, 2002; Lewis and Esralew, 2009).

Only 17 stations in the State met these criteria for unregulated conditions and record length, hence additional stations were selected to cover areas of the State that would not have been adequately represented. In addition, because so many streams in Oklahoma are regulated, inclusion of regulated streams in the analysis was needed. However, only the regulated period of record was used in the trend analysis to eliminate the start date of regulation as a possible cause of streamflow trends. For all stations in which streamflow was affected by regulation, the year of construction of the flow controlling structure that resulted in 20 percent of the drainage-basin area of the station being affected by regulation marked the beginning of the regulated period of record.

Thirty-seven stations were selected for trend analysis. Two stations with an unregulated streamflow record of at least 34 years were selected. Fourteen stations selected for the analysis were regulated by water-supply reservoirs (table 1). For these stations, the regulating reservoirs were far upstream from the station (40 river miles or greater) or were not on the main stem of the river. Therefore, an assumption was made that the regulation was moderate, and those stations were considered acceptable for use in the trend analysis.

Eight stations in which streamflow was regulated by floodwater-retarding (FWR) structures also were evaluated for this report. Streamflow at four of the eight stations also

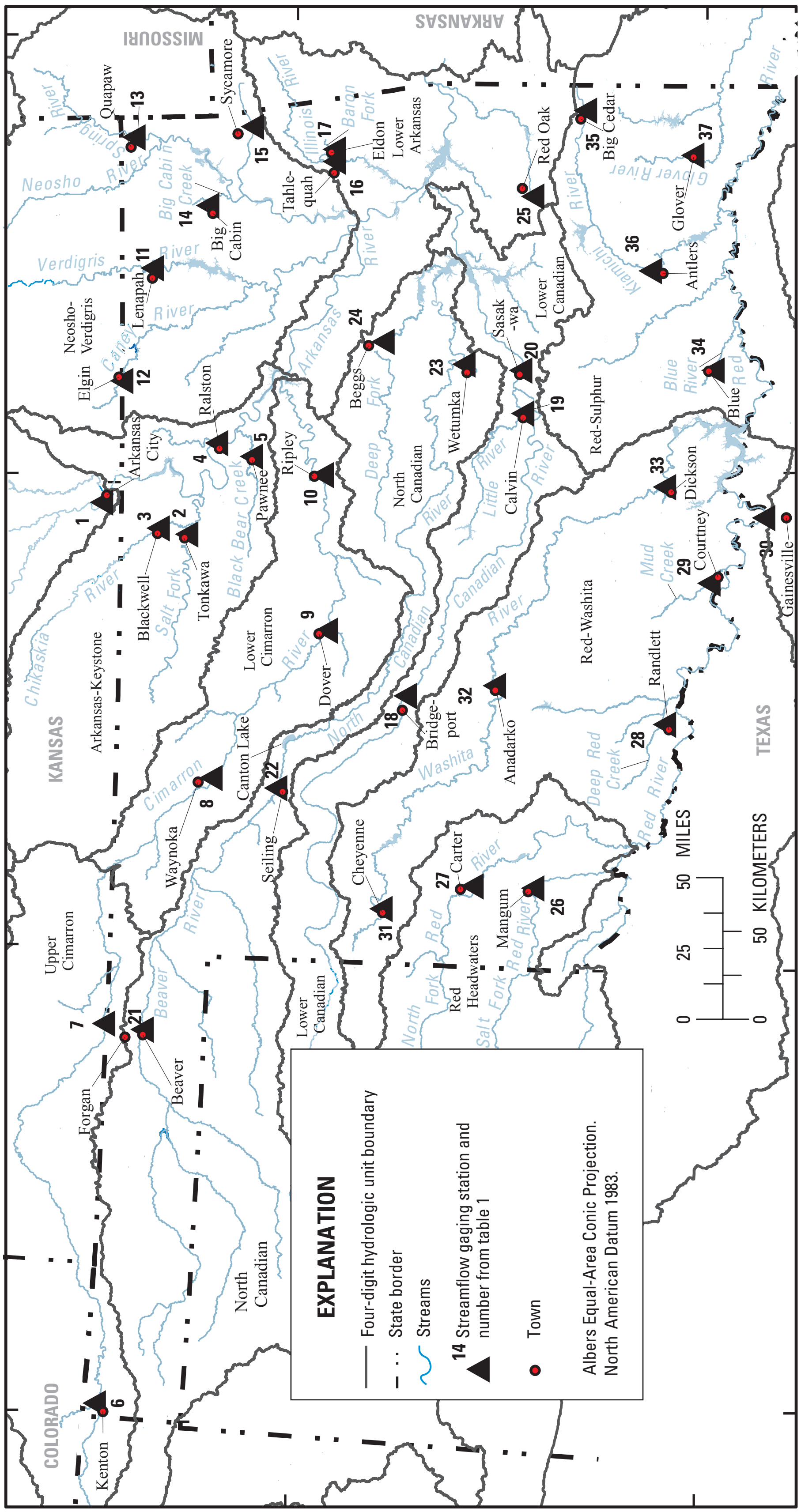

Figure 1. Location of streamflow-gaging stations used in trends analyses.

Table 1. Summary of streamflow period of record for selected continuous-record streamflow-gaging stations used in study.

[no., number; USGS station ID, U.S. Geological Survey station identifier; nr, near; Ck, Creek; Climate Division, the climate division in which the gage is located, codes are defined in table 2; mi², square miles; I, irrigation; U, unregulated; R, regulated; dms, degrees, minutes, seconds; WS, water-supply reservoir; FWR, Natural Resources Conservation Service floodwater-retarding structure; WY, water year; --, none]

Station no. (fig. 1)	USGS station ID	Station name	Climate division	Drainage area (mi²)	Latitude (dms)	Longitude (dms)	Type of record	Type of regulation[1]	Continuous period of record (WY)	Was period used for statistical trend analysis?
1	07146500	Arkansas River nr Arkansas City, Kans.	KS-8	36,106	370323	0970332	U	--	1922-1942	No
							R	WS	1943-2008	Yes
2	07151000	Salt Fork Arkansas River at Tonkawa, Okla.[2]	OK-2	4,520	364019	0971833	U	--	1936-1940	No
							R	WS	1942-2008	Yes
3	07152000	Chikaskia River nr Blackwell, Okla.	OK-2	1,859	364841	0971637	U	--	1937-2008	Yes
4	07152500	Arkansas River at Ralston, Okla.[2]	OK-3	54,465	363015	0964341	U	--	1926-1975	No
							R	WS	1977-2008	Yes
5	07153000	Black Bear Ck at Pawnee, Okla.[2]	OK-3	576	362037	0964757	U	--	1945-1962	No
							R	FWR	1968-2008	Yes
6	07154500	Cimarron River nr Kenton, Okla.	OK-1	1,038	365536	1025731	U	--	1951-2008	Yes
7	07156900	Cimarron River nr Forgan, Okla.[2]	KS-7	4,220	370040	1002929	U	--	1966-2008	Yes
8	07158000	Cimarron River nr Waynoka, Okla.	OK-2	8,504	363102	0985245	U	--	1938-2008	Yes
9	07159100	Cimarron River nr Dover, Okla.	OK-5	10,787	355706	0975451	U	--	1974-2008	Yes
10	07161450	Cimarron River nr Ripley, Okla.[4]	OK-5	13,053	355909	0965443	U	--	1940-2008	Yes
11	07171000	Verdigris River nr Lenapah, Okla.[2]	OK-3	3,639	365104	0953509	U	--	1939-1959	No
							R	WS	1967-2008	Yes
12	07172000	Caney River nr Elgin, Kans.	KS-9	445	370014	0961859	U	--	1940-1964	No
							R	FWR	1965-2008	Yes

Table 1. Summary of streamflow period of record for selected continuous-record streamflow-gaging stations used in study. —Continued

[no., number; USGS station ID, U.S. Geological Survey station identifier; nr, near; Ck, Creek; Climate Division, the climate division in which the gage is located, codes are defined in table 2; mi^2, square miles; I, irrigation; U, unregulated; R, regulated; dms, degrees, minutes, seconds; WS, water-supply reservoir; FWR, Natural Resources Conservation Service floodwater-retarding structure; WY, water year; --, none]

Station no. (fig. 1)	USGS station ID	Station name	Climate division	Drainage area (mi^2)	Latitude (dms)	Longitude (dms)	Type of record	Type of regulation[1]	Continuous period of record (WY)	Was period used for statistical trend analysis?
13	07188000	Spring River nr Quapaw, Okla.	OK-3	2,510	365604	0944446	U	--	1940-2008	Yes
14	07191000	Big Cabin Ck. nr Big Cabin, Okla.	OK-3	450	363406	0950907	U	--	1948-2008	Yes
15	07191220	Spavinaw Ck. nr Sycamore, Okla.	OK-3	133	362007	0943827	U	--	1962-2008	Yes
16	07196500	Illinois River nr Tahlequah, Okla.	OK-6	635	360748	0943419	U	--	1936-2008	Yes
17	07197000	Baron Fork at Eldon, Okla.	OK-6	304	355516	0945018	U	--	1949-2008	Yes
18	07228500	Canadian River at Bridgeport, Okla.[2]	OK-7	20,475	353237	0981903	U	--	1945-1964	No
							R	WS	1970-2008	Yes
19	07231000	Little River nr Sasakwa, Okla.[2]	OK-5	884	345755	0963044	U	--	1943-1961	No
							R	WS/FWR	1966-2008	Yes
20	07231500	Canadian River at Calvin, Okla.[5]	OK-6	23,151	345840	0961436	U	--	1939-1964	No
							R	WS	1965-2008	Yes
21	07234000	Beaver River at Beaver, Okla. [6]	OK-1	3,685	364920	1003108	U	--	1938-1971	No
							IR	WS	1979-2008	Yes
22	07238000	North Canadian River nr Seiling, Okla.[7]	OK-2	7,414	361100	0985515	U	--	1947-1971	No
							IR	WS	1979-2008	Yes
23	07242000	North Canadian River nr Wetumka, Okla.	OK-6	9,391	351556	0961221	R	WS	1938-2008	Yes
24	07243500	Deep Fork nr Beggs, Okla.	OK-6	2,018	354026	0960406	U	--	1939-1967	No
							R	WS/FWR	1968-2008	Yes
25	07247500	Fourche Maline nr Red Oak, Okla. [2,7]	OK-9	122	345445	0950920	U	--	1939-1963	Yes
							R	FWR	1966-2008	No
26	07300500	Salt Fork Red River at Mangum, Okla.	OK-7	1,357	345130	0993030	U	--	1938-2008	Yes
27	07301500	North Fork Red River nr Carter, Okla.[8]	OK-4	1,938	351005	0993025	U	--	1938-2008	Yes
28	07311500	Deep Red Ck nr Randlett, Okla.	OK-7	617	341315	0982710	U	--	1970-2008	Yes
29	07315700	Mud Creek nr Courtney, Okla.	OK-8	572	340015	0973400	U	--	1961-2008	Yes

Table 1. Summary of streamflow period of record for selected continuous-record streamflow-gaging stations used in study. —Continued

[no., number; USGS station ID, U.S. Geological Survey station identifier; nr, near; Ck, Creek; Climate Division, the climate division in which the gage is located, codes are defined in table 2; mi^2, square miles; I, irrigation; U, unregulated; R, regulated; dms, degrees, minutes, seconds; WS, water-supply reservoir; FWR, Natural Resources Conservation Service floodwater-retarding structure; WY, water year; --, none]

Station no. (fig. 1)	USGS station ID	Station name	Climate division	Drainage area (mi^2)	Latitude (dms)	Longitude (dms)	Type of record	Type of regulation[1]	Continuous period of record (WY)	Was period used for statistical trend analysis?
30	07316000	Red River nr Gainesville, Tex.[2]	OK-8	24,846	334340	0970935	U	--	1937-1943	No
							R		1945-2008	Yes
31	07316500	Washita River nr Cheyenne, Okla.	OK-4	794	353735	0994005	U	--	1938-1960	No
							R	FWR	1961-2008	Yes
32	07326500	Washita River at Anadarko, Okla.	OK-7	3,635	350503	0981435	R	WS/FWR	1964-2008	Yes
33	07331000	Washita River nr Dickson, Okla.[2]	OK-8	7,202	341400	0965832	U	--	1929-1960	No
							R	WS/FWR	1962-2008	Yes
34	07332500	Blue River nr Blue, Okla.	OK-8	476	335949	0961427	U	--	1937-2008	Yes
35	07335700	Kiamichi River nr Big Cedar, Okla.	OK-9	40	343818	0943645	U	--	1966-2008	Yes
36	07336200	Kiamichi River nr Antlers, Okla.[2]	OK-9	1,138	341455	0953618	U	--	1973-1982	No
							R	WS	1984-2008	Yes
37	07337900	Glover River nr Glover, Okla.	OK-9	315	340551	0945407	U	--	1962-2008	Yes

[1] Streamflow at stations is considered substantially affected by regulation when at least 20 percent of the drainage-area is upstream from water-supply reservoirs or floodwater retarding structures (Lewis and Esralew, 2009).

[2] Streamflow record period is omitted during transition between unregulated and regulated periods when reservoir (s) under construction.

[3] Streamflow data not available for water year 1987

[4] Includes streamflow record 1940-89 from nearby station 07161000, Cimarron River at Perkins, Okla.

[5] Streamflow data not available for water years 1943-1944

[6] Pre- and post-irrigation development as defined in Wahl and Tortorelli (1997). Through water year 1971 is unregulated, water year 1972-78 are transition years to full irrigation development and regulated by reservoir.

[7] Streamflow data not available for water year 1991

[8] Streamflow data not available for water years 1963-1964

were regulated by water-supply reservoirs. Many of the FWR structures were constructed in the late 1950s and 1960s by the Soil Conservation Service, now the Natural Resources Conservation Service (NRCS) (Smith and Esralew, 2010). With the exception of a few areas in southwestern and eastern Oklahoma, most FWR structures are concentrated in flood-prone regional areas such as the Washita River Basin (fig. 1) and north-central Oklahoma (Smith and Esralew, 2009). The effects of regulation of streamflow by FWR structures on base flow and total flow may be regional because of the large number of these structures in Oklahoma. Analysis of streamflow data in basins affected by FWR structures gives a representation of potential trends for streams in and around these regions, and therefore can be useful for water resources management in the State.

An irrigation period of record was defined for stations in the Beaver/North Canadian River Basin above Canton Lake (fig. 1), which have been substantially affected by irrigation development since 1978 as described in Wahl and Tortorelli (1997). Stations where the irrigated period previously was defined by using trend analysis include the Beaver River near Beaver (station 21, fig. 1), and North Canadian River near Seiling (station 22, fig. 1). For this report, the more recent irrigated period after 1978 was used in the trend analysis for consistency in order to reflect the most recent conditions in the Beaver/North Canadian River Basin. Streamflow at some other stations, including those in the Upper Cimarron Basin River (fig. 1), likely has been affected by groundwater development and surface-water withdrawals for irrigation (Lewis and Esralew, 2009), but trends have not been previously calculated to document the period of record most likely to be affected by these activities. The entire period of record for all stations with long-term record through water year 2008 in the Upper Cimarron River Basin was included in the trend analysis.

Precipitation Data

Trends in annual and seasonal precipitation were calculated to evaluate potential sources of streamflow trends caused by changes in climate over the study period. Precipitation rates and amounts are highly variable temporally and spatially. Areal averages likely are better indicators of the amounts of precipitation that may appear as runoff at a station than are the precipitation amounts measured at individual stations (Tortorelli and others, 2005). Dating back to 1895, monthly and annual precipitation data are available for National Weather Service Climate Divisions, which summarize areal averages of precipitation data collected from individual stations into climate divisions (National Oceanic and Atmospheric Administration, 2009). Stations used in this analysis are located in nine climate divisions in Oklahoma and three climate divisions in southern Kansas (table 1, fig. 2).

For precipitation, trend analysis was done by analyses of data from annual and seasonal water years. An annual water year is defined as the 12-month period of October 1 through September 30. Seasonal water years are divided into winter-spring months and summer-autumn months to correlate to regulatory periods of the Oklahoma Water Resources Board. For this report, a winter-spring water year is defined as the 6-month period of November 1 through May 30, and a summer-autumn water year is defined as the 6-month period of June 1 to October 30. The winter-spring and summer-autumn water years are designated by the annual water year for which the seasonal water year starts. For example, a winter-spring water year starting in November of 2007 and a summer-autumn water year starting in June of 2008 would be designated as winter-spring water year 2008 and summer-autumn water year 2008, respectively.

For purposes of this report, all annual and seasonal analysis periods are defined by the water years used for analysis followed by the streamflow parameter. For example, annual precipitation computed for the entire annual water year is referred to as “annual precipitation”; whereas, seasonal precipitation computed for just winter-spring or summer-autumn water years is referred to as “winter-spring precipitation” and “summer-autumn precipitation”, respectively.

Streamflow Data

Trends were calculated for annual and seasonal time periods for base-flow and total-flow volumes, base-flow index, and the number of days with streamflow less than 1 ft^3/s and days with streamflow equal to zero ft^3/s. For purposes of this report, the number of days with streamflow less than 1 ft^3/s and days with streamflow equal to zero ft^3/s also are referred to as “extreme low-flow days”. Trends also were calculated for annual instantaneous peak flow trends only for annual water years.

For this report, notation for annual and seasonal streamflow is similar to the notation for precipitation. For example, annual base-flow volume computed for an entire water year is referred to as “annual base-flow volume”; whereas, annual base-flow volume analyzed for just winter-spring or summer-autumn water years is referred to as “winter-spring base-flow volume” and “summer-autumn base-flow volume”, respectively. Base-flow and total-flow volumes, base-flow index, and the number of extreme low-flow days were computed only for annual and seasonal water years that had complete water years of record in the analysis periods from table 1. Annual instantaneous peak flow values were only analyzed for periods with continuous daily mean streamflow record selected for analysis (table 1).

Groundwater-Level Data

Trends in winter groundwater levels were calculated to evaluate potential sources of streamflow trends arising from changes in groundwater storage and local and regional groundwater use for irrigation and public supply. Trends in winter groundwater levels were calculated for 35 wells in Oklahoma.

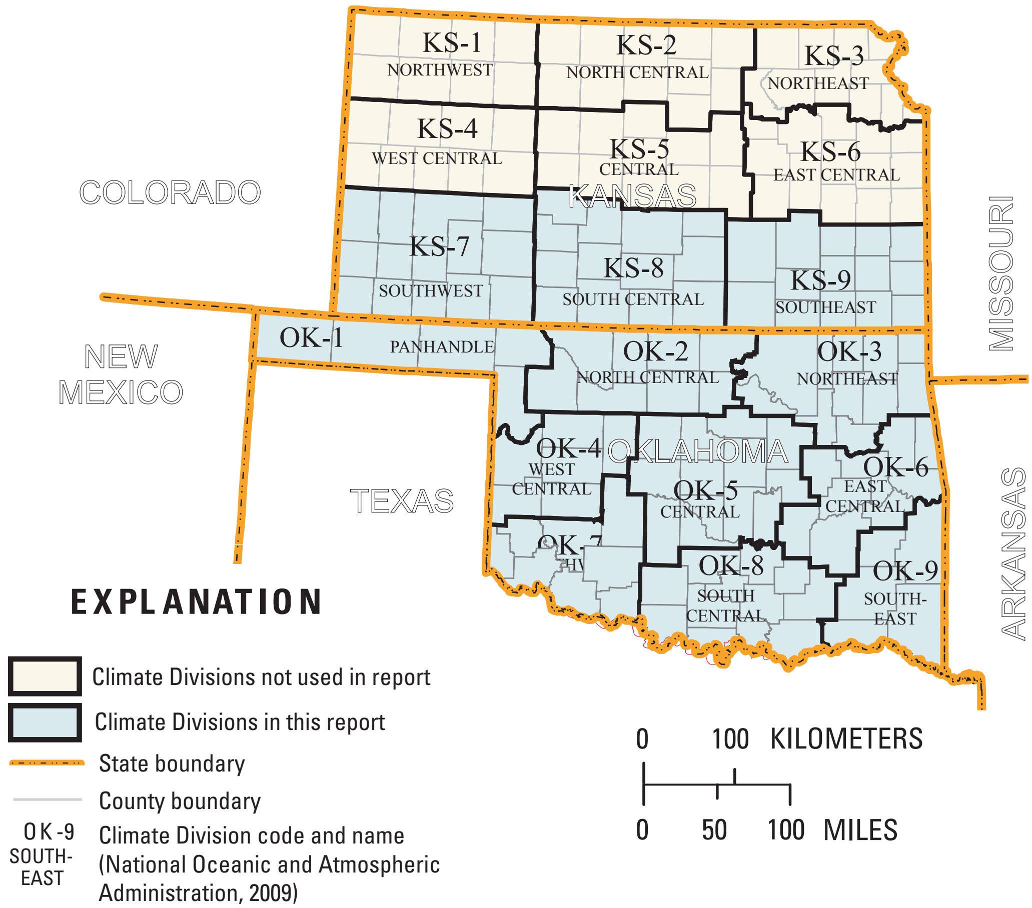

Figure 2. National Weather Service Climate Divisions used in annual and seasonal precipitation analysis.

Data from 33 wells were obtained from the Oklahoma Water Resources Board annual mass measurement program (Oklahoma Water Resources Board, 2008). Data from 2 wells were obtained from the USGS National Water Information System (*http://waterdata.usgs.gov/nwis*).

Most of the winter groundwater level data were from shallow wells completed in major aquifers (groundwater levels less than 100 feet below land surface). Water-level data from several deep wells (groundwater levels greater than 100 feet below land surface), such as those in the High Plains aquifer, also were analyzed. All groundwater level data were from groundwater sources that were likely to be hydraulically connected to local streams. Winter water-level measurements were used for the trend analysis because those measurements are least affected by seasonal transpiration and localized irrigation pumping. If data were unavailable for the period of late December through the end of March, groundwater levels collected during the year were omitted from analysis. Early January measurements were used when available, and when unavailable, the closest measurements made in late December, late January, February, or March were substituted. Trends in winter groundwater levels were calculated for the entire period of record for each well.

Methods of Analysis

Computation of Base-Flow volume and Base-Flow Index

A base-flow separation method was used to determine the base-flow component of streamflow. Base-flow separation partitions the streamflow hydrograph into the components of direct runoff and base flow. Historically, hydrologists computed base-flow separation by hand, but different analysts given the same data would arrive at different base flows. A computerized method of base-flow separation was used for consistency and to handle large amounts of data. A FORTRAN program called Base Flow Index (BFI) was used for this report (Wahl, 1988; Wahl and Wahl, 1995). BFI implements a procedure developed by the Institute of Hydrology (1980a, 1980b) that divides the water year into n-day increments, identifying the minimum streamflow during each n-day period. The BFI program defaults the n-day period to 5 days. Minimum streamflows then are compared to adjacent minimums to determine turning points on a base-flow hydrograph. Straight lines drawn between turning points define the base-flow hydrograph; the area beneath the hydrograph is an estimate of the volume of base flow. The ratio of the base-flow volume to the total volume of streamflow for the period is defined as the base-flow index. Although these procedures may not always yield the true base-flow volume of the stream, tests in Great Britain (Institute of Hydrology, 1980b), Canada (Swan and Condie, 1983), and the United States (Wahl and Wahl, 1988) indicate that the results of this base-flow separation procedure were consistent and indicative of the true base-flow volume.

The default partition length of 5-day increments was not appropriate for certain stations. The defaults on the BFI program were modified for each station by varying the partition length (n-day, or *N*) periods. To determine an appropriate *N* for each station, the base-flow index values were all computed for *N* values ranging from 0 to 10 days. A graph for each station of base-flow index compared to *N* was constructed to visually identify a slope change. The number of days where the slope no longer substantially changed indicated an appropriate value for *N* (Wahl and Wahl, 1995). Substantial changes in slope were determined by using visual judgment. Figure 3 shows an example of the procedure used to select the optimal value for *N*. For the Blue River near Blue, Oklahoma, (station 34, table 1), a substantial slope change occurs at *N*=2 days.

The default value of the turning point parameter (*f*) 0.9 was accepted at all stations. The BFI method has not proven to be highly sensitive to variations of *f* (Wahl and Wahl, 1995). In addition, careful considerations need to be made when using this program for regulated stations. For all stations in which streamflow was affected by regulation, the BFI output was examined to ensure that base-flow volume was appropriately computed. For stations in which streamflow was affected by regulation, computations of base-flow and total-flow volumes reflect a combination of unregulated streamflow and reservoir releases.

Graphical Analysis and LOESS Trend Lines

Prior to trend analysis, graphs were developed to visually identify potential trends in streamflow. Bar charts of base-flow volume, total-flow volume, base-flow index, annual peak flow, and annual precipitation were made for the analysis period for each station. Bar charts for the above parameters were developed only for the annual analysis periods. Bar charts also were developed for the number of extreme low-flow days (on an annual and seasonal basis) if at least 10 percent of the water years in one of the three analysis period types (annual, winter-spring, or summer-autumn) had at least 1 day where streamflow was zero or less than 1 ft^3/s.

In addition to bar charts, LOESS trend lines also were made to aid in visual analysis of trends. LOESS or LOcally EStimated Scatterplot Smoothing (also referred to as LOWESS in other publications or LOcally WEighted Scatterplot Smoothing) (Cleveland and Devlin, 1988, Helsel and Hirsch, 2002) is a nonparametric regression procedure that reduces the influence of outliers and displays a smooth or trend line for the entire range of data. A LOESS trend line is derived from a LOESS regression (Helsel and Hirsch, 2002). All bar charts and LOESS trend lines were produced in the statistical computer program S-Plus (Insightful Corporation, 2007). The LOESS lines were used for trend visualization purposes only and were not used to determine the statistical significance of trends.

LOESS plots were developed on an annual basis for base-flow volume, total-flow volume, base-flow index, peak streamflow, and precipitation and are shown on bar charts. For the number of extreme low-flow days, many stations did not have a substantial number of days where streamflow was zero or less than 1 ft^3/s, which may result in a large number of zeros in the LOESS plots. An excessive number of zeros (greater than 70 percent, for example) in the data used for LOESS plots may result in trend lines that are highly variable because the lines are more susceptible to influence from periodic dry years, making visual analysis of trends difficult. For this report, LOESS trend lines were developed only when at least 30 percent of the years during the analysis period (annual or seasonal) for each station had at least 1 day where streamflow was equal to zero or was less than 1 ft^3/s.

Kendall's Tau Test

Kendall's tau trend analysis was completed for annual and seasonal (winter-spring and summer-autumn) base-flow volume, total-flow volume and base-flow index. Kendall's tau also was calculated for annual and seasonal precipitation, the number of days where streamflow was zero or less than 1 ft^3/s, annual peak flow, and annual winter groundwater levels. The Kendall's tau test was conducted by using the statistical computer program S-Plus contained in the U.S. Geological Survey library (Insightful Corporation, 2007; David Lorenz, U.S. Geological Survey, written commun., January 2009).

Kendall's tau (Kendall and Gibbons, 1990), which served as the statistical test for significant trends, is a nonparametric statistical test that can be used to indicate the likelihood of an upward or downward trend with time. The Kendall's tau test is effective for identifying trends in streamflow because extremely high or low data outliers and skewness in the dataset have little effect on the outcome of the test (Helsel and Hirsch, 2002). Using the Kendall's tau test, the rank of each data observation is compared to the rank of the data observations following it in a ranked annual series. If the data observations in the series are consistently higher than the first observation, the tau coefficient is positive. If the data observations in the series are consistently lower than the first observation,

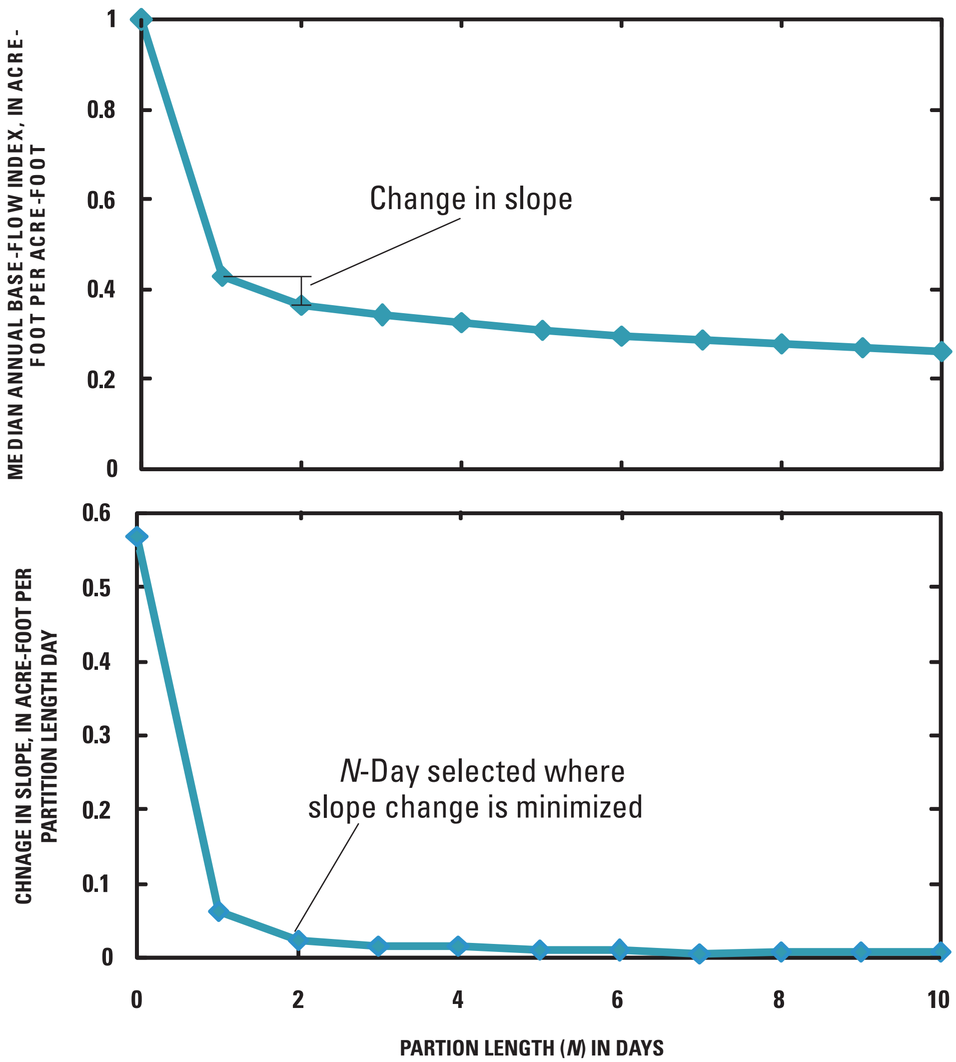

Figure 3. Procedure used to select an optimal partition length (*N*) for computation of base-flow volume by minimizing the slope change between a relation of median annual base-flow index and partition length for Blue River near Blue, Oklahoma, (USGS Station Identifier 07332500; station 34, table 1).

the tau coefficient is negative. Tau coefficients range from -1.0 to 1.0, where -1.0 indicates that every data observation has decreased with time, and 1.0 indicates that every data observation has increased with time. An equal number of negative and positive changes in data observations indicates that a trend does not exist, and the tau coefficient would be equal to zero.

For this report, a trend was considered to be statistically significant if the probability value (p-value, which is the probability that a true null hypothesis of no trend is erroneously rejected) was less than or equal to 0.05. This p-value represents a 95-percent confidence level in the correctness of the calculated trend.

A trend slope is a measure of the magnitude of a trend and was computed by using the Sen Slope Estimator (Sen, 1968; Helsel and Hirsch, 2002). The Sen slope is estimated by computing the median slope of all possible slopes between each possible two-point data pair in the time series, and like the Kendall's tau estimate, is considered insensitive to extreme outliers (Dietz, 1989; Helsel and Hirsch, 2002, p. 267).

Kendall's tau analysis for the number of extreme low-flow days poses complications because streamflow for some stations for many years never are equal to zero or go below 1 ft^3/s. These deficiencies in extreme low-flow days result in a potential for a high number of zeros in the dataset, which creates a lower limit on the dataset. However, the Kendall's tau analysis is still possible because all years that have a lower limit (zero days) are computed as tied values (Helsel and Hirsch, 2002, p. 353). Similar to the LOESS trend line, Kendall's tau was only calculated for datasets for which at least 30 percent of the years during the analysis period (annual or seasonal) had at least 1 day where streamflow was equal to zero or less than 1 ft^3/s. Although the sign of the estimated

Sen slope is more accurate for data with a lower limit, the magnitude of the slope estimate is likely to be in error (Helsel and Hirsch, 2002, p. 353). For this reason, a Sen slope was not computed for the number of extreme low-flow days.

Streamflow data were first transformed into natural logarithms prior to the Kendall's tau analysis to express the Sen slope roughly as a percent per year. The slope of a trend line fitted to the natural log of the data is equal to the average percentage growth in the original series because changes in the natural logarithm are roughly equivalent to percentage change in a data series (Helsel and Hirsch, 2002, p. 346). Transformations were not needed for base-flow index and the number of extreme low-flow days because base-flow index was already expressed as a percent, and the Sen slope for the number of days of extreme low flow was not computed.

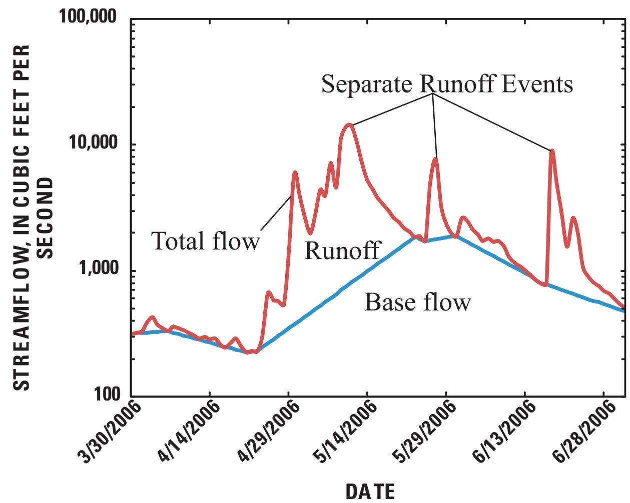

Figure 4. Base-flow separation during sequential storms for Spring River near Quapaw, Oklahoma, (USGS Station Identifier 07188000; station 13, table 1).

Kendall's Tau Test for Streamflow Volume Adjusted for Annual Precipitation

In the application of Kendall's tau method used in this report, the only influence on streamflow being analyzed is time. However, variables other than time can have considerable influence on streamflow. Unfortunately, a strong correlation between annual precipitation and streamflow may obscure underlying trends in streamflow, such as downward trends that are caused by other factors such as surface-water diversions or groundwater withdrawals from the drainage basin. These "exogenous" variables can be precipitation, temperature, or other factors. By removing the annual and seasonal variation in streamflow caused by precipitation, the background underlying trends in streamflow can be more clearly observed (Helsel and Hirsch, 2002, p. 329). For this report, the procedure of removing the effects of annual precipitation from streamflow trends is referred to as "precipitation-adjusted" trend analysis. For the remainder of this report, base-flow and total-flow volumes are referred to collectively as "streamflow volume". Precipitation-adjusted trends were calculated for annual and seasonal streamflow volumes to identify the presence of underlying trends in streamflow that are not associated with annual or seasonal variations in precipitation.

The influence of annual variability of precipitation on total-flow volume trends is intuitive. However, annual variability of precipitation also can influence annual base-flow volume. Precipitation from sequential storms can yield an elevated base-flow volume if the hydrograph from the first storm has not yet receded to prestorm levels prior to the start of another runoff event (fig. 4). Localized recharge from previous rainfall events also can lead to an elevated base-flow volume depending on the initial soil saturation at the start of a precipitation event (which affects the volume of overland and subsurface flow), the lag time between events occurring in the upper part of the watershed and the time when streamflow reaches the streamflow-gaging station, and the recharge rate and recharge potential of the aquifers that supply flow to a stream. These factors may result in a significant correlation between annual base-flow volume and annual precipitation, which can increase the likelihood that an upward trend in base-flow volume is because of an increase in precipitation (fig. 5).

The error residuals from a regression between the streamflow parameter and annual precipitation can be computed, and a trend developed between the error residuals and time. This procedure results in a removal of the effect of annual or seasonal precipitation (Helsel and Hirsch, 2002, p. 331-335). Error residuals (R) were computed as:

$$R = Y - \hat{Y} \tag{1}$$

where,

Y is observed annual or seasonal streamflow volume, and

$\hat{Y}$ is the fitted value from a linear regression using annual precipitation to estimate annual streamflow volume.

Kendall's tau was used to test for a time trend in error residuals (R) from the LOESS regression between annual and seasonal precipitation and annual and seasonal streamflow volume. This precipitation-adjusted streamflow trend, if significant, can be viewed as a trend that may be a result of factors other than the variation of annual or seasonal precipitation, such as withdrawals, diversions, and irrigation returns.

For this report, a nonparametric approach (Helsel and Hirsch, 2002, p. 334) was selected because of the high likelihood of a skewed distribution of annual or seasonal streamflow and the possibility of a skewed or nonlinear relation between annual or seasonal precipitation and streamflow. LOESS was used to describe the relation between annual or

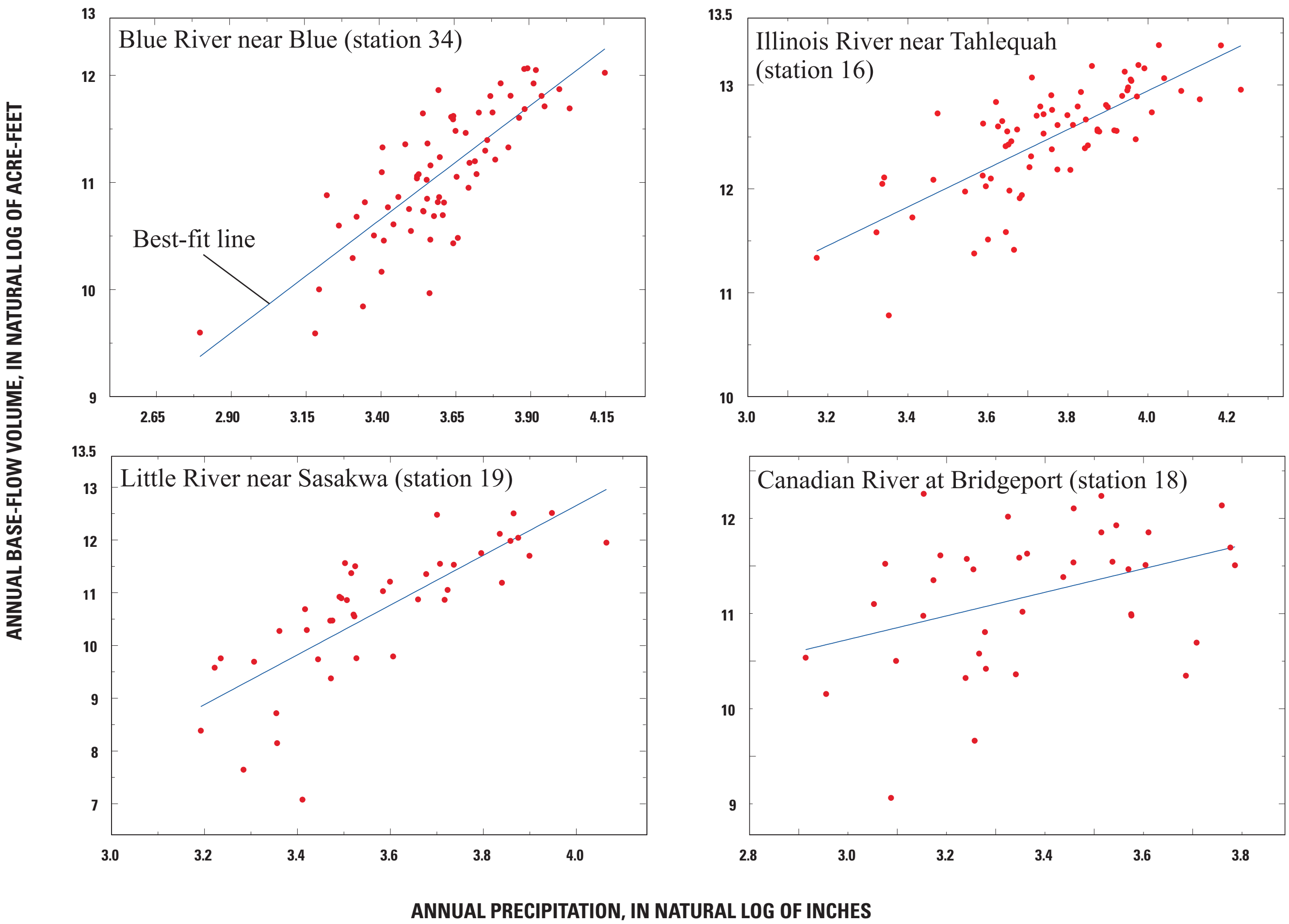

Figure 5. Relation between annual base-flow volume and annual precipitation at four streamflow-gaging stations in Oklahoma. Station numbers are referenced on table 1.

seasonal precipitation and annual and seasonal streamflow volume (Helsel and Hirsch, 2002, p. 336).

When developing the LOESS regression, even though the technique allows for a curved relation, if the error residuals are not normally distributed or there are extreme outliers in the relation, the regression line may be biased towards those outliers that will affect the magnitude of the residuals and may result in a biased trend (Helsel and Hirsch, 2002, p. 332; David K. Mueller, U.S. Geological Survey, oral and written commun., March 2009). For this report, the LOESS regression was calculated on the natural logarithms of annual or seasonal precipitation and annual and seasonal streamflow volume.

An example of the precipitation adjustment trend procedure is presented in figure 6 for Spavinaw Creek near Sycamore (station 15) (fig. 1). No trend in annual base-flow volume existed with a simple trend with time (fig. 6A). An increase in precipitation was observed during the analysis period (fig. 6B). There is a statistically significant correlation between precipitation and base-flow volume (fig. 6C). A trend of the error residuals with time indicates further support for this observation because there is a statistically significant downward trend. The downward trend (fig. 6D) in residuals indicates that when precipitation is not considered in the trend, base-flow volume is decreasing. Another interpretation of this result is that with time, the same amount of precipitation in a given year is yielding a lesser volume of base flow than in previous years.

The LOESS regression was developed for the natural logarithms of annual and seasonal base-flow volume, total-flow volume, and the natural logarithms of annual or seasonal precipitation. A partial t-test from a linear regression, which is a test to determine if the correlation between parameters is statistically significant (Ott and Longnecker, 1995, p. 590–597; Helsel and Hirsch, 2002, p. 311-312), was used to evaluate the correlation between the natural logarithms of annual and seasonal base-flow volume and total-flow volume, and the natural logarithms of annual, winter-spring, and summer-autumn precipitation. The relation with the highest correlation coefficient and t-value was selected as the precipitation parameter used in the LOESS regression. If there was no statistically significant correlation between streamflow volume (a t-value between -2.0 and 2.0) and any of the precipitation parameters, precipitation adjustment was not justified and was not calculated.

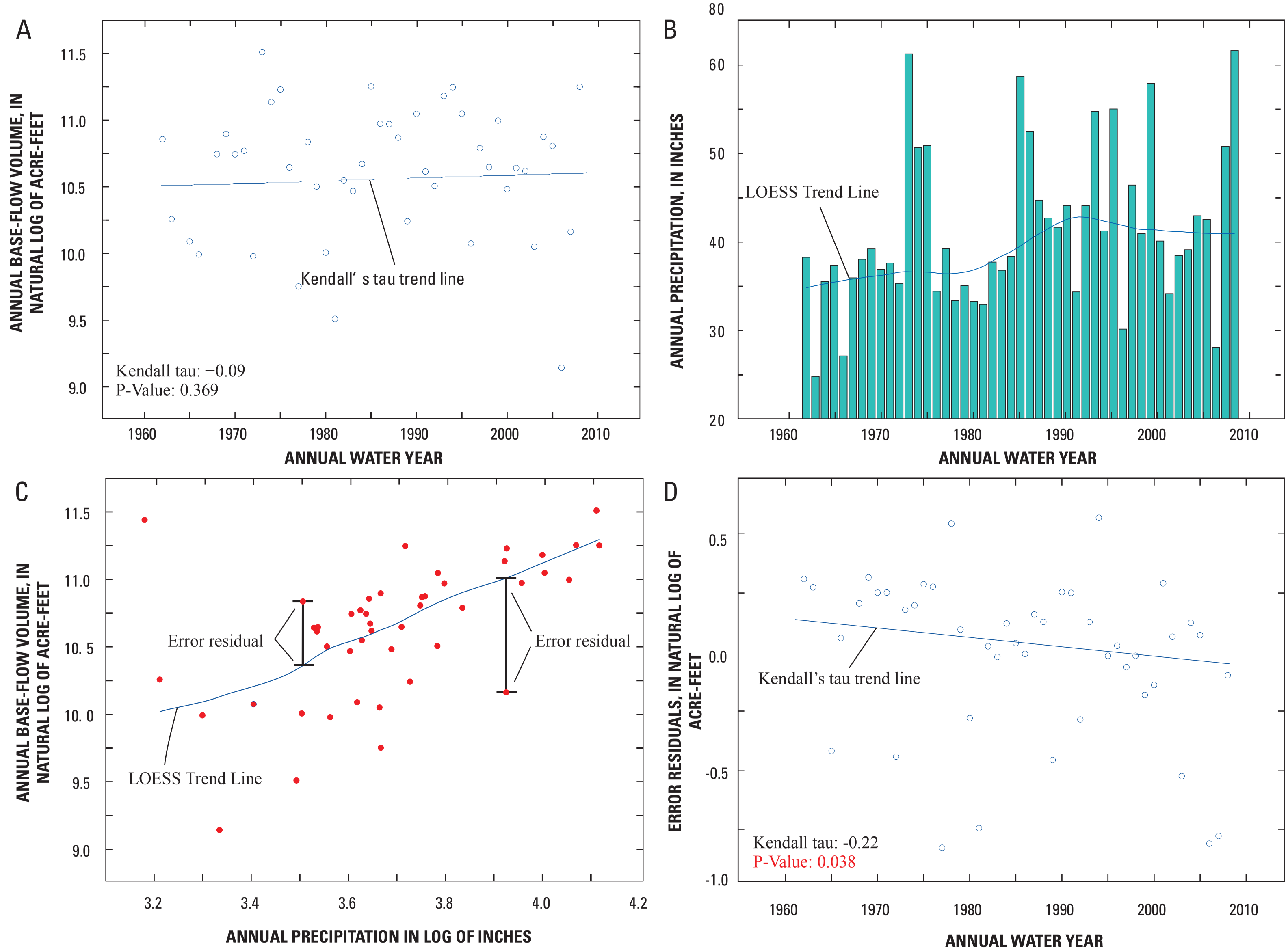

Figure 6. Trends in base-flow volume at Spavinaw Creek near Sycamore, Oklahoma, (USGS Station Identifier 07191220; station 15, table 1), showing (A) not significant (p-value less than or equal to 0.5) Kendall's tau base-flow trend line over time, (B) annual precipitation over time, (C) LOESS relation between annual precipitation and base flow with error residuals, and (D) significant Kendall's tau precipitation adjusted base-flow trend line over time in error residuals for the LOESS relation between annual base flow and annual precipitation.

Several limitations of this approach exist for evaluation of trends in precipitation-adjusted streamflow volume. Even if streamflow volume and precipitation are significantly correlated, the result of precipitation-adjusted trend analysis may not be different than the result of simple trend analysis if the correlation is weak (the correlation has a low t-value or low R^2, for example), because the residuals are substantially large in magnitude with a weak correlation. A weak correlation may indicate that streamflow is not dependent on the annual or seasonal precipitation but is more affected by other variables. For this report, results of precipitation adjustment are not presented for base-flow index. Precipitation adjustment could not be calculated for the annual or seasonal base-flow index for 29 of 37 stations because base-flow index was not significantly correlated to precipitation. For the remainder of stations that did have a significant correlation between annual or seasonal base-flow index and precipitation, the average absolute t-test score was relatively low (less than 4.5). Such a low t-test score indicates that the correlation between variables is statistically significant (at the 95th percent confidence level) but weak. Precipitation and base-flow index were uncorrelated or weakly correlated probably because increases in precipitation result in an increase to base flow and total flow, which may affect the ratio between these two parameters. Most significant correlations were negative (increases in precipitation resulted in decreases in base-flow index).

In addition, trend analysis of precipitation-adjusted streamflow may be subject to serial auto-correlation. Serial auto-correlation is the correlation between a data point and the adjacent points in a time series (Helsel and Hirsch, 2002, p. 251-252). Procedures used to compute trends in precipitation-adjusted streamflow volume incorporate same-year data pairs of precipitation and streamflow in the LOESS relation. A drainage basin, which is fed by groundwater and not prone to flash floods, may result in base-flow volumes that also are correlated to precipitation amounts from previous years as a result of long-term aquifer recharge to an aquifer with substantial storage capacity after a series of years with above-average precipitation. In this example, trend analysis of precipitation-adjusted streamflow, which incorporated a LOESS relation between same-year data pairs of precipitation and streamflow, would be biased toward upward trends for drainage basins that exhibit these characteristics because the correlation of base flow to precipitation from previous years was not accounted for. Whereas, this bias may be a limitation of the method, trends in precipitation-adjusted streamflow volume, which are subject to serial auto-correlation, may help to highlight those stations where streamflow volume may be affected by long-term recharge of underlying aquifers. This information can be beneficial for water-resources planning. Further analysis is warranted into the relation of streamflow to precipitation of previous years, or use of additional exogenous variables, to better evaluate how climate and recharge affect base-flow volume trends (David K. Mueller, U.S. Geological Survey, oral and written commun., May 2009).

The precipitation-adjusted methods used in this report only test for a change in the intercept in the relation between streamflow volume and precipitation. If there is a change in slope in this relation, the results of the trend analysis by using these procedures may or may not reflect those changes. Additional analysis into the changes in the relation between these two parameters would help to further investigate the causes of a change in slope (Helsel and Hirsch, 2002, p. 336).

Trends in Base Flow, Total Flow, and Base-Flow Index

In this section, results of trend analysis for precipitation are presented for the 12 climate divisions, because precipitation change is the most direct potential cause of streamflow change. Next, results of trend analysis for base flow, total flow, and base-flow index are presented by station, for the study area, and then by major drainage basin. In subsequent sections, trends for peak flow, number of extreme low-flow days, and groundwater levels are described.

Precipitation Trend Analysis

Bar charts and LOESS plots of annual precipitation for all 12 climate divisions (fig. 2) analyzed in this report are presented in figures 7–9 (back of report). Results of the Kendall's tau test for trends in annual and seasonal precipitation are presented in table 2 and figure 10. All 12 climate divisions had upward trends in annual and seasonal precipitation, but trends in many climate divisions were not statistically significant (fig. 2, table 2). These trends are similar to those reported by Tortorelli and others (2005) that summarized annual precipitation trends for climate divisions through 2003. All climate divisions that were analyzed in both this report and Tortorelli (2005) had upward trends in annual precipitation, some of which were not significant. More climate divisions indicated statistically significant upward trends in the analysis presented in this report than in Tortorelli (2005). This difference may have occurred because water years 2007 and 2008 were considered wet years for many climate divisions in the state (National Climatic Data Center, National Oceanic and Atmospheric Administration, 2009).

In general, significant upward trends in precipitation were detected in central Oklahoma and central and southeastern Kansas (fig. 10). More climate divisions had statistically significant upward trends in total precipitation for annual water years (fig. 10) than in winter-spring or summer-autumn water years (fig. 10). Significant upward trends in annual precipitation were detected in western and central Oklahoma, and in south-central and southeast Kansas (fig. 10). Significant upward trends in winter-spring precipitation were detected for south-central and southeast Kansas and west-central Oklahoma (fig. 10). Significant upward trends in summer-autumn

Table 2. Results of Kendall's tau trend analyses of total annual and seasonal precipitation in Oklahoma and portions of Kansas, water years 1895-20081.

[shading indicates statistically significant upwards trend at 95-percent confidence level (probability value less than or equal to 0.05), no downwards trends were observed; yr, year]

Climate division number - region descriptor[1]	Climate division code	Total precipitation trends														
		Annual					Winter-spring[2]					Summer-autumn[2]				
		Median precipitation (inches)	Kendall's tau	Probability value	Trend slope (inch/year)	Trend slope (percent)	Median precipitation (inches)	Kendall's tau	Probability value	Trend slope (inch/year)	Trend slope (percent)	Median precipitation (inches)	Kendall's tau	Probability value	Trend slope (inch/year)	Trend slope (percent)
Kansas																
7 - Southwest	KS-7	18.770	0.091	0.152	0.017	0.093	7.560	0.033	0.611	0.004	0.048	11.060	0.052	0.419	0.008	0.069
8 - South Central	KS-8	26.750	0.162	0.029	0.066	0.245	11.730	0.148	0.046	0.035	0.300	19.400	0.146	0.050	0.051	0.261
9 - Southeast	KS-9	38.030	0.152	0.041	0.082	0.215	17.780	0.190	0.011	0.055	0.310	19.980	0.072	0.334	0.026	0.132
Oklahoma																
1 - Panhandle	OK-1	19.620	0.096	0.133	0.021	0.108	8.100	0.065	0.313	0.010	0.118	11.270	0.076	0.234	0.013	0.112
2 - North Central	OK-2	28.750	0.162	0.011	0.047	0.164	13.300	0.112	0.079	0.022	0.166	14.260	0.134	0.036	0.032	0.221
3 - Northeast	OK-3	39.020	0.080	0.211	0.027	0.068	20.460	0.105	0.101	0.028	0.135	18.860	0.044	0.493	0.011	0.059
4 - West Central	OK-4	26.520	0.172	0.007	0.047	0.176	12.470	0.129	0.043	0.027	0.213	13.170	0.115	0.072	0.025	0.187
5 - Central	OK-5	33.640	0.142	0.026	0.050	0.149	17.320	0.112	0.079	0.024	0.136	16.370	0.118	0.063	0.027	0.168
6 - East Central	OK-6	42.850	0.103	0.107	0.039	0.090	23.100	0.102	0.111	0.025	0.109	18.980	0.032	0.618	0.008	0.040
7 - Southwest	OK-7	27.640	0.117	0.067	0.035	0.127	13.400	0.088	0.168	0.017	0.126	13.180	0.117	0.066	0.025	0.191
8 - South Central	OK-8	37.040	0.086	0.177	0.032	0.087	20.350	0.050	0.439	0.012	0.058	16.310	0.092	0.150	0.021	0.131
9 - Southeast	OK-9	48.430	0.115	0.072	0.048	0.099	28.670	0.052	0.413	0.016	0.057	18.540	0.108	0.089	0.028	0.152
Oklahoma Statewide																
	ST34	33.505	0.178	0.017	0.068	0.204	17.375	0.159	0.032	0.039	0.226	16.115	0.112	0.131	0.028	0.173

[1]From *http://www.ncdc.noaa.gov/oa/climate/onlineprod/drought/ftppage.html*

[2]Winter-spring precipitation indicates that annual precipitation data used in the trend analysis were only from the months of November through May, and Summer-autumn indicates that annual precipitation data used in the trend analysis were only from the months of June through October. Water years (defined as the period from October 1 of the preceding calendar year through September 30 of the current calendar year) analyzed for the summer-autumn period also include October precipitation from the proceeding water year.

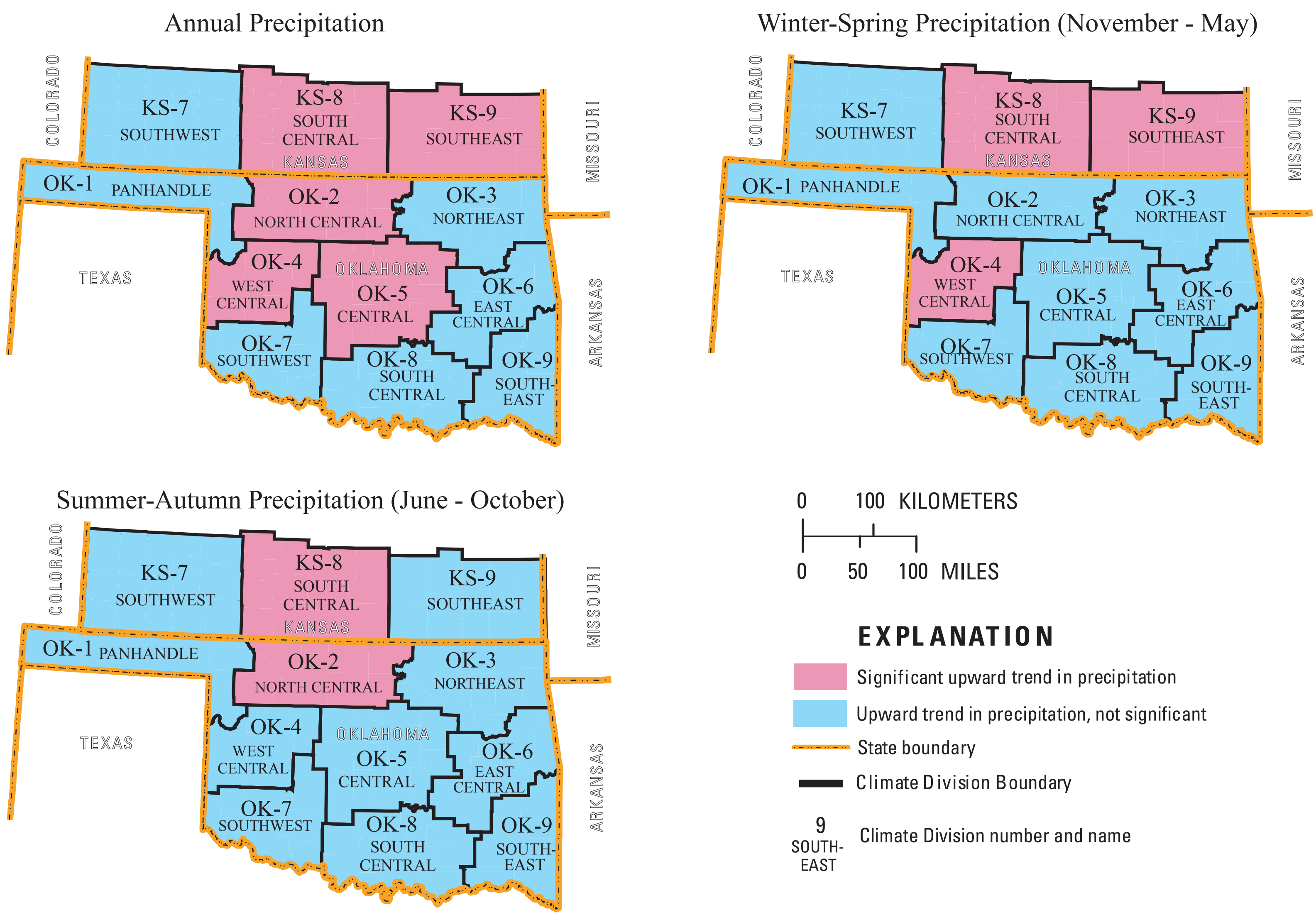

Figure 10. Results of Kendall's Tau trend analysis of annual precipitation data from National Weather Service Climate Divisions (National Oceanic and Atmospheric Administration, 2009).

precipitation were only detected for north-central Oklahoma and south-central Kansas (fig. 10).

Streamflow Volume and Base-Flow Index Trend Analysis

Graphs showing LOESS plots for annual base-flow volume, total-flow volume, and base-flow index are shown in figures 11–47 (back of report). LOESS plots for Beaver River at Beaver, Oklahoma, (station 21) and North Canadian River near Seiling, Oklahoma, (station 22) were created for the entire period of record, and not just the period used for statistical analysis (table 1), for visual comparison of streamflow during the unregulated period and irrigated period. Results of trend analysis of unadjusted and precipitation-adjusted base-flow volume, total-flow volume, and base-flow index for annual and seasonal water years are presented in tables 3–9. Maps were developed to display spatial patterns in trend results for annual and seasonal streamflow volume and base-flow index (figs. 48–62, back of report). Maps show the direction of the trend and whether the trend was statistically significant. Maps showing results from trends in unadjusted and precipitation-adjusted base-flow and total-flow volumes are presented for visual comparison (figs. 48–62). The significance and direction of a trend in precipitation–adjusted streamflow volume in which streamflow volume was not significantly correlated to precipitation would be the same as a trend in unadjusted streamflow volume. For ease of comparison between maps, if trends in precipitation-adjusted streamflow volume were not calculated, the results from trend analysis of unadjusted streamflow volume also were displayed on the map with trends in precipitation-adjusted streamflow volume.

Significant trends in base-flow volume were detected at most stations, most of which were upward in direction. Significant trends in annual or seasonal base-flow volume were detected at 22 of 37 stations analyzed. All stations with significant trends (upward or downward) in winter-spring or summer-autumn base-flow volume (21 and 17 stations, respectively) also had significant trends in annual base-flow volume in the same direction (tables 3 through 5). Significant upward trends in annual or seasonal base-flow volume were detected for 19 stations (19 stations the annual period, 18 stations for the winter-spring period, and 14 stations for the summer-autumn period). Significant downward trends in annual and seasonal base-flow volume were detected for 3 stations: Cimarron River near Kenton and Forgan, Oklahoma, and Beaver River at Beaver, Oklahoma, (stations 6, 7, and 21, respectively).

Precipitation-adjustment changed the results (significance only or significance and direction) of annual or seasonal base-flow trends for 12 stations (9 stations for the annual period, 6 stations for the winter-spring period, and 5 stations for the summer-autumn period). Precipitation adjustment did not change the results (significance only or significance and direction) of most significant trends in unadjusted base-flow volume (tables 3–5). However, precipitation adjustment reduced the magnitude of most of the significant upward base-flow trends. Significant trends in precipitation-adjusted base-flow volume that were in the same direction as significant trends in unadjusted base-flow volume for each respective season were detected for 13 stations for the annual period, 14 stations for the winter-spring period, and 10 stations for the summer-autumn period. For the annual period, significant downward trends in precipitation-adjusted base-flow volume that were not significant prior to precipitation adjustment were detected for two stations: Arkansas River near Arkansas City, Kansas, and Spavinaw Creek near Sycamore, Oklahoma, (stations 1 and 15, respectively). Only station 1 had a significant downward trend in winter-spring base-flow volume that was not significant prior to precipitation adjustment (table 4).

Fewer stations had significant trends in total-flow volume than stations that had significant trends in base-flow volume, and most of the significant trends in annual and winter-spring total-flow volume were upward (tables 6–8). Many stations that had significant upward trends in total-flow volume had significant upward trends in base-flow volume for the same period with the exception of station 14, which had a significant upward trend in winter-spring total-flow volume but no significant trend in base-flow volume. Significant trends in annual or seasonal total-flow volume were detected for 14 stations, 9 of which had significant upward trends (8 stations for the annual period, 9 stations for the winter-spring period, and 4 stations for the summer-autumn period). Significant downward trends in total-flow volume were detected for four stations for the annual period, three stations for the winter-spring period, and five stations for the summer-autumn period.

Precipitation adjustment changed the trend results (significance only or significance and direction) of annual or seasonal total-flow volume for 13 stations (8 stations for the annual period, 7 stations for the winter-spring period, and 5 stations for the summer-autumn period). No significant trends in precipitation-adjusted total-flow volume were detected where significant trends were detected for unadjusted total-flow volume for five stations for the annual period, and four stations for the winter-spring period and summer-autumn period (table 7). Significant upward trends in precipitation-adjusted total-flow volume that were in the same direction as significant upward trends for unadjusted total-flow volume for each respective station were detected for three stations for the annual period, five stations for the winter-spring period, and no stations for the summer-autumn period. Significant downward trends in precipitation-adjusted annual total-flow volume that were not significant prior to precipitation adjustment were detected for three stations: North Canadian River near Seiling, Oklahoma, Salt Fork Red River at Mangum, Oklahoma, and North Fork Red River near Carter, Oklahoma, (stations 22, 26, and 27, respectively) (table 6). Significant downward trends in precipitation-adjusted winter-spring total-flow volume that were not significant prior to precipitation adjustment were detected for three stations: Cimarron River near Waynoka,

Table 3. Results of trend analysis for annual base-flow volume for 37 selected streamflow-gaging stations in and near Oklahoma.

[no., number; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; P-value, probability value; <, less than; ac-ft, acre-feet; Adjusted trend, trend adjusted for changes in annual or seasonal precipitation; A, annual total precipitation; WS, winter-spring total precipitation; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend; --, trend test not performed]

Station no. (fig. 1)	USGS station ID	Median base-flow volume (acre-feet)	Annual base-flow trends: Trend slope (percent/year)	Annual base-flow trends: Tau	Annual base-flow trends: p-value	Annual adjusted base-flow trends: Precipitation parameter[1]	Annual adjusted base-flow trends: T-test score	Annual adjusted base-flow trends: Trend slope (percent/year)[2]	Annual adjusted base-flow trends: Tau[2]	Annual adjusted base-flow trends: p-value[2]
1	07146500	725,800	-0.15	-0.03	0.690	A	6.73	-0.45	-0.18	0.031
2	07151000	208,700	1.72	0.27	0.001	A	9.29	0.88	0.19	0.027
3	07152000	96,760	1.85	0.38	<0.001	A	7.48	1.00	0.30	0.000
4	07152500	2,035,000	1.58	0.17	0.168	A	6.31	0.34	0.03	0.808
5	07153000	22,210	3.78	0.28	0.010	WS	7.44	2.25	0.33	0.002
6	07154500	768	-3.95	-0.36	<0.001	WS	1.02	--	--	--
7	07156900	25,130	-1.75	-0.74	<0.001	A	0.34	--	--	--
8	07158000	40,480	1.11	0.18	0.025	A	6.18	0.47	0.11	0.190
9	07159100	201,700	1.22	0.14	0.256	A	3.41	0.46	0.07	0.570
10	07161450	327,100	2.25	0.38	<0.001	A	7.29	1.70	0.39	0.000
11	07171000	501,100	1.45	0.13	0.242	WS	8.65	-0.37	-0.05	0.665
12	07172000	44,740	1.95	0.17	0.108	WS	8.17	-0.25	-0.02	0.832
13	07188000	588,200	0.83	0.19	0.020	A	8.77	0.44	0.12	0.157
14	07191000	29,380	0.92	0.14	0.104	A	7.87	0.09	0.02	0.867
15	07191220	42,100	0.48	0.09	0.369	A	5.74	-0.61	-0.22	0.038
16	07196500	288,300	0.60	0.19	0.020	A	9.47	0.26	0.12	0.136
17	07197000	88,230	1.00	0.21	0.016	A	10.31	0.30	0.11	0.214
18	07228500	95,340	3.72	0.42	<0.001	WS	2.66	3.48	0.44	0.000
19	07231000	52,890	3.04	0.20	0.057	A	7.94	0.07	0.01	0.967
20	07231500	336,000	3.60	0.33	0.002	A	6.39	2.04	0.28	0.007
21	07234000	53,840	-3.17	-0.38	<0.001	WS	2.01	-3.88	-0.44	<0.001
22	07238000	49,120	1.06	0.14	0.107	A	6.17	0.48	0.07	0.409
23	07242000	224,700	1.48	0.25	0.002	A	8.17	0.92	0.26	0.002
24	07243500	123,200	1.13	0.11	0.318	WS	7.69	0.86	0.14	0.204
25	07247500	15,050	0.26	0.02	0.884	A	6.83	-0.41	-0.07	0.537
26	07300500	9,509	2.31	0.35	<0.001	A	5.01	1.56	0.29	0.000
27	07301500	28,330	2.33	0.35	<0.001	A	5.52	1.48	0.24	0.004
28	07311500	4,476	1.87	0.10	0.371	A	5.79	0.18	0.02	0.885
29	07315700	6,332	4.00	0.26	0.010	A	8.13	1.76	0.18	0.071
30	07316000	454,800	1.12	0.21	0.016	A	6.52	0.42	0.13	0.143

Table 3. Results of trend analysis for annual base-flow volume for 37 selected streamflow-gaging stations in and near Oklahoma. —Continued

[no., number; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; P-value, probability value; <, less than; ac-ft, acre-feet; Adjusted trend, trend adjusted for changes in annual or seasonal precipitation; A, annual total precipitation; WS, winter-spring total precipitation; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend; --, trend test not performed]

Station no. (fig. 1)	USGS station ID	Median base-flow volume (acre-feet)	Annual base-flow trends: Trend slope (percent/year)	Annual base-flow trends: Tau	Annual base-flow trends: p-value	Annual adjusted base-flow trends: Precipitation parameter[1]	Annual adjusted base-flow trends: T-test score	Annual adjusted base-flow trends: Trend slope (percent/year)[2]	Annual adjusted base-flow trends: Tau[2]	Annual adjusted base-flow trends: p-value[2]
31	07316500	5,635	3.96	0.43	<0.001	A	3.82	3.29	0.36	0.000
32	07326500	116,100	3.34	0.37	<0.001	A	4.40	2.69	0.33	0.002
33	07331000	377,900	3.51	0.37	<0.001	A	5.23	2.20	0.35	0.001
34	07332500	65,340	0.40	0.09	0.254	A	11.01	0.04	0.02	0.850
35	07335700	14,200	1.01	0.24	0.025	A	5.57	0.76	0.19	0.076
36	07336200	221,000	-1.53	-0.17	0.234	A	7.22	-0.46	-0.05	0.726
37	07337900	65,680	0.76	0.10	0.322	A	7.19	-0.03	-0.02	0.883

[1] Winter-spring indicates that year precipitation totals used in trend adjustment were only from the months of November through May and summer-autumn indicates that yearly precipitation totals used in trend adjustment were only from the months of June through October.

[2] If the t-test score for correlation with the precipitation parameter was between -2.0 and 2.0, then trend adjustment was not performed.

Table 4. Results of trend analysis for winter-spring base-flow volume for 37 selected streamflow-gaging stations in and near Oklahoma.

[no., number; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; P-value, probability value; <, less than; ac-ft, acre-feet; Adjusted trend, trend adjusted for changes in annual or seasonal precipitation; A, annual total precipitation; WS, winter-spring total precipitation; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend; --, trend test not performed]

Station no. (fig. 1)	USGS station ID	Median winter-spring base-flow volume (acre-feet)	Winter-spring base-flow trends: Trend slope (percent/year)	Winter-spring base-flow trends: Tau	Winter-spring base-flow trends: p-value	Winter-spring adjusted base-flow trends: Precipitation parameter[1]	Winter-spring adjusted base-flow trends: T-test score	Winter-spring adjusted base-flow trends: Trend slope (percent/year)[2]	Winter-spring adjusted base-flow trends: Tau[2]	Winter-spring adjusted base-flow trends: p-value[2]
1	07146500	413,200	-0.14	-0.03	0.690	WS	4.89	-0.52	-0.17	0.049
2	07151000	118,700	1.82	0.27	0.001	WS	6.79	1.03	0.18	0.035
3	07152000	66,070	1.91	0.37	<0.001	A	5.05	1.36	0.35	<0.001
4	07152500	1,171,000	1.28	0.13	0.323	WS	4.89	1.12	0.15	0.237
5	07153000	15,040	3.57	0.22	0.044	WS	7.66	2.29	0.25	0.021
6	07154500	419	-3.18	-0.28	0.002	WS	1.73	--	--	--
7	07156900	16,660	-1.66	-0.72	<0.001	WS	0.73	--	--	--
8	07158000	29,940	1.23	0.21	0.011	A	5.07	0.67	0.14	0.092
9	07159100	119,400	1.00	0.08	0.495	WS	3.16	1.14	0.15	0.201
10	07161450	178,300	2.41	0.40	<0.001	A	5.68	2.01	0.39	<0.001

Table 4. Results of trend analysis for winter-spring base-flow volume for 37 selected streamflow-gaging stations in and near Oklahoma. —Continued

[no., number; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; P-value, probability value; <, less than; ac-ft, acre-feet; Adjusted trend, trend adjusted for changes in annual or seasonal precipitation; A, annual total precipitation; WS, winter-spring total precipitation; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend; --, trend test not performed]

			Winter-spring base-flow trends			Winter-spring adjusted base-flow trends				
Station no. (fig. 1)	USGS station ID	Median winter-spring base-flow volume (acre-feet)	Trend slope (percent/year)	Tau	p-value	Precipitation parameter[1]	T-test score	Trend slope (percent/year)[2]	Tau[2]	p-value[2]
11	07171000	288,900	0.89	0.06	0.573	WS	7.55	-0.58	-0.06	0.588
12	07172000	34,400	1.44	0.12	0.270	WS	6.32	-0.73	-0.07	0.485
13	07188000	381,100	1.04	0.21	0.010	WS	7.94	0.45	0.11	0.190
14	07191000	21,210	0.95	0.12	0.165	WS	6.50	-0.61	-0.09	0.287
15	07191220	31,990	0.42	0.07	0.486	A	5.04	-0.74	-0.20	0.051
16	07196500	207,600	0.66	0.19	0.017	A	8.57	0.31	0.11	0.187
17	07197000	67,300	0.98	0.23	0.011	A	9.28	0.35	0.11	0.223
18	07228500	67,930	3.57	0.40	<0.001	WS	2.62	3.54	0.41	<0.001
19	07231000	32,060	2.70	0.18	0.090	WS	6.06	1.44	0.14	0.180
20	07231500	235,000	3.42	0.30	0.004	A	5.74	2.04	0.28	0.007
21	07234000	38,650	-2.90	-0.30	<0.001	WS	2.11	-3.74	-0.42	<0.001
22	07238000	35,410	1.14	0.17	0.062	A	5.23	0.68	0.15	0.099
23	07242000	119,000	1.74	0.27	0.001	A	6.66	1.17	0.27	0.001
24	07243500	92,350	0.92	0.07	0.508	WS	7.81	0.52	0.07	0.522
25	07247500	12,890	0.26	0.03	0.762	WS	6.21	-0.72	-0.16	0.147
26	07300500	7,572	2.49	0.38	<0.001	A	3.40	1.83	0.26	0.001
27	07301500	20,510	2.51	0.37	<0.001	A	4.70	1.71	0.25	0.002
28	07311500	3,179	2.09	0.11	0.333	A	4.75	0.18	0.02	0.885
29	07315700	3,585	4.47	0.22	0.027	A	6.12	1.64	0.15	0.138
30	07316000	248,400	1.21	0.20	0.018	WS	6.44	0.90	0.20	0.019
31	07316500	5,016	3.80	0.40	<0.001	WS	3.17	3.68	0.35	0.001
32	07326500	77,240	3.08	0.41	<0.001	A	3.02	2.50	0.33	0.002
33	07331000	256,700	3.07	0.34	0.001	WS	4.91	1.97	0.31	0.003
34	07332500	43,410	0.56	0.10	0.200	A	8.84	0.20	0.06	0.457
35	07335700	12,870	0.97	0.20	0.054	A	5.71	0.72	0.20	0.063
36	07336200	207,100	-2.00	-0.23	0.118	A	5.63	-0.77	-0.08	0.591
37	07337900	56,230	0.65	0.10	0.340	A	6.84	0.02	0.00	0.971

[1]Winter-spring indicates that year precipitation totals used in trend adjustment were only from the months of November through May and summer-autumn indicates that yearly precipitation totals used in trend adjustment were only from the months of June through October.

[2]If the t-test score for correlation with the precipitation parameter was between -2.0 and 2.0, then trend adjustment was not performed.

Table 5. Results of trend analysis for summer-autumn base-flow volume for 37 selected streamflow-gaging stations in and near Oklahoma. —Continued

[no., number; USGS station ID, U.S. Geological Survey station ID; Tau, Kendall's tau; P-value, probability value; <, less than; ac-ft, acre-feet; Adjusted trend, trend adjusted for changes in annual or seasonal precipitation; A, annual total precipitation; SA, summer-autumn total precipitation; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend; --, trend test not performed]

Station no. (fig. 1)	USGS station ID	Median summer-autumn base-flow volume (acre-feet)	Summer-autumn base-flow trends			Summer-autumn adjusted base-flow trends				
			Trend slope (percent/year)	Tau	p-value	Precipitation parameter[1]	T-test score	Trend slope (percent/year)[2]	Tau[2]	p-value[2]
1	07146500	280,400	0.18	0.03	0.690	A	13.48	-0.37	-0.14	0.109
2	07151000	54,170	1.98	0.23	0.007	A	13.53	0.51	0.12	0.147
3	07152000	29,380	1.94	0.30	<0.001	A	12.57	0.91	0.25	0.002
4	07152500	769,100	3.01	0.17	0.189	A	5.87	0.59	0.06	0.662
5	07153000	5,153	4.71	0.26	0.018	A	6.29	2.51	0.23	0.038
6	07154500	107	-6.34	-0.37	<0.001	SA	1.98	--	--	--
7	07156900	8,734	-2.04	-0.67	<0.001	SA	0.85	--	--	--
8	07158000	6,662	0.83	0.07	0.361	A	7.88	-0.81	-0.11	0.190
9	07159100	52,860	0.77	0.05	0.712	A	5.25	-0.36	-0.06	0.629
10	07161450	105,000	1.94	0.28	0.001	A	9.13	1.28	0.30	<0.001
11	07171000	99,580	2.12	0.13	0.242	A	5.47	1.47	0.12	0.251
12	07172000	6,712	2.41	0.18	0.087	A	7.63	1.21	0.15	0.143
13	07188000	164,100	0.28	0.06	0.484	A	8.38	0.18	0.05	0.538
14	07191000	3,520	0.97	0.08	0.360	A	8.99	-0.30	-0.05	0.546
15	07191220	10,170	0.94	0.11	0.279	A	6.99	-0.28	-0.05	0.647
16	07196500	73,320	0.63	0.17	0.034	A	10.57	0.25	0.11	0.169
17	07197000	17,950	0.92	0.18	0.043	A	9.24	0.40	0.12	0.178
18	07228500	12,010	4.89	0.36	0.001	A	4.44	3.64	0.38	0.001
19	07231000	10,020	2.99	0.14	0.180	A	8.91	-0.11	-0.01	0.917
20	07231500	68,500	3.90	0.26	0.013	A	6.12	2.09	0.21	0.051
21	07234000	6,733	-5.33	-0.34	<0.001	A	3.17	-5.82	-0.41	<0.001
22	07238000	13,190	1.65	0.13	0.131	A	7.19	-0.05	-0.01	0.952
23	07242000	75,190	1.20	0.18	0.024	A	9.11	0.79	0.19	0.022
24	07243500	30,560	0.44	0.02	0.831	A	6.25	0.35	0.03	0.796
25	07247500	1,550	-1.19	-0.10	0.375	A	3.97	-1.19	-0.11	0.318
26	07300500	1,367	2.11	0.18	0.027	A	6.55	1.47	0.13	<0.001
27	07301500	4,680	2.13	0.20	0.017	A	8.97	0.38	0.04	0.645
28	07311500	1,461	0.39	0.04	0.753	A	6.74	0.20	0.02	0.847
29	07315700	1,161	2.37	0.16	0.116	A	6.93	1.05	0.09	0.369
30	07316000	172,400	0.63	0.11	0.196	A	6.92	0.16	0.04	0.664

Table 5. Results of trend analysis for summer-autumn base-flow volume for 37 selected streamflow-gaging stations in and near Oklahoma. —Continued

[no., number; USGS station ID, U.S. Geological Survey station ID; Tau, Kendall's tau; P-value, probability value; <, less than; ac-ft, acre-feet; Adjusted trend, trend adjusted for changes in annual or seasonal precipitation; A, annual total precipitation; SA, summer-autumn total precipitation; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend; --, trend test not performed]

Station no. (fig. 1)	USGS station ID	Median summer-autumn base-flow volume (acre-feet)	Summer-autumn base-flow trends: Trend slope (percent/year)	Tau	p-value	Summer-autumn adjusted base-flow trends: Precipitation parameter[1]	T-test score	Trend slope (percent/year)[2]	Tau[2]	p-value[2]
31	07316500	755	7.71	0.42	<0.001	A	6.09	4.62	0.34	0.001
32	07326500	45,280	3.42	0.29	0.005	A	7.16	2.20	0.28	0.007
33	07331000	121,600	3.91	0.33	0.001	A	6.36	2.40	0.31	0.003
34	07332500	20,180	-0.16	-0.04	0.670	A	12.99	-0.43	-0.14	0.079
35	07335700	1,116	1.65	0.12	0.250	SA	4.49	1.86	0.20	0.071
36	07336200	15,280	-6.27	-0.26	0.072	SA	4.63	-1.16	-0.07	0.624
37	07337900	6,022	1.49	0.16	0.107	SA	5.57	1.86	0.20	0.059

[1]Winter-spring indicates that year precipitation totals used in trend adjustment were only from the months of November through May and summer-autumn indicates that yearly precipitation totals used in trend adjustment were only from the months of June through October.

[2]If the t-test score for correlation with the precipitation parameter was between -2.0 and 2.0, then trend adjustment was not performed.

Oklahoma, Salt Fork Red River at Mangum, Oklahoma, and Kiamichi River near Big Cedar, Oklahoma, (stations 8, 26, and 35) (table 7). A significant downward trend in precipitation-adjusted summer-autumn total-flow volume that was not significant prior to precipitation adjustment was only detected for one station, North Canadian River near Seiling, Oklahoma, (station 22) (table 8).

Significant trends in base-flow index were detected for a majority of stations, and most of these trends were upward in direction (table 9). Significant trends in base-flow index for the annual or seasonal period were detected for 25 stations. Significant upward trends in base-flow index were detected for 22 stations for the annual period, 18 stations for the winter-spring period, and 16 stations for the summer-autumn period. A significant downward trend in winter-spring base-flow index was detected for only one station, Arkansas River near Arkansas City, Kansas, (station 1). A significant downward trend in summer-autumn base-flow index was detected for only one station, Cimarron River near Kenton, Oklahoma, (station 6).

Many stations that had significant upward trends in annual or seasonal base-flow index also had significant upward trends in annual or seasonal base-flow volume. Significant upward trends in both base-flow index and base-flow volume, accompanied by no significant downward trends in total-flow volume, were detected for 18 stations annually or seasonally (17 for the annual period, 12 stations for the winter-spring period, and 10 stations for the summer-autumn period). These results indicate that significant upward trends in annual or seasonal base-flow index at these stations likely were driven by increases in base flow as opposed to decreases in runoff. Significant upward trends in base-flow index followed by significant downward trends in annual and seasonal base-flow volume and total-flow volume were detected for 2 stations: Cimarron River near Forgan, Oklahoma, and Beaver River at Beaver, Oklahoma, (stations 7 and 21, respectively). Even though streamflow volume was decreasing, base-flow decreased at a slower rate than runoff decreased at these stations, which is the likely cause of significant upward trends in base-flow index. Only one station, Cimarron River near Waynoka, Oklahoma, (station 8) had an upward trend in summer-autumn base-flow index, a downward trend in total-flow volume, and no significant trend in base-flow volume for the same period. Upward trends in base-flow index at this station likely are driven by decreases in runoff as opposed to increases in base-flow volume. Only one station, Cimarron River near Kenton, Oklahoma, (station 6), had a downward trend in summer-autumn base-flow index, base-flow volume, and total-flow volume. Downward trends in summer-autumn base-flow index at this station are likely driven by faster decreases in runoff than in base-flow volume.

Table 6. Results of trend analysis for annual total flow volume for 37 selected streamflow-gaging stations in and near Oklahoma.

[no., number; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; P-value, probability value; <, less than; ac-ft, acre-feet; Adjusted trend, trend adjusted for changes in annual or seasonal precipitation; A, annual total precipitation; WS, winter-spring total precipitation; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend; --, trend test not performed]

Station no. (fig. 1)	USGS station ID	Median total-flow volume (acre-feet)	Annual total-flow trends			Annual adjusted total-flow trends				
			Trend slope (percent/ year)	Tau	p-value	Precipi-tation param-eter[1]	T-test score	Trend slope (percent/year)[2]	Tau[2]	p-value[2]
1	07146500	1,452,000	0.08	0.01	0.894	A	6.73	-0.30	-0.16	0.0614
2	07151000	588,600	1.32	0.20	0.019	A	9.29	0.31	0.08	0.3354
3	07152000	359,800	1.45	0.24	0.003	A	7.48	0.34	0.13	.119
4	07152500	4,055,000	2.13	0.24	0.058	A	6.31	0.64	0.09	0.4856
5	07153000	142,600	2.68	0.18	0.103	A	7.44	0.66	0.10	0.3749
6	07154500	6,235	-3.42	-0.37	<0.001	SA	1.35	--	--	--
7	07156900	29,660	-2.61	-0.74	<0.001	SA	-0.62	--	--	--
8	07158000	167,000	-1.14	-0.20	0.016	A	6.18	-1.61	-0.39	<0.001
9	07159100	562,900	0.24	0.02	0.865	A	3.41	-0.41	-0.05	0.6701
10	07161450	976,700	1.31	0.23	0.005	A	7.29	0.78	0.22	0.0079
11	07171000	1,862,000	0.90	0.11	0.298	A	8.65	-0.08	-0.01	0.9482
12	07172000	201,100	1.68	0.18	0.091	WS	8.17	-0.01	0.00	0.9919
13	07188000	1,454,000	0.59	0.12	0.132	A	8.77	0.12	0.04	0.6374
14	07191000	235,300	0.52	0.09	0.299	A	7.87	-0.35	-0.11	0.2297
15	07191220	70,850	0.83	0.12	0.233	A	5.74	-0.54	-0.16	0.119
16	07196500	665,500	0.32	0.09	0.271	A	9.47	-0.05	-0.02	0.786
17	07197000	236,300	0.65	0.14	0.115	A	10.31	0.05	0.02	0.8234
18	07228500	198,100	1.62	0.18	0.100	A	3.72	0.80	0.14	0.2084
19	07231000	230,700	1.60	0.14	0.202	A	7.94	-0.95	-0.18	0.0823
20	07231500	998,500	2.11	0.23	0.031	A	6.39	0.56	0.12	0.2531
21	07234000	228,000	-5.71	-0.60	<0.001	WS	1.58	--	--	--
22	07238000	107,800	-0.23	-0.04	0.688	A	6.17	-1.12	-0.23	0.009
23	07242000	505,500	1.01	0.17	0.038	A	8.17	0.44	0.14	0.0756
24	07243500	560,900	0.64	0.07	0.552	A	7.69	-0.32	-0.06	0.5976
25	07247500	105,800	0.06	0.01	0.955	A	6.83	-0.26	-0.09	0.4383
26	07300500	51,020	-0.63	-0.12	0.156	A	5.01	-1.12	-0.24	0.0027
27	07301500	79,660	-0.07	-0.01	0.881	A	5.52	-0.75	-0.18	0.0256
28	07311500	80,800	0.63	0.05	0.681	A	5.79	-0.90	-0.13	0.2358
29	07315700	89,690	1.85	0.15	0.147	A	8.13	-0.36	-0.05	0.6124
30	07316000	1,835,000	0.39	0.06	0.455	A	6.52	-0.16	-0.04	0.6061

Table 6. Results of trend analysis for annual total flow volume for 37 selected streamflow-gaging stations in and near Oklahoma. —Continued

[no., number; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; P-value, probability value; <, less than; ac-ft, acre-feet; Adjusted trend, trend adjusted for changes in annual or seasonal precipitation; A, annual total precipitation; WS, winter-spring total precipitation; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend; --, trend test not performed]

Station no. (fig. 1)	USGS station ID	Median total-flow volume (acre-feet)	Annual total-flow trends			Annual adjusted total-flow trends					
			Trend slope (percent/ year)	Tau	p-value	Precipi-tation param-eter[1]	T-test score	Trend slope (percent/year)[2]	Tau[2]	p-value[2]
31	07316500	11,560	2.63	0.29	0.004	A	4.83	1.17	0.19	0.0614
32	07326500	271,500	2.84	0.31	0.003	A	4.40	1.78	0.30	0.0042
33	07331000	1,054,000	2.86	0.32	0.002	A	5.23	1.47	0.27	0.007
34	07332500	184,100	0.17	0.03	0.728	A	11.01	-0.17	-0.05	0.506
35	07335700	64,540	0.37	0.08	0.464	A	5.57	-0.12	-0.06	0.6008
36	07336200	1,214,000	-1.86	-0.13	0.388	A	7.22	-0.34	-0.07	0.6238
37	07337900	348,200	0.92	0.16	0.111	A	7.19	0.04	0.01	0.9269

[1] Winter-spring indicates that year precipitation totals used in trend adjustment were only from the months of November through May and summer-autumn indicates that yearly precipitation totals used in trend adjustment were only from the months of June through October.

[2]If the t-test score for correlation with the precipitation parameter was between -2.0 and 2.0, then trend adjustment was not performed.

Spatial Patterns in Results for Entire Study Area

Maps were used to evaluate spatial patterns in stations with significant trends. Trend results were highly variable throughout the State. However, some recurring patterns in locations of stations with similar trend results were detected (figs. 48–62).

Base Flow

Significant downward trends in annual and seasonal base-flow volume were detected for stations 6, 7, and 21 in the Oklahoma Panhandle. In contrast, upward trends in annual and seasonal base-flow volume were detected for many stations in central, southwestern, and south-central Oklahoma. For many stations in southwestern and south-central Oklahoma, precipitation adjustment did not change the results (direction or significance) of the trends in unadjusted base-flow volume. A recurring spatial pattern in the locations of stations with precipitation-adjusted base-flow trends (fig. 63) was observed for a grouping of 12 stations in central and north-central Oklahoma (stations 2, 3, 5, 10, 20, 23), and a grouping of stations in southwestern and south-central Oklahoma (stations 18, 26, 27, 31, 32, and 33) (fig. 63). Significant upward annual and winter-spring base-flow trends even after precipitation adjustment were detected for stations in these groupings. For the summer-autumn period, upward trends in unadjusted summer-autumn base-flow volume also were detected for the grouping of stations in southwestern and south-central Oklahoma (fig. 52), but there was no clear spatial pattern in the locations of stations with significant precipitation-adjusted base-flow trends (fig. 53). Prior to precipitation adjustment, significant upward trends in annual or seasonal base-flow volume were detected for four stations in eastern Oklahoma—defined as stations located in Neosho-Verdigris, Lower Arkansas, and Red-Sulphur Basins (figs. 48, 50, and 52). However, after precipitation adjustment, significant upward trends in base-flow volume were not detected for any stations in eastern Oklahoma and a significant downward trend in precipitation-adjusted annual base-flow volume was detected for one station, Spavinaw Creek near Sycamore, Oklahoma, (station 15) (figs. 49, 51, and 53).

Total Flow

Similar to base flow, significant downward trends in total-flow volume were detected for stations in the Oklahoma Panhandle. No definitive regional patterns were detected for unadjusted or adjusted total-flow volume trends for stations in west-central Oklahoma (stations 8, 22, 26–28, and 31). For the annual and winter-spring period, a spatial pattern in the locations of stations with significant upward unadjusted

Table 7. Results of trend analysis for winter-spring total flow volume for 37 selected streamflow-gaging stations in and near Oklahoma.

[no., number; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; p-value, probability value; <, less than; ac-ft, acre-feet; Adjusted trend, trend adjusted for changes in annual or seasonal precipitation; A, annual total precipitation; WS, winter-spring total precipitation; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend; --, trend test not performed]

Station no. (fig. 1)	USGS station ID	Median winter-spring total-flow volume (acre-feet)	Winter-spring total-flow trends			Winter-spring adjusted total-flow trends				
			Trend slope (percent/year)	Tau	p-value	Precipitation parameter[1]	T-test score	Trend slope (percent/year)[2]	Tau[2]	p-value[2]
1	07146500	786,200	0.22	0.04	0.650	WS	4.89	-0.41	-0.13	0.119
2	07151000	324,800	1.41	0.17	0.039	WS	6.79	0.42	0.08	0.341
3	07152000	227,000	1.64	0.25	0.002	WS	10.55	0.54	0.15	0.071
4	07152500	2,578,000	1.40	0.17	0.178	WS	4.89	1.05	0.15	0.237
5	07153000	88,920	1.88	0.13	0.221	WS	7.66	0.52	0.06	0.567
6	07154500	930	-3.41	-0.26	0.005	WS	2.12	-3.52	-0.27	0.003
7	07156900	19,800	-2.17	-0.75	<0.001	SA	-1.17	--	--	--
8	07158000	83,060	-0.64	-0.11	0.168	WS	5.07	-1.01	-0.26	0.002
9	07159100	309,600	-0.48	-0.05	0.670	WS	3.16	-0.11	-0.02	0.865
10	07161450	543,400	1.79	0.26	0.002	WS	9.50	1.29	0.27	0.001
11	07171000	1,277,000	0.33	0.04	0.729	WS	7.55	-0.56	-0.07	0.544
12	07172000	166,600	1.51	0.15	0.166	WS	6.32	-0.58	-0.08	0.473
13	07188000	877,200	0.90	0.15	0.062	WS	7.94	0.01	0.00	0.988
14	07191000	151,000	1.52	0.19	0.028	WS	6.50	-0.52	-0.11	0.216
15	07191220	56,450	0.63	0.10	0.340	WS	5.04	-0.97	-0.16	0.111
16	07196500	489,300	0.26	0.06	0.426	WS	8.57	-0.05	-0.01	0.868
17	07197000	172,400	0.67	0.16	0.077	A	9.28	0.01	0.00	0.975
18	07228500	125,500	1.20	0.15	0.183	WS	4.25	0.91	0.17	0.134
19	07231000	165,400	1.32	0.13	0.241	WS	6.06	-0.26	-0.03	0.786
20	07231500	590,100	2.27	0.21	0.044	WS	5.74	0.86	0.14	0.199
21	07234000	87,280	-4.65	-0.48	<0.001	WS	2.67	-4.67	-0.52	<0.001
22	07238000	56,380	0.33	0.05	0.562	WS	5.23	-0.27	-0.06	0.496
23	07242000	274,900	1.19	0.19	0.019	WS	6.66	0.89	0.25	0.003
24	07243500	388,200	0.86	0.07	0.552	WS	7.81	0.11	0.01	0.920
25	07247500	87,110	0.07	0.01	0.937	WS	6.21	-0.43	-0.14	0.213
26	07300500	26,240	-0.05	-0.01	0.945	WS	6.10	-0.67	-0.17	0.041
27	07301500	44,350	0.26	0.06	0.478	WS	4.70	-0.05	-0.01	0.889
28	07311500	43,350	1.10	0.06	0.595	WS	4.75	0.16	0.02	0.885
29	07315700	56,240	2.08	0.15	0.138	WS	6.12	-0.26	-0.05	0.650
30	07316000	788,800	0.47	0.07	0.414	WS	6.44	0.15	0.02	0.794

Table 7. Results of trend analysis for winter-spring total flow volume for 37 selected streamflow-gaging stations in and near Oklahoma. —Continued

[no., number; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; p-value, probability value; <, less than; ac-ft, acre-feet; Adjusted trend, trend adjusted for changes in annual or seasonal precipitation; A, annual total precipitation; WS, winter-spring total precipitation; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend; --, trend test not performed]

Station no. (fig. 1)	USGS station ID	Median winter-spring total-flow volume (acre-feet)	Winter-spring total-flow trends			Winter-spring adjusted total-flow trends				
			Trend slope (percent/year)	Tau	p-value	Precipitation parameter[1]	T-test score	Trend slope (percent/year)[2]	Tau[2]	p-value[2]
31	07316500	7,333	2.38	0.29	0.004	WS	4.41	2.02	0.28	0.006
32	07326500	142,600	3.04	0.32	0.002	WS	4.58	1.89	0.28	0.007
33	07331000	591,000	2.83	0.32	0.002	WS	4.91	1.53	0.27	0.008
34	07332500	134,800	0.29	0.05	0.538	WS	8.84	0.11	0.03	0.721
35	07335700	53,450	0.32	0.04	0.691	WS	5.71	-0.43	-0.25	0.019
36	07336200	1,076,000	-1.23	-0.13	0.362	A	5.63	-0.35	-0.07	0.624
37	07337900	295,800	0.68	0.13	0.193	WS	6.84	-0.20	-0.09	0.379

[1]Winter-spring indicates that year precipitation totals used in trend adjustment were only from the months of November through May and summer-Autumn indicates that yearly precipitation totals used in trend adjustment were only from the months of June through October.

[2]If the t-test score for correlation with the precipitation parameter was between -2.0 and 2.0, then trend adjustment was not performed.

total-flow volume trends was observed for most stations in the grouping of stations in central and north-central Oklahoma (fig. 63) and stations along the Washita River, but there was no clear spatial pattern in the locations of stations with significant trends in precipitation-adjusted total-flow volume. For most stations with significant upward trends in total-flow volume, precipitation adjustment changed these trends to not significant upward or downward trends, except for three stations in central and south-central Oklahoma, Cimarron River near Ripley, Oklahoma, Washita River at Anadarko, Oklahoma, and Washita River near Dickson, Oklahoma, (stations 10, 32, and 33, respectively). Precipitation adjustment did not change the significance or direction of upward trends in annual or winter-spring total-flow volume for these stations. In eastern Oklahoma, with the exception of Kiamichi River near Big Cedar, Oklahoma, (station 35), where a downward trend in precipitation-adjusted winter-spring total-flow volume was detected, and Big Cabin Creek near Big Cabin, Oklahoma, (station 14), where an upward trend in unadjusted winter-spring base-flow volume was detected, no stations had significant total-flow volume trends before or after precipitation adjustment.

Base-Flow index

Similar to base flow, significant upward trends in annual and seasonal base-flow index were detected for many stations in central and western Oklahoma. A significant downward trend in winter-spring base-flow index was detected for one station near north-central Oklahoma, Arkansas River near Arkansas City, Kansas, (station 1). The westernmost station in the study area, Cimarron River near Kenton, Oklahoma, (station 6), was the only station in western Oklahoma with a significant downward trend in base-flow index, and the trend was detected only for the summer-autumn period (table 9). Significant upward trends in annual or seasonal base-flow index were detected only for three stations in eastern Oklahoma (stations 13, 16, and 35) (figs. 60–62).

Results by Major Drainage Basin

Red Headwaters

Stations in the Red Headwaters Basin include Salt Fork Red River at Mangum, Oklahoma, (station 26) and North Fork Red River near Carter, Oklahoma, (station 27) (figs. 36, 37, and 48). Whereas, trends at these stations were highly variable between the annual and seasonal periods and between unadjusted and precipitation-adjusted streamflow volume, most significant trends in base-flow volume and base-flow index were upward in direction, and most significant trends in total-flow volume were downward in direction. In general,

Table 8. Results of trend analysis for summer-autumn total flow volume for 37 selected streamflow-gaging stations in and near Oklahoma.

[no., number; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; p-value, probability value; <, less than; ac-ft, acre-feet; Adjusted trend, trend adjusted for changes in annual or seasonal precipitation; A, annual total precipitation; SA, summer-autumn total precipitation; WS, winter-spring total precipitation; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend; --, trend test not performed]

Station no. (fig. 1)	USGS station ID	Median summer-autumn total-flow volume (acre-feet)	Summer-autumn total-flow trends			Summer-autumn adjusted total-flow trends				
			Trend slope (percent/year)	Tau	p-value	Precipitation parameter1	T-test score	Trend slope (percent/year)2	Tau2	p-value2
1	07146500	632,500	0.19	0.04	0.682	A	13.48	-0.49	-0.15	0.071
2	07151000	207,300	1.25	0.14	0.107	A	13.53	-0.24	-0.05	0.530
3	07152000	162,900	1.31	0.20	0.013	A	12.57	0.48	0.10	0.212
4	07152500	1,814,000	2.90	0.21	0.089	A	5.87	1.25	0.16	0.200
5	07153000	41,680	2.24	0.11	0.296	A	6.29	1.08	0.10	0.387
6	07154500	4,548	-3.71	-0.36	<0.001	SA	1.86	--	--	--
7	07156900	9,880	-2.92	-0.67	<0.001	WS	-0.56	--	--	--
8	07158000	68,740	-1.91	-0.23	0.005	SA	7.88	-2.33	-0.34	<0.001
9	07159100	223,600	1.16	0.09	0.443	A	5.25	0.06	0.01	0.977
10	07161450	418,800	0.85	0.13	0.129	A	9.13	0.44	0.11	0.188
11	07171000	558,600	0.65	0.05	0.681	A	5.47	0.30	0.04	0.745
12	07172000	41,030	2.06	0.15	0.160	SA	7.63	0.94	0.10	0.368
13	07188000	395,000	-0.21	-0.03	0.698	A	8.38	-0.39	-0.08	0.318
14	07191000	42,010	-0.40	-0.03	0.714	SA	8.99	-0.88	-0.13	0.137
15	07191220	13,780	0.52	0.06	0.533	A	6.99	-0.83	-0.12	0.219
16	07196500	137,700	0.49	0.10	0.236	A	10.57	0.00	0.00	0.996
17	07197000	40,970	0.87	0.11	0.209	A	9.24	0.07	0.01	0.883
18	07228500	49,960	1.95	0.13	0.246	SA	4.44	1.69	0.17	0.128
19	07231000	53,220	1.28	0.07	0.503	A	8.91	-0.57	-0.07	0.530
20	07231500	308,000	1.77	0.14	0.179	A	6.12	0.74	0.11	0.298
21	07234000	124,300	-8.13	-0.58	<0.001	SA	1.09	--	--	--
22	07238000	38,800	-1.11	-0.11	0.214	A	7.19	-2.10	-0.31	<0.001
23	07242000	187,000	0.58	0.08	0.307	A	9.11	0.33	0.08	0.356
24	07243500	200,700	0.35	0.03	0.814	A	6.25	0.06	0.01	0.937
25	07247500	14,700	-0.25	-0.03	0.762	SA	3.97	0.72	0.07	0.522
26	07300500	19,550	-1.40	-0.19	0.020	SA	5.02	-1.76	-0.26	0.001
27	07301500	23,850	-0.58	-0.06	0.434	SA	8.97	-1.02	-0.15	0.068
28	07311500	36,990	-1.20	-0.07	0.545	SA	6.74	-1.08	-0.10	0.358
29	07315700	23,270	0.86	0.06	0.552	SA	6.93	0.66	0.08	0.450
30	07316000	691,900	0.23	0.03	0.750	A	6.92	-0.19	-0.03	0.698

Table 8. Results of trend analysis for summer-autumn total flow volume for 37 selected streamflow-gaging stations in and near Oklahoma. —Continued

[no., number; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; p-value, probability value; <, less than; ac-ft, acre-feet; Adjusted trend, trend adjusted for changes in annual or seasonal precipitation; A, annual total precipitation; SA, summer-autumn total precipitation; WS, winter-spring total precipitation; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend; --, trend test not performed]

Station no. (fig. 1)	USGS station ID	Median summer-autumn total-flow volume (acre-feet)	Summer-autumn total-flow trends			Summer-autumn adjusted total-flow trends				
			Trend slope (percent/year)	Tau	p-value	Precipitation parameter[1]	T-test score	Trend slope (percent/year)[2]	Tau2	p-value2
31	07316500	3,034	3.78	0.25	0.011	A	6.09	1.45	0.13	0.198
32	07326500	111,800	2.74	0.25	0.016	A	7.16	1.30	0.20	0.054
33	07331000	431,600	2.35	0.21	0.037	A	6.36	1.29	0.20	0.052
34	07332500	46,910	-0.27	-0.04	0.599	A	12.99	-0.46	-0.10	0.226
35	07335700	9,918	0.58	0.05	0.660	SA	4.49	0.55	0.08	0.464
36	07336200	176,300	-4.93	-0.27	0.065	SA	4.63	-0.70	-0.10	0.498
37	07337900	50,010	1.22	0.13	0.206	SA	5.57	1.16	0.16	0.107

[1]Winter-spring indicates that year precipitation totals used in trend adjustment were only from the months of November through May and summer-autumn indicates that yearly precipitation totals used in trend adjustment were only from the months of June through October.

[2]If the t-test score for correlation with the precipitation parameter was between -2.0 and 2.0, then trend adjustment was not performed.

there was a shift from runoff-dominated streamflow to base flow-dominated streamflow at those two stations.

Significant upward trends in annual and seasonal base-flow volume were detected at both stations (figs. 48, 50, and 52). After precipitation adjustment, the upward trends remained significant (figs. 49, 51, and 53), except for station 27 for the summer-autumn period.

Some significant downward trends in total-flow volume were detected for stations in this basin both before and after precipitation adjustment (figs. 54–59). Prior to precipitation adjustment, no significant trends in annual or winter-spring total-flow volume were detected at either station (figs. 54 and 56). A significant downward trend in summer-autumn total-flow volume was observed, however, for station 26 (fig. 58). After precipitation adjustment, however, significant downward trends in annual total-flow volume at both stations were detected (fig. 55); whereas, the downward trend in winter-spring total-flow volume at station 26 became significant (fig. 57). Precipitation adjustment did not change the direction or significance of summer-autumn total-flow volume trends at either station (fig. 59).

Significant upward trends in base-flow index were detected at both stations both annually and seasonally (figs. 60–62). Upward trends in base-flow index for both stations appear to be a result of either upward trends in base-flow volume, downward trends in total-flow volume, or both. This observation indicates that base flow has likely increased; whereas, runoff has likely decreased at these stations.

Red-Washita

Stations in the Red-Washita Basin include Washita River stations—the Washita River near Cheyenne, at Anadarko, and near Dickson, Oklahoma, (stations 31, 32, and 33, respectively); Red River stations that include tributaries to the Red River — Deep Red Creek near Randlett, Oklahoma, (station 28), and Mud Creek near Courtney, Oklahoma, (station 29); and one main-stem Red River station— Red River near Gainesville, Texas, (station 30) (figs. 31–33, 48). Trends generally differed between the Washita River and the Red River stations. All trends that were significant in this basin were also upward in direction.

Significant upward trends in base-flow volume were detected both annually and seasonally for all Washita River stations, even after precipitation adjustment, but not for all Red River stations (figs. 48–53). Significant upward trends in annual and winter-spring base-flow volume were detected for stations 29 and 30 prior to precipitation adjustment. Most of the base-flow trends (either annual or seasonal) were not significant after precipitation-adjustment, with the exception of Red River near Gainesville, Texas (station 30) for the winter-spring period that had an upward base-flow trend that remained significant (fig. 51). Station 28 did not have any annual or seasonal base-flow trends before or after precipitation adjustment.

Significant upward trends in total-flow volume were detected for all three Washita River stations, annually and

Table 9. Results of trend analysis for annual, winter-spring, and summer-autumn base-flow index for 37 selected streamflow-gaging stations in and near Oklahoma.

[no., number; USGS station ID, U.S. Geological Survey station identifier; fraction, ratio of base-flow volume to total-flow volume; Tau, Kendall's tau; p-Value, probability level; <, less than; ac-ft, acre-feet; the shaded values are statistically significant at the 95 percent confidence interval, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend]

Station no. (fig. 1)	USGS station ID	Annual base p-value-flow index trends				Winter-spring base-flow index trends[1]				Summer-autumn base-flow index trends[1]			
		Median base-flow index (fraction)	Trend Slope (fraction/year)	Tau	p-value	Media base-flow index (fraction)	Trend Slope (fraction/year)	Tau	p-value	Median base-flow index (fraction)	Trend Slope (fraction/year)	Tau	p-value
1	07146500	0.48	-0.001	-0.15	0.078	0.59	-0.002	-0.18	0.036	0.46	-0.000	-0.04	0.658
2	07151000	0.33	0.002	0.23	0.006	0.44	0.000	0.09	0.279	0.34	0.002	0.17	0.038
3	07152000	0.26	0.001	0.19	0.018	0.34	0.001	0.06	0.487	0.19	0.001	0.18	0.022
4	07152500	0.49	-0.002	-0.17	0.168	0.49	-0.000	-0.01	0.935	0.49	-0.004	-0.17	0.168
5	07153000	0.16	0.002	0.29	0.008	0.17	0.002	0.22	0.042	0.13	0.002	0.26	0.016
6	07154500	0.09	-0.000	-0.07	0.437	0.45	-0.001	-0.07	0.461	0.03	-0.001	-0.25	0.005
7	07156900	0.82	0.007	0.59	<0.001	0.84	0.005	0.51	<0.001	0.79	0.007	0.52	<0.001
8	07158000	0.27	0.006	0.60	<0.001	0.43	0.007	0.45	<0.001	0.11	0.003	0.43	<0.001
9	07159100	0.35	0.003	0.22	0.069	0.39	0.007	0.31	0.010	0.33	-0.002	-0.08	0.495
10	07161450	0.34	0.003	0.42	<0.001	0.41	0.002	0.17	0.036	0.32	0.002	0.28	0.001
11	07171000	0.25	0.002	0.17	0.119	0.26	0.001	0.09	0.386	0.19	0.003	0.19	0.079
12	07172000	0.20	0.000	0.02	0.848	0.24	0.000	0.03	0.769	0.16	0.000	0.02	0.864
13	07188000	0.40	0.001	0.25	0.003	0.43	0.001	0.10	0.220	0.37	0.002	0.17	0.034
14	07191000	0.11	0.000	0.11	0.202	0.13	-0.000	-0.03	0.780	0.08	0.001	0.16	0.076
15	07191220	0.56	-0.000	-0.00	1.000	0.55	-0.001	-0.05	0.608	0.59	0.001	0.06	0.533
16	07196500	0.46	0.001	0.22	0.006	0.44	0.002	0.22	0.005	0.55	0.001	0.06	0.426
17	07197000	0.38	0.001	0.16	0.077	0.38	0.001	0.15	0.084	0.48	0.001	0.03	0.764
18	07228500	0.35	0.009	0.40	<0.001	0.51	0.009	0.38	0.001	0.26	0.005	0.26	0.019
19	07231000	0.26	0.004	0.28	0.008	0.26	0.004	0.30	0.005	0.25	0.001	0.09	0.391
20	07231500	0.31	0.005	0.44	<0.001	0.32	0.005	0.36	0.001	0.25	0.004	0.25	0.020

Table 9. Results of trend analysis for annual, winter-spring, and summer-autumn base-flow index for 37 selected streamflow-gaging stations in and near Oklahoma. —Continued

[no., number; USGS station ID, U.S. Geological Survey station identifier; fraction, ratio of base-flow volume to total-flow volume; Tau, Kendall's tau; p-Value, probability level; <, less than; ac-ft, acre-feet; the shaded values are statistically significant at the 95 percent confidence interval, green shade indicates a statistically significant upwards trend, orange shade indicates a statistically significant downwards trend]

		Annual base p-value-flow index trends				Winter-spring base-flow index trends[1]				Summer-autumn base-flow index trends[1]			
Station no. (fig. 1)	USGS station ID	Median base-flow index (fraction)	Trend Slope (fraction/year)	Tau	p-value	Media base-flow index (fraction)	Trend Slope (fraction/year)	Tau	p-value	Median base-flow index (fraction)	Trend Slope (fraction/year)	Tau	p-value
21	07234000	0.19	0.007	0.43	<0.001	0.44	0.007	0.32	<0.001	0.10	0.004	0.35	<0.001
22	07238000	0.53	0.008	0.52	<0.001	0.61	0.007	0.45	<0.001	0.35	0.008	0.43	<0.001
23	07242000	0.40	0.002	0.32	<0.001	0.44	0.002	0.20	0.014	0.41	0.002	0.17	0.032
24	07243500	0.26	0.001	0.13	0.221	0.26	0.000	0.05	0.678	0.21	-0.000	-0.02	0.884
25	07247500	0.15	0.000	0.01	0.937	0.16	0.000	0.03	0.796	0.11	-0.000	-0.06	0.598
26	07300500	0.19	0.006	0.52	<0.001	0.32	0.007	0.47	<0.001	0.08	0.003	0.46	<0.001
27	07301500	0.36	0.008	0.58	<0.001	0.46	0.009	0.53	<0.001	0.18	0.004	0.42	<0.001
28	07311500	0.05	0.001	0.14	0.217	0.08	-0.000	-0.02	0.866	0.03	0.000	0.13	0.256
29	07315700	0.08	0.001	0.31	0.002	0.09	0.002	0.27	0.007	0.06	0.001	0.15	0.124
30	07316000	0.27	0.002	0.35	<0.001	0.33	0.002	0.25	0.003	0.27	0.002	0.16	0.065
31	07316500	0.54	0.007	0.37	<0.001	0.65	0.006	0.38	<0.001	0.23	0.007	0.38	<0.001
32	07326500	0.48	0.004	0.26	0.013	0.58	0.002	0.11	0.278	0.42	0.004	0.20	0.059
33	07331000	0.38	0.003	0.31	0.003	0.42	0.002	0.12	0.219	0.33	0.004	0.24	0.016
34	07332500	0.36	0.001	0.11	0.175	0.35	0.001	0.14	0.078	0.44	0.000	0.01	0.880
35	07335700	0.24	0.002	0.21	0.047	0.26	0.002	0.22	0.038	0.16	0.001	0.12	0.276
36	07336200	0.18	-0.000	-0.01	0.944	0.20	-0.001	-0.07	0.657	0.11	0.002	0.09	0.559
37	07337900	0.17	0.000	0.01	0.927	0.19	0.000	0.06	0.545	0.12	0.000	0.04	0.728

[1]Winter-spring indicates that annual BFI fractions used in trend adjustment were only from the months of November through May and summer-autumn indicates that annual BFI fractions used in trend analysis were only from the months of June through October.

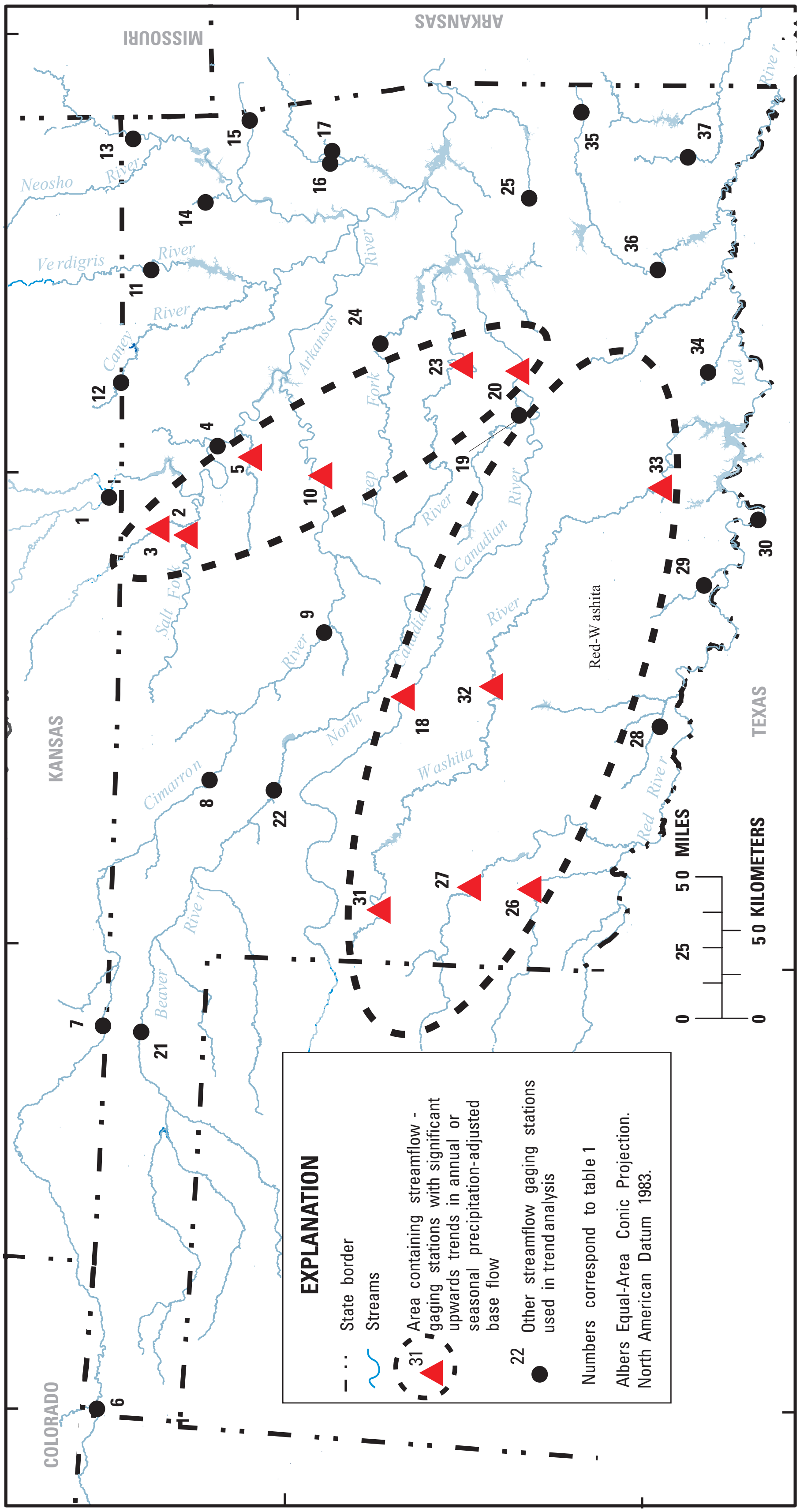

Figure 63. Areas where streamflow-gaging stations had significant upward trends in annual or seasonal precipitation-adjusted base-flow volume.

seasonally, but no significant annual or seasonal trends in total-flow value were detected for the Red River stations (even after precipitation adjustment) (figs. 54–59). Upward trends at all three Washita River stations were still upward in direction after precipitation adjustment, but the significance of many annual or seasonal trends changed. Station 31, the most upstream station in the basin, did not have significant trends in precipitation-adjusted annual or summer-autumn total-flow volume (figs. 55 and 59); whereas, trends in total-flow volume after precipitation adjustment remained significant and upward for the two downstream stations. This observation was the same for the winter-spring period except that the upward trend in total-flow volume at the upstream station 31 remained significant after precipitation adjustment (fig. 57). For the summer-autumn period, precipitation adjustment resulted in no trends at all three Washita River stations (fig. 59).

Significant upward trends in annual base-flow index were found at all three stations along the Washita River and two of three Red River stations (fig. 60). At these stations, upward trends in winter-spring and summer-autumn base-flow index also were detected, but not all trends were significant (figs. 61 and 62). Station 31, the upstream station, had significant upward trends for both seasons, station 32 did not have significant trends, and station 33 had significant upward trends during the summer-autumn period only. Significant upward trends in annual and winter-spring base-flow index were detected at stations 29 and 30, but significant trends for the summer-autumn base-index were not observed. No significant base-flow index trends were detected at station 28.

Upper Cimarron

Stations in this basin include Cimarron River near Kenton and Forgan, Oklahoma, (stations 6 and 7, respectively) (figs. 16, 17, and 48). Significant downward trends in streamflow volume were detected for these two stations both annually and seasonally (figs. 48–59). Trends in precipitation-adjusted streamflow volume were not calculated for either station annually or seasonally because these parameters were not significantly correlated to precipitation.

Base-flow index trends were not significant for the annual and winter-spring periods for station 6 (figs. 60 and 61), but a significant downward trend was observed for the summer-autumn period (fig. 62). However, a significant upward trend in annual and seasonal base-flow index was observed for station 7. A possible reason for the difference in results between the two stations may be that base flow was a much lesser component of total flow at station 6 than station 7, and therefore, decreasing total flow at station 6 played a greater role in the observed base-flow index trends than at station 7 (figs. 16 and 17). Base flow generally is higher at station 7 than at station 6, and is decreasing at a slower rate than total flow, which would result in upward trends in base-flow index.

Lower Cimarron

Stations in the Lower Cimarron Basin include Cimarron River near Waynoka, Dover, and Ripley, Oklahoma, (stations 8, 9, and 10, respectively) (figs. 18–20, 48). In general, trend results for stations in the Lower Cimarron Basin were different from the Upper Cimarron Basin. Although trend results were highly variable for stations in this basin, upward trends in streamflow volume annually and seasonally were detected even after precipitation adjustment (figs. 48-–59). In general, significant downward trends in streamflow volume in the Upper Cimarron River transition to significant upward trends in a downstream direction.

Station 8, which is the most upstream station in the basin, showed a significant upward trend in annual and winter-spring base-flow volume but did not show a significant trend in summer-autumn base-flow volume or annual and seasonal precipitation-adjusted base-flow volume (figs. 48–52). No significant trends in base-flow volume were detected for station 9. Station 10, which is the most downstream station in the basin, showed significant upward trends in annual and seasonal base-flow volume even after precipitation adjustment.

Results of trends remained generally unchanged for annual total-flow volume for all three stations after precipitation adjustment. An exception to this pattern was found for the winter-spring period, for which precipitation adjustment resulted in a significant downward trend in total-flow volume for station 8 (fig. 57). A notable observation is that streamflow at station 9, which is between stations 8 and 10, did not have any significant trends in streamflow volume, even after precipitation adjustment.

Significant upward trends in annual and seasonal base-flow index were detected for stations 8 and 10 (figs. 60–62). All three stations had significant upward trends in winter-spring base-flow index (fig. 61).

North Canadian

Stations in the North Canadian Basin include Beaver River at Beaver, which also is the North Canadian River (station 21), North Canadian near Seiling and Wetumka, Oklahoma, (stations 22 and 23), and Deep Fork near Beggs, Oklahoma, (station 24). In general, moving downstream along the North Canadian River, downward trends in streamflow volume transitioned to upward trends (figs. 31–34, 48).

In the upper part of the North Canadian Basin, station 21 had significant downward trends in annual and seasonal base-flow volume (figs. 48, 50, and 52). Precipitation adjustment was not calculated for this station because streamflow volume and precipitation were not significantly correlated for any season. No significant trends in base-flow volume were detected for the next station downstream (station 22) even after precipitation adjustment. However, moving downstream to station 23, a significant upward trend in base-flow volume was detected during the annual and seasonal periods; this trend result did not change after precipitation adjustment. Deep Fork near Beggs (station 24), a tributary to the North Canadian

River, did not have any significant unadjusted or adjusted base-flow trends.

Similar to base-flow volume, a significant downward trend in total-flow volume was observed at station 21 annually and seasonally. No significant trends in unadjusted total-flow volume were detected for station 22, however, after precipitation adjustment, significant downward trends were detected for the annual and summer-autumn period only. No significant trends in winter-spring total-flow volume were detected for this station even after precipitation adjustment. Significant upward trends in total-flow volume were detected for station 23 during the annual and winter-spring periods only (figs. 54 and 56), but after precipitation adjustment, the annual total-flow volume trend was not significant; whereas, the winter-spring upward trend remained significant (figs. 55 and 57). Similar to base-flow volume, no significant trends in total-flow volume were detected for station 24.

All three main-stem North Canadian River stations had significant upward trends in base-flow index (figs. 60–62). Similar to base flow and total flow, no significant base-flow index trends were detected for station 24. Station 21 had similar results to station 7 in the Upper Cimarron. At both stations, significant downward trends in streamflow volume were detected for all periods (annual and seasonal), and upward trends in base-flow index also were detected. This observation indicated that total flow was decreasing at a faster rate than base flow. Station 22 did not have significant trends in base-flow volume, but had significant downward trends in annual and summer-autumn total-flow volume. This observation indicated that, similar to station 21, the upward trends in base-flow index were likely caused by decreases in runoff rather than increases in base flow.

Lower Canadian

Stations in the Lower Canadian Basin include the Canadian River at Brideport, Oklahoma, and at Calvin, Oklahoma (stations 18 and 20, respectively), and Little River near Sasakwa, Oklahoma, (station 19) which enters the Canadian River upstream from station 20 (figs. 28–30, 48). Trend results for these stations were variable between the annual and seasonal periods and for unadjusted and precipitation-adjusted streamflow volume, but all trends that were significant were upward in direction.

Most of the base-flow trends for stations along the mainstem of the Canadian River were upward and significant (figs. 48–53). A significant upward trend in base-flow volume was observed for station 18 both annually and seasonally, even after precipitation adjustment. Moving downstream to station 20, the results were the same as station 18, except that the summer-autumn base-flow trends became insignificant after precipitation adjustment. However, no significant trends in base-flow volume were detected for station 19 before or after precipitation adjustment.

Upward trends in total-flow volume (annually or seasonally) were detected for some stations on the Canadian River prior to precipitation adjustment (figs. 54–59). No significant trends in total-flow volume were detected for station 18, but significant upward trends in annual and winter-spring total-flow volume were detected downstream. No significant trends in precipitation-adjusted total-flow volume were detected for any station in the basin. No significant trends in total-flow volume were detected for station 19 before or after precipitation adjustment.

All three stations had significant upward trends in base-flow index for the annual and winter-spring periods (figs. 60–62). The mainstem Canadian stations also had upward trends in the summer-autumn base-flow index, but the upward trend at station 19 was not significant. Because significant upward trends in total-flow volume were detected prior to and after precipitation adjustment, upward trends in base-flow index are likely caused by increases in base-flow volume as opposed to decreases in runoff.

Arkansas-Keystone

Stations in the Arkansas-Keystone Basin include the tributaries to the Arkansas River: Salt Fork Arkansas River at Tonkawa, Oklahoma, Chikaskia River near Blackwell, Oklahoma, and Black Bear Creek at Pawnee, Oklahoma, (station 2, 3, and 5, respectively), and one main-stem Arkansas River station, Arkansas River at Ralston, Oklahoma, (station 4) (figs. 12–15, 48). Another main-stem Arkansas River station, Arkansas River near Arkansas City, Kansas, (station 1) is not in the Arkansas-Keystone Basin, but is upstream from and in close proximity to the basin boundary and was included in the discussion of this basin.

Trends in the Arkansas-Keystone Basin were highly variable, but similarities were detected in streamflow volume trends for tributaries to the Arkansas River, whereas few similarities in trends were detected at the two main-stem Arkansas River stations. Most trends in streamflow volume that were significant were also upward in direction.

Significant upward trends in base-flow volume were detected for all three tributaries to the Arkansas River for the annual and winter-spring periods (figs. 48–53). After precipitation adjustment, however, results for these stations generally remained the same except for the summer-autumn period where the upward precipitation-adjusted base-flow trend at station 2 was not significant. No significant upward trends in annual or seasonal base-flow volume were detected for either of the main-stem Arkansas River stations. After precipitation adjustment, the annual and winter-spring base-flow trends at station 1, the upstream station, were downward and significant, whereas the trend in annual and seasonal base-flow volume at station 4 downstream did not change in significance. Precipitation adjustment did not change the results of base-flow trends on the main-stem Arkansas River stations for the summer-autumn period.

Some significant upward total-flow trends were detected for the tributaries to the Arkansas River (stations 2 and 3 for the annual and winter-spring period and only station 3 for the summer-autumn period) (figs. 54–59). After precipitation adjustment, however, no significant trends in annual or seasonal total-flow volume were detected at any of these stations. No significant trends in total-flow volume were detected at either Arkansas River main-stem station even after precipitation adjustment.

Significant upward trends in base-flow index were detected for the tributary stations during the annual and summer-autumn periods (figs. 60–62). Only station 5 had a significant upward trend in winter-spring base-flow index. Most significant base-flow trends found at these three stations were upward in direction; whereas, total-flow trends generally were not significant. This observation indicates that the increases in base-flow index were likely caused by increases in base-flow volume rather than decreases in runoff. Results were different along the main-stem Arkansas River stations and the Arkansas River tributary stations. No significant trends in base-flow index were detected for either station for the annual and summer-autumn period, but a significant downward trend was observed at the upstream station (station 1) for the winter-spring period. Because downward trends in winter-spring base-flow volume were detected for station 1 (which were significant only for precipitation-adjusted base-flow volume) but no significant trends in total-flow volume were detected, the significant downward trend in base-flow index is likely caused by decreases in base flow rather than decreases in runoff at this station.

Neosho-Verdigris

The Neosho-Verdigris Basin includes three stations that are tributaries to the Neosho River: Spring River near Quapaw, Oklahoma, (station 13), Big Cabin Creek near Big Cabin, Oklahoma, (station 14), and Spavinaw Creek near Sycamore, Oklahoma, (station 15) (figs. 23–25, 48). This basin also includes Verdigris River stations, including Verdigris River near Lenapah (station 11) and Caney River near Elgin, Kansas, (station 12) (fig. 48). Most stations in this basin did not have significant streamflow volume or base-flow index trends.

Only station 13, the easternmost station in the basin, had a significant upward trend in base-flow volume but only for the annual and winter-spring periods (figs. 48–53). After precipitation adjustment, however, trends at station 13 were not significant, and a significant downward trend in precipitation-adjusted base-flow volume was observed at station 15 for the annual period.

No significant trends in total-flow volume were detected for most stations in this basin (figs. 54–59) except for station 14, which had an upward trend in total-flow volume only for the winter-spring period (fig. 56). No significant trends in total-flow volume were detected after precipitation adjustment.

No base-flow index trends were significant for stations in this basin except for station 13, where significant upward trends were detected during the annual and summer-autumn periods (figs. 60–62). Based on the observation of upward base-flow trends prior to precipitation adjustment for this station with no trends in total-flow volume, the increase in base-flow index likely corresponds to increases in base flow rather than decreases in runoff.

Lower Arkansas

Stations in the Lower Arkansas Basin include two stations in the Illinois River Basin, Illinois River near Tahlequah, Oklahoma, (station 16) and Baron Fork at Eldon, Oklahoma, (station 17) (figs. 26–27, 48), and Fourche Maline near Red Oak, Oklahoma, (station 25) which is located farther south than the two Illinois River stations. Most stations in the Lower Arkansas Basin did not have significant trends, even after precipitation adjustment.

Significant upward trends in base-flow volume were found at stations 16 and 17 prior to precipitation adjustment, but after adjustment no significant base-flow trends were detected for these stations (figs. 48–53). Station 25 did not have any annual or seasonal base-flow trends before or after precipitation adjustment. No significant trends in annual or seasonal total-flow volume were detected for any of the three stations even after precipitation adjustment (figs. 54–59).

Significant upward trends in base-flow index were detected for station 16 for the annual and winter-spring periods only (figs. 60–62). Otherwise, no station in the basin had significant base-flow index trends. The upward trend in base-flow index likely corresponds to increases in base flow rather than decreases in runoff.

Red-Sulphur

Stations in the Red-Sulphur Basin include four stations on three rivers that are tributaries to the Red River: Blue River near Blue, Oklahoma, (station 34), Kiamichi River near Big Cedar, Oklahoma, (station 35), Kiamichi River near Antlers, Oklahoma, (station 36), and Glover River near Glover, Oklahoma, (station 37) (figs. 44–48). Like the other easternmost basins in the study area (Neosho-Verdigris and Lower Arkansas Basins), stations in this basin had few significant trends in streamflow volume or base-flow index.

A significant trend in base-flow volume was detected only for station 35, in which an upward trend was observed during the annual period only (fig. 48). After precipitation adjustment, no stations in the basin had significant base-flow trends (figs. 49, 51, and 53).

Similar to base flow, a significant upward trend in total-flow volume was detected only for station 35. However, station 35 had a downward trend in total-flow volume during the winter-spring period after precipitation adjustment (figs. 54–59).

Similar to base flow and total flow, a significant upward trend in base-flow index was detected only for station 35 for the annual and winter-spring periods only (figs. 60–62). Increases in base flow rather than decreases in runoff probably caused the significance of the base-flow index trend at this station. However, the results of the winter-spring streamflow volume trend analysis indicate that the upward trend in winter-spring base-flow index is more likely caused by a decrease in runoff.

Annual Peak Flow Trend Analysis

Graphs showing bar charts and LOESS plots of annual peak flow are presented with plots of annual base-flow volume, total-flow volume, and base-flow index (figs. 11–47). Results of peak flow trend analysis are presented in table 10. A map was developed to show trends in annual peak flow (fig. 64).

The Kendall's tau analysis of annual peak flow indicated that less than one-third of stations had significant trends. Only three stations (stations 4, 5, and 32), all in central Oklahoma, had significant upward trends. For the most part, upward trends in streamflow volume did not correspond to upward trends in peak flow with the exception of station 32 ,which also had upward trends in total-flow volume after precipitation adjustment, annually and seasonally. Significant trends in total-flow volume were not detected for stations 4 and 5.

Significant downward trends in peak flow were detected at eight stations in or near western Oklahoma (near the Texas Panhandle or the Oklahoma Panhandle). Downward trends in peak flow did not always correspond to trends in total-flow volume. Only four stations with downward trends in peak flow (6, 7, 8, and 21) also had downward trends in total-flow volume, annually or seasonally.

Washita River near Cheyenne, Oklahoma, (station 31) was the only station that had a significant downward trend in peak flow but had a significant upward trend in total-flow volume annually and seasonally and an upward trend in total-flow volume after precipitation adjustment for winter-spring water years. However, this station had a high base-flow index (with a median over 0.50) and significant upward base-flow index trends as well as significant upward base-flow trends (even after precipitation adjustment). This observation indicated that upward trends in base-flow volume, a large component of total-flow volume at this station, probably contributed to the upward trend in total flow; whereas, runoff and peak flow may have decreased with time.

Number of Extreme Low-Flow Days Trend Analysis

Bar charts showing the number of days where streamflow was zero or less than 1 ft^3/s were created for 20 stations where 10 percent or more of the years in the analysis period for annual or seasonal water years had at least 1 or more days that met this criterion (table 11, figs. 65–84, back of report). A LOESS plot also was shown with bar charts if at least 30 percent of the years during the analysis period (annual or seasonal) had at least 1 or more days where streamflow was zero or less than 1 ft^3/s. Table 11 lists the percent of years in the analysis period for each station where annual or seasonal number of extreme low-flow days were equal to at least 1 day. Table 11 also lists the percent of extreme low-flow days in the analysis (annually and seasonally). Fewer than half of the stations analyzed in this report had enough days that met this streamflow criterion for LOESS lines to be developed or trends to be calculated.

Results of trend analysis of the number of extreme low-flow days are presented in table 12 and figures 85–87 (back of report). In table 12, a negative tau denotes a negative trend in the number of days of extreme low flow and indicates that low flow may be increasing, whereas a positive tau indicates that low flow may be decreasing. A majority of stations could not be analyzed for trends because they did not have a substantial number of days where streamflow met these criteria. For trend analysis of the number of zero-flow days, 12 stations were analyzed for annual water years, 5 stations were analyzed for winter-spring water years, and 11 stations were analyzed for summer-autumn water years. For trend analysis of the number of days where streamflow was less than 1 ft^3/s, 17 stations were analyzed for annual water years, 8 stations were analyzed for winter-spring water years, and 15 stations were analyzed for summer-autumn water years (table 12).

Significant trends in the number of extreme low-flow days were downward in direction for most stations. Where analyzed, most stations that had significant trends in the number of days where streamflow was less than 1 ft^3/s also had significant trends in the number of zero-flow days that were in the same direction. Of 17 stations analyzed for the annual period, 7 stations had significant downward trends in the number of days less than 1 ft^3/s (5 of which also had significant downward trends in the number of zero-flow days and 2 of which could not be analyzed for the number of zero-flow days). Of eight stations analyzed for the winter-spring period, four stations had significant downward trends in the number of days less than 1 ft^3/s (three of which also had significant downward trends and one of which did not have significant trends in the number of zero-flow days, and one of which could not be analyzed for the number of zero-flow days). Of 15 stations analyzed for the summer-autumn period, 6 stations had significant downward trends in the number of days less than 1 ft^3/s (4 of which also had significant downward trends in the number of zero-flow days and two of which could not be analyzed for the number of zero-flow days). Cimarron River near Kenton, Oklahoma, (station 6) had a significant upward trend in extreme low-flow days (except for the number of zero-flow days for the winter-spring period where no significant trends were detected); Kiamichi River near Antlers, Oklahoma, (station 36) had a significant upward trend for the number of days where streamflow was less than 1 ft^3/s for the annual period only. Caution needs to be taken with interpretation of the trends at station 36 because the start of the analysis period was during the wet period, 1980–2000, which may have resulted in the significant upward trend in the number of days where streamflow was less than 1 ft^3/s.

Stations with significant upward or downward trends in the number of extreme low-flow days might be expected to have significant downward or upward trends in streamflow

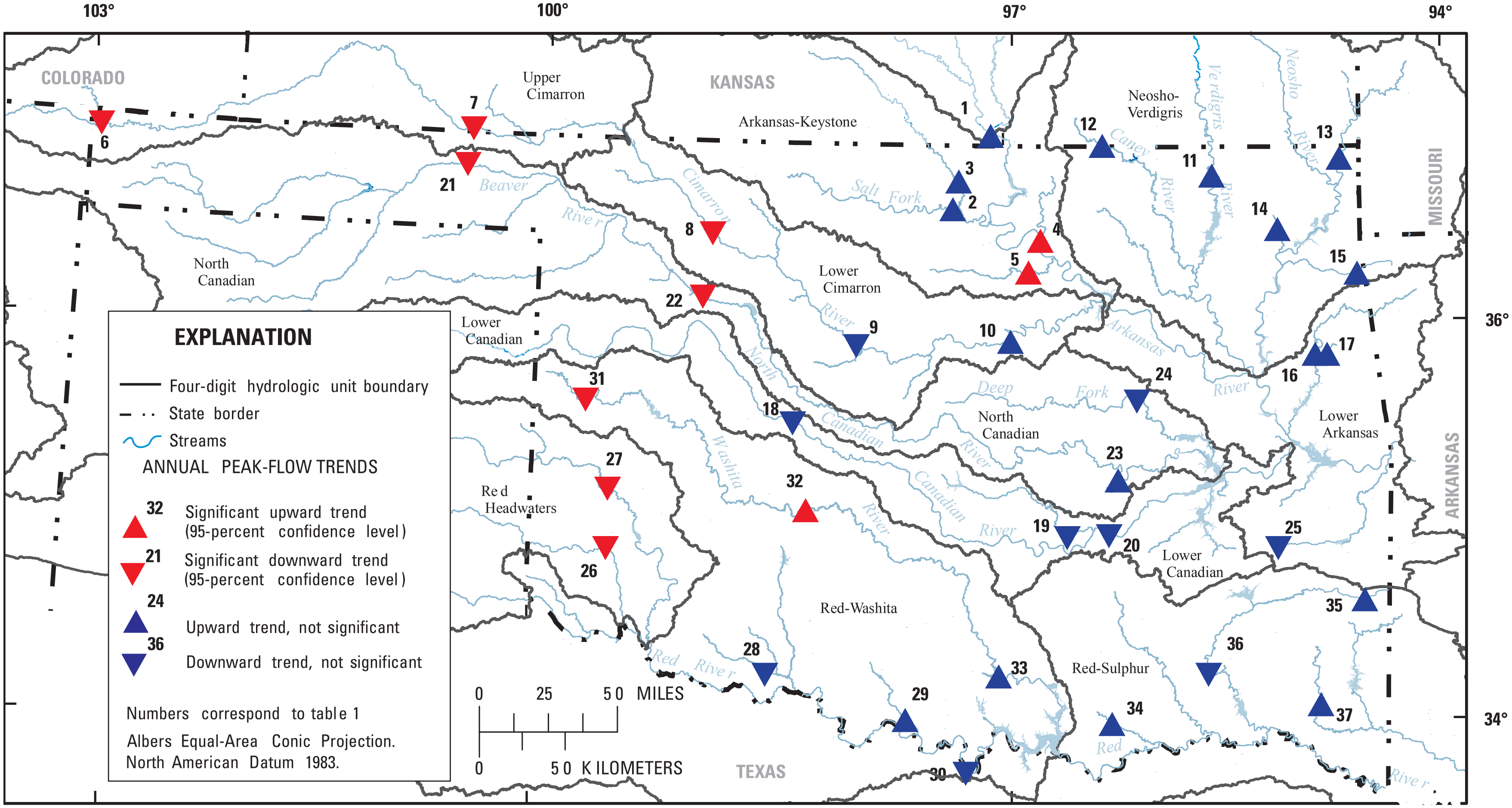

Figure 64. Results of Kendall's tau trend analyses of annual peak flow at selected streamflow-gaging stations in and near Oklahoma.

Table 10. Results of trend analyses of annual peak flows for 37 selected streamflow-gaging stations in and near Oklahoma.

[USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; p-value, probability level; ft³/s, cubic feet per second; the shaded values are statistically significant at the 0.05 level, green shade indicates a statistically significant upward trend, orange shade indicates a statistically significant downward trend]

Station number (fig. 1)	USGS station ID	Median annual peak flow (ft³/s)	Trend slope ([ft³/s]/year)	Trend slope (percent of median)	Kendall's tau	p-value
1	07146500	25,550	121	0.47	0.093	0.273
2	07151000	15,500	115	0.74	0.143	0.088
3	07152000	22,550	113	0.50	0.111	0.170
4	07152500	52,750	1134	2.15	0.25	0.046
5	07153000	5,870	100	1.70	0.242	0.027
6	07154500	4,020	-105	-2.61	-0.322	<0.001
7	07156900	686	-37	-5.40	-0.405	<0.001
8	07158000	14,100	-333	-2.36	-0.411	<0.001
9	07159100	25,900	-336	-1.30	-0.118	0.327
10	07161450	41,900	113	0.27	0.054	0.514
11	07171000	31,650	137	0.43	0.080	0.461
12	07172000	17,900	129	0.72	0.125	0.237
13	07188000	36,100	68.4	0.19	0.047	0.576
14	07191000	13,600	42.5	0.31	0.062	0.482
15	07191220	3,900	26.7	0.68	0.068	0.509
16	07196500	19,800	2.6	0.01	0.001	0.992
17	07197000	15,650	83.8	0.54	0.084	0.345
18	07228500	15,500	-97	-0.63	-0.063	0.578
19	07231000	7,470	-2	-0.03	-0.007	0.958
20	07231500	47,900	-2	-0.00	-0.001	1.000
21	07234000	3,320	-153	-4.61	-0.666	<0.001
22	07238000	2,880	-67	-2.33	-0.378	<0.001
23	07242000	11,400	0.0	0.00	0.000	1.000
24	07243500	8,350	-1	-0.01	-0.001	1.000
25	07247500	3,430	-48	-1.38	-0.191	0.074
26	07300500	10,200	-207	-2.03	-0.388	<0.001
27	07301500	6,140	-100	-1.63	-0.292	<0.001
28	07311500	8,500	-34	-0.40	-0.036	0.753
29	07315700	5,115	70.6	1.38	0.129	0.198
30	07316000	47,300	-92	-0.19	-0.037	0.668
31	07316500	580	-17	-3.01	-0.231	0.021
32	07326500	4,700	69.2	1.47	0.213	0.040

Table 10. Results of trend analyses of annual peak flows for 37 selected streamflow-gaging stations in and near Oklahoma. —Continued

[USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; p-value, probability level; ft³/s, cubic feet per second; the shaded values are statistically significant at the 0.05 level, green shade indicates a statistically significant upward trend, orange shade indicates a statistically significant downward trend]

Station number (fig. 1)	USGS station ID	Median annual peak flow (ft³/s)	Trend slope ([ft³/s]/year)	Trend slope (percent of median)	Kendall's tau	p-value
33	07331000	30,000	145	0.48	0.088	0.389
34	07332500	8,650	20.0	0.23	0.049	0.547
35	07335700	9,260	35.0	0.38	0.040	0.714
36	07336200	27,300	-267	-0.98	-0.093	0.528
37	07337900	26,400	23.5	0.09	0.011	0.920

Table 11. Percent of period of record with extreme low-flow days for 37 selected streamflow-gaging stations.

[no., number; USGS station ID, U.S. Geological Survey station identifier; % Years, the percent of years for the specified water-year type where at least one day is greater than zero; % Days, the percent of days for the specified water-year type that are greater than zero]

Station no. (fig. 1)	USGS station ID	Number of zero-flow days						Number of days where flow is less than 1 cubic foot per second					
		Annual water years		Winter-spring water years[1]		Summer-autumn water years[1]		Annual water years		Winter-spring water years[1]		Summer-autumn water years[1]	
		% Years	% Days	% Years	% Days	% Years	% Days	% Years	% Days	% Years	% Days	% Years	% Days
1	07146500	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	07151000	3.0	0.2	0.0	0.0	1.5	0.4	4.5	0.3	0.0	0.0	3.0	0.8
3	07152000	2.8	0.1	0.0	0.0	2.8	0.2	13.9	0.7	4.2	0.2	9.7	1.5
4	07152500	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	07153000	26.8	1.4	9.8	0.4	20.0	2.7	53.7	6.4	20.0	3.1	39.0	10.9
6	07154500	94.8	25.1	74.1	14.6	84.5	39.9	100.0	55.4	100.0	51.4	100.0	61.4
7	07156900	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	07158000	71.8	7.6	21.1	1.1	67.6	16.6	85.9	10.4	31.0	1.9	77.5	22.2
9	07159100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	07161450	0.0	0.0	0.0	0.0	0.0	0.0	2.5	0.0	1.2	0.0	0.0	0.0
11	07171000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	07172000	48.9	4.3	13.3	2.2	37.8	7.1	73.3	11.0	26.7	6.9	64.4	16.6
13	07188000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	07191000	0.0	0.0	0.0	0.0	0.0	0.0	59.0	4.0	16.4	1.2	59.0	7.9
15	07191220	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	07196500	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	1.4	0.1
17	07197000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	07228500	12.8	0.9	0.0	0.0	12.8	2.2	15.4	1.2	0.0	0.0	15.4	2.8

Table 11. Percent of period of record with extreme low-flow days for 37 selected streamflow-gaging stations. —Continued

[no., number; USGS station ID, U.S. Geological Survey station identifier; % Years, the percent of years for the specified water-year type where at least one day is greater than zero; % Days, the percent of days for the specified water-year type that are greater than zero]

Station no. (fig. 1)	USGS station ID	Number of zero-flow days						Number of days where flow is less than 1 cubic foot per second					
		Annual water years		Winter-spring water years[1]		Summer-autumn water years[1]		Annual water years		Winter-spring water years[1]		Summer-autumn water years[1]	
		% Years	% Days	% Years	% Days	% Years	% Days	% Years	% Days	% Years	% Days	% Years	% Days
19	07231000	32.6	2.9	7.0	0.7	25.6	5.9	51.2	7.9	14.0	3.2	44.2	14.2
20	07231500	13.6	0.8	2.3	0.0	11.4	1.9	27.3	1.4	4.5	0.2	22.7	3.1
21	07234000	70.0	19.7	36.7	9.6	66.7	33.3	100.0	54.1	80.0	43.7	96.7	68.5
22	07238000	16.7	0.5	0.0	0.0	16.7	1.3	43.3	2.1	0.0	0.0	26.7	5.0
23	07242000	5.6	0.4	5.6	0.0	5.6	1.0	5.6	0.4	5.6	0.0	2.8	1.0
24	07243500	0.0	0.0	0.0	0.0	0.0	0.0	2.4	0.0	0.0	0.0	2.4	0.0
25	07247500	39.0	2.3	7.3	0.6	36.6	4.7	90.2	11.8	26.8	3.9	75.6	22.1
26	07300500	84.5	20.9	47.9	9.8	81.7	36.2	93.0	24.8	56.3	11.8	88.7	42.6
27	07301500	82.6	19.3	30.4	9.5	73.9	32.5	88.2	21.6	31.9	10.6	81.2	36.6
28	07311500	69.5	11.3	28.8	5.9	67.8	18.9	83.1	24.9	47.5	19.4	78.0	32.8
29	07315700	66.7	10.7	22.9	4.9	60.4	18.7	89.6	26.5	58.3	19.5	93.8	36.3
30	07316000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31	07316500	83.3	18.4	31.3	5.5	72.9	36.2	91.7	23.9	47.9	8.9	81.3	44.7
32	07326500	2.2	0.0	0.0	0.0	2.2	0.0	4.4	0.0	0.0	0.0	4.4	0.1
33	07331000	2.1	0.0	0.0	0.0	0.0	0.0	2.1	0.1	0.0	0.0	2.1	0.2
34	07332500	2.8	0.1	0.0	0.0	1.4	0.3	5.6	0.3	0.0	0.0	4.2	0.8
35	07335700	81.4	9.8	14.0	1.3	69.8	21.6	95.3	18.4	23.3	2.8	95.3	40.1
36	07336200	20.0	2.6	4.0	0.9	16.0	5.0	36.0	4.0	4.0	1.5	28.0	7.4
37	07337900	27.7	1.8	2.1	0.1	25.5	4.0	57.4	4.6	8.5	0.8	55.3	9.8

[1]Winter-spring water years indicate that record used in analysis was only from the months of November through May and summer-autumn water years indicates that record used in analysis was only from the months of June through October.

Table 12. Results of Kendall's tau trend analyses on the number of extreme low-flow days for 17 selected streamflow-gaging stations in and near Oklahoma.

[no., number; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; p-value, probability value; <, less than; --, trend analysis was not performed; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant downward trend, orange shade indicates a statistically significant upward trend; --, trend test not performed]

Station no. (fig. 1)	USGS station ID	Numer of zero-flow days						Number of days where flow is less than 1 cubic foot per second					
		Annual water years		Winter-spring water years[1]		Summer-autumn water years[1]		Annual water years		Winter-spring water years[1]		Summer-autumn water years[1]	
		Tau	p-value	Tau	p-value	Tau	p-value	Tau	p-value	Tau	p-value	Tau	p-value
5	07153000	--	--	--	--	--	--	-0.26	0.010	--	--	-0.22	0.019

Table 12. Results of Kendall's tau trend analyses on the number of extreme low-flow days for 17 selected streamflow-gaging stations in and near Oklahoma. —Continued

[no., number; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; p-value, probability value; <, less than; --, trend analysis was not performed; the shaded values are statistically significant at the 95 percent confidence level, green shade indicates a statistically significant downward trend, orange shade indicates a statistically significant upward trend; --, trend test not performed]

Station no. (fig. 1)	USGS station ID	Numer of zero-flow days						Number of days where flow is less than 1 cubic foot per second					
		Annual water years		Winter-spring water years[1]		Summer-autumn water years[1]		Annual water years		Winter-spring water years[1]		Summer-autumn water years[1]	
		Tau	p-value	Tau	p-value	Tau	p-value	Tau	p-value	Tau	p-value	Tau	p-value
6	07154500	0.27	0.003	0.03	0.715	0.28	0.002	0.36	<0.001	0.30	0.001	0.32	<0.001
8	07158000	0.06	0.485	--	--	0.07	0.396	0.01	0.909	-0.08	0.251	0.05	0.500
12	07172000	-0.12	0.221	--	--	-0.16	0.087	-0.09	0.386	--	--	-0.15	0.154
14	07191000	--	--	--	--	--	--	0.05	0.574	--	--	0.05	0.531
19	07231000	-0.19	0.034	--	--	--	--	-0.32	0.002	--	--	-0.30	0.002
21	07234000	-0.05	0.717	-0.12	0.290	-0.05	0.729	0.03	0.830	-0.04	0.774	0.17	0.205
22	07238000	--	--	--	--	--	--	-0.23	0.048	--	--	--	0.084
25	07247500	0.05	0.635	--	--	0.10	0.290	0.02	0.866	--	--	0.04	0.700
26	07300500	-0.32	<0.001	-0.38	<0.001	-0.25	0.002	-0.28	0.001	-0.39	<0.001	-0.18	0.024
27	07301500	-0.37	<0.001	-0.29	<0.001	-0.33	<0.001	-0.36	<0.001	-0.30	<0.001	-0.32	<0.001
28	07311500	-0.26	0.003	--	--	-0.26	0.003	-0.20	0.029	-0.19	0.024	-0.17	0.049
29	07315700	-0.08	0.399	--	--	-0.13	0.183	-0.19	0.062	-0.12	0.209	-0.18	0.068
31	07316500	-0.44	<0.001	-0.24	0.004	-0.42	<0.001	-0.44	<0.001	-0.26	0.005	-0.40	<0.001
35	07335700	0.14	0.175	--	--	0.15	0.145	0.07	0.523	--	--	0.08	0.464
36	07336200	--	--	--	--	--	--	0.29	0.020	--	--	--	0.097
37	07337900	--	--	--	--	--	--	-0.14	0.166	--	--	-0.16	0.108

[1]Winter-Spring water years indicate that record used in analysis was only from the months of November through May and summer-autumn water years indicates that record used in analysis was only from the months of June through October.

volume, respectively. However, stations with significant trends in the number of extreme low-flow days did not always correspond to trends in streamflow volume. Little River near Sasakwa, Oklahoma, Deep Creek near Randlett, Oklahoma, and Kiamichi River near Antlers, Oklahoma, (stations 19, 28, and 36, respectively; stations 19 and 36 are regulated by water-supply reservoirs) had significant downward trends in the number of extreme low-flow days annually or seasonally but did not have any significant upward trends in streamflow volume. However, most stations that had downward trends in the number of days where streamflow met these criteria also had upward trends in base-flow index, although not all of those base-flow volume or base-flow index trends were significant.

Groundwater Level Trend Analysis

Graphs showing LOESS plots of winter groundwater levels for 35 wells that were analyzed for trends are presented in figures 88–96 (back of report). Results of trend analyses for winter groundwater levels are presented in table 13. A map was developed to display spatial patterns in trend results for winter groundwater levels (fig. 97). The groundwater levels used represent the depth below ground surface of the water table. Therefore, a negative Kendall's tau represents an increase in the groundwater-level elevation (closer to surface). Figure 97 uses upward arrows to indicate an upward trend in groundwater level (a negative Kendall's tau), and a downward arrow to indicate a downward trend in groundwater level (positive Kendall's tau).

Groundwater levels in 25 of the 35 groundwater wells used in the water-level trend analysis had significant trends, 18 of which were significant upward trends. Results of this analysis were very similar to those reported by Tortorelli and others (2005). Significant downward trends in groundwater levels were detected for seven wells. Five of these seven wells were mostly located in the Oklahoma Panhandle. The remaining two wells with significant downward trends in groundwater levels included one well in the Edwards-Trinity

Table 13. Results of Kendall's tau trend analyses of annual winter groundwater levels for entire period of record in 35 selected ground water wells in Oklahoma.

[no., number; OWRB, Oklahoma Water Resources Board; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; p-value, probability value; <, less than; WY, water year; feet/yr, feet below land surface per year; A&T, Alluvial and Terrace Deposits; shading indicates trend significance at 95-percent confidence level (probability value less than or equal to 0.05), green shade indicates a statistically significant downward trend in depth of water below land surface, orange shade indicates a statistically significant upward trend in depth of water below land surface, Principal aquifer or geologic unit data from USGS National Water Information System, http://waterdata.usgs.gov/nwis]

Well no. (fig 97)	OWRB well number	USGS station ID	County	Principal aquifer or geologic unit in which well is completed	Use	Start-end WY	Number of missing years	Kendall's tau	p-value	Trend slope (feet/yr)
1	2300	364620102282001	Cimarron	High Plains[1]	Irrigation	1967-2008	2	0.764	<0.001	1.32
2	2074	363110102064001	Cimarron	High Plains[1]	Irrigation	1967-2008	2	0.883	<0.001	1.11
3	9695	363405101390401	Texas	High Plains[1]	Irrigation	1966-2008	1	0.995	<0.001	1.38
4	1362	365028101215901	Texas	High Plains[1]	Irrigation	1966-2008	1	0.986	<0.001	2.76
5	572	365141100542101	Beaver	High Plains[1]	Irrigation	1968-2008	2	0.741	<0.001	0.52
6	9031	363600100144701	Beaver	High Plains[1]	Irrigation	1967-2007	3	-0.568	<0.001	-0.68
7	9436	344630099370201	Greer	Blaine[1]	Irrigation	1951-2008	10	-0.358	<0.001	-0.38
8	--	361714099315101	Woodward	High Plains[1]	Observation	1958-2008	7	-0.568	<0.001	-0.19
9	9497	343913099313901	Jackson	Blaine[1]	Irrigation	1954-2008	9	-0.293	0.004	-0.18
10	9818	342628099082401	Tillman	A&T North Fork Red River[1]	Irrigation	1945-2008	7	-0.313	0.001	-0.16
11	9871	361610099070901	Woodward	A&T North Canadian River[1]	Domestic	1977-2008	5	-0.356	0.01	-0.20
12	9857	363658098502601	Woods	A&T Cimarron River[1]	Irrigation	1975-2008	9	-0.727	<0.001	-0.33
13	9842	351308098395701	Washita	Rush Springs[1]	Irrigation	1975-2008	6	-0.952	<0.001	-1.52
14	9587	362716098243001	Major	A&T Cimarron Terrace[1]	Observation	1974-2008	5	-0.271	0.037	-0.06
15	9006	364837098205501	Alfalfa	A&T Salt Fork Arkansas River[1]	Irrigation	1975-2008	9	-0.483	0.001	-0.20
16	9522	360052097564801	Kingfisher	A&T Cimarron River[1]	Domestic	1951-2007	6	-0.442	<0.001	-0.17
17	9419	362650097562301	Garfield	A&T Enid Isolated[1]	Domestic	1975-2008	6	-0.698	<0.001	-0.78
18	9509	365824097272901	Kay	Quaternary Alluvium[2]	Irrigation	1975-2008	10	-0.185	0.215	-0.03
19	9608	352637097253701	Oklahoma	Central Oklahoma[1]	Water Supply	1976-2008	7	-0.154	0.280	-0.76
20	9262	350430097175501	Cleveland	Central Oklahoma[1]	Domestic	1983-2008	5	0.371	0.020	0.38
21	9424	344844096575701	Garvin	Gerty Sand[1]	Irrigation	1975-2008	4	-0.435	0.001	-0.23
22	9504	341243096534501	Johnston	Edwards Trinity[1]	Domestic	1977-2007	4	-0.345	0.012	-0.23
23	9558	352907096411001	Lincoln	Ada Vamoosa[1]	Irrigation	1980-2008	6	-0.779	<0.001	-0.58
24	--	343457096404501	Potontoc	A&T North Canadian River[1]	Observation	1960-2008	2	-0.149	0.142	-0.14
25	9588	335621096380301	Marshall	Edwards Trinity[1]	Domestic	1978-2007	4	0.908	<0.001	1.27

Table 13. Results of Kendall's tau trend analyses of annual winter groundwater levels for entire period of record in 35 selected ground water wells in Oklahoma.—Continued

[no., number; OWRB, Oklahoma Water Resources Board; USGS station ID, U.S. Geological Survey station identifier; Tau, Kendall's tau; p-value, probability value; <, less than; WY, water year; feet/yr, feet below land surface per year; A&T, Alluvial and Terrace Deposits; shading indicates trend significance at 95-percent confidence level (probability value less than or equal to 0.05), green shade indicates a statistically significant downward trend in depth of water below land surface, orange shade indicates a statistically significant upward trend in depth of water below land surface, Principal aquifer or geologic unit data from USGS National Water Information System, http://waterdata.usgs.gov/nwis]

Well no. (fig 97)	OWRB well number	USGS station ID	County	Principal aquifer or geologic unit in which well is completed	Use	Start-end WY	Number of missing years	Kendall's tau	p-value	Trend slope (feet/yr)
26	9626	361526096084201	Osage	Chanute Formation[2]	Domestic	1979-2008	4	-0.080	0.582	-0.16
27	9131	340135096013601	Bryan	Edwards Trinity[1]	Domestic	1977-2008	4	-0.786	<0.001	-1.15
28	9840	364919095523101	Washington	Dewey Limestone[2]	Irrigation	1977-2008	4	-0.103	0.453	-0.03
29	9841	365557095521501	Washington	Wann Formation[2]	Domestic	1979-2008	5	-0.323	0.025	-0.12
30	9602	365439095270101	Nowata	Oologah Limestone[2]	Domestic	1979-2007	5	-0.196	0.189	-0.07
31	9278	363220095132701	Craig	Savanna Sandstone[2]	Domestic	1979-2008	5	-0.133	0.362	-0.03
32	9172	355920095111001	Cherokee	Roubidoux[2]	Domestic	1979-2008	5	-0.190	0.191	-0.08
33	9672	353117095065201	Sequoyah	A&T Arkansas River[1]	Observation	1977-2008	4	-0.492	<0.001	-0.26
34	9627	365745094580101	Ottawa	Boone[2]	Domestic	1979-2008	4	-0.062	0.675	-0.02
35	9000	355742094331201	Adair	Pitkin Limestone[2]	Domestic	1979-2008	5	-0.167	0.253	-0.17

[1] Principal aquifer

[2] Geologic unit

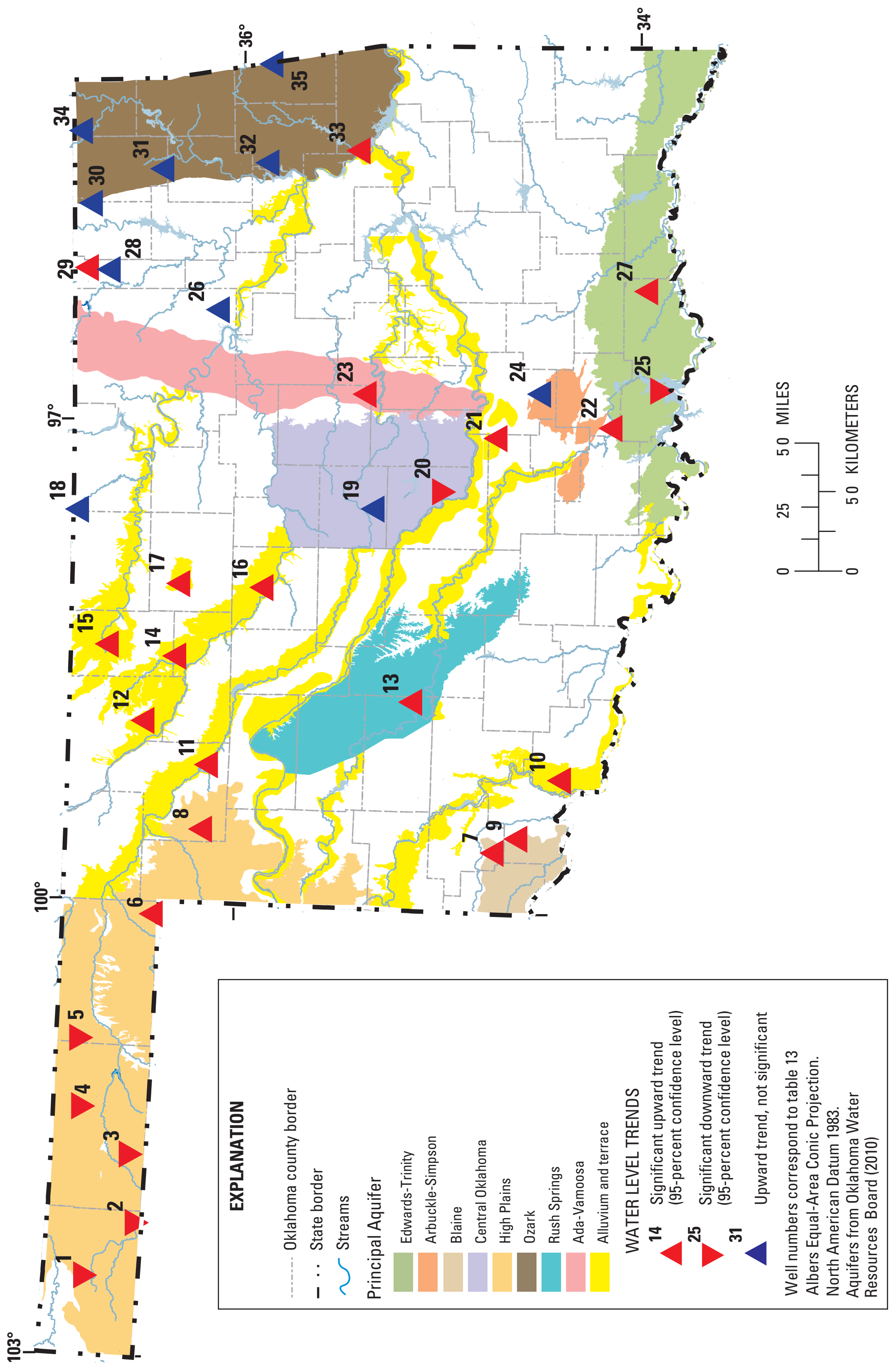

Figure 97. Locations of groundwater wells used in trend analyses with principal aquifer boundaries and results of Kendall's tau trend analyses of annual winter groundwater levels for entire period of record in 35 selected groundwater wells in Oklahoma.

(also referred to as the Antlers) aquifer (well 25, table 13) and one well in the Central Oklahoma (also referred to as the Garber-Wellington) aquifer (well 20). Both wells were located in central Oklahoma. Wells with significant upward trends in groundwater levels were generally located in western and central Oklahoma with the exception of one domestic well in northeastern Oklahoma (well 29) and one well in eastern Oklahoma in the alluvial terrace aquifer of the Arkansas River (well 33) (fig. 97, table 13).

Evaluation of Potential Causes of Trends

This section includes evaluation of potential causes of streamflow trends, including results of trend analysis for precipitation, precipitation-adjusted streamflow, groundwater levels, and a summary of historic water use and water-management practices that may have an effect on streamflow trends.

Precipitation Trends

The most direct potential cause of an upward trend in streamflow volume with time is an increase in the amount of precipitation. Results of the trend analysis for annual and seasonal precipitation indicated that all climate divisions had upward trends in annual precipitation since 1895 (table 2), and many climate divisions had statistically significant upward trends annually and seasonally (fig. 10). Increased precipitation likely caused higher streamflow volume, higher annual peak flow, and fewer number of extreme low-flow days.

Many stations with significant upward trends in streamflow volume are located in climate divisions that had significant upward trends in annual precipitation, which indicates that increases in precipitation may have been the primary cause of upward trends in total-flow volume at these stations. Upward trends in annual and winter-spring total-flow volume also were detected at the downstream Washita River stations (stations 32 and 33), North Canadian River near Wetumka, Oklahoma, (station 23), and Canadian River at Calvin, Oklahoma, (station 20), but the stations are located in climate divisions in which significant upward trends in annual precipitation were not detected. However, these stations have large drainage-basin areas that partially contain climate divisions that had significant upward trends in total precipitation either annually or seasonally.

Upward trends in base-flow volume and base-flow index, as well as upward trends in the number of days where flow was zero or less than 1 ft^3/s, were most commonly observed at stations throughout central Oklahoma, including south-central and west-central Oklahoma. Whereas, upward trends in base-flow index were detected in all climate divisions, significant upward trends in annual and seasonal precipitation were more commonly found in north-central Oklahoma and south-central Kansas. These trends generally support a conclusion that increases in total annual or seasonal precipitation during the last part of the 20^{th} century (1980-2000) contributed to increases in streamflow volume, increases in precipitation may not be the only cause of the upward trends in these streamflow parameters.

LOESS plots of total annual precipitation for climate divisions indicate that most increases in annual precipitation started during the last 20 years of the 20^{th} century. Graphs showing streamflow volume with time and LOESS trend lines indicate that, like annual precipitation (figs. 7–9, back of report), there was an increase in annual streamflow volume and base-flow index for many stations starting in the early 1980s and extending through the year 2000 (figs. 11–47, back of report). Graphical trends in annual streamflow volume and base-flow index were detected in one, two, or all three of these parameters for about one-third of the stations analyzed. Upward trends in streamflow starting in the early 1980s also were reported by Tortorelli and others (2005) for many stations throughout the study area and by Garbrecht and others (2004) for 10 long-term stations in the Great Plains of Oklahoma (located in the central and western part of the State). Increases in annual precipitation starting around 1980 may have caused many of the significant upward trends in streamflow volume, as well as annual peak flows, and decreases in the number of extreme low-flow days.

Increases in total annual or seasonal precipitation are not necessarily indicators of increases or decreases in rainfall intensity. Increases in rainfall intensity and duration could cause higher runoff from individual rainfall events, which would likely affect peak flow and may affect total flow. Karl and Knight (1998) reported that the number of storms and the amount of rainfall during intense precipitation increased significantly during the period 1910-1996 in the regions containing Kansas, Oklahoma, and Nebraska. However, no stations with upward trends in annual peak flow were located in climate divisions that had upward trends in annual or seasonal precipitation. Three stations that had upward trends in annual peak flow that were not located in a climate division that had an upward trend in annual or seasonal precipitation (stations 4, 5, and 32) had drainage areas that crossed the boundaries of climate divisions with significant upward trends in annual or seasonal precipitation.

No significant downward precipitation trends in climate divisions were found in western Kansas, Oklahoma, and Texas, where many stations had significant downward trends in streamflow volume and annual peak flow. This inconsistency between trends in precipitation and streamflow volume indicated that downward trends in streamflow and annual peak flow may be attributed to factors other than total precipitation (Tortorelli and others, 2005).

Trends Adjusted for Annual or Seasonal Precipitation

In the previous section, upward trends in annual precipitation, especially during the wet period from 1980–2000, were described as a likely cause of significant upward trends in streamflow volume and base-flow index for many stations. The results from the trend analysis of precipitation-adjusted streamflow volume were used to analyze whether the annual or seasonal variation in precipitation is the likely cause of trends in streamflow volume.

For example, LOESS plots for Mud Creek near Courtney, Oklahoma, (station 29, fig. 39) indicate an increase in streamflow volume during the wet period (1980-2000), but a return to lesser streamflow volumes after that time, which may have been the cause of significant upward trends in base-flow volume during the annual and winter-spring periods. When precipitation adjustment was calculated, no significant trends for these parameters were detected. This observation indicated that changes in annual or winter-spring precipitation were the likely cause of the significant upward trends.

LOESS plots for Washita River near Cheyenne (station 31, fig. 41) indicate that although annual streamflow volume started to increase after 1980, increases in these parameters remained evident after the end of the wet period (the year 2000). As expected, although precipitation adjustment generally reduced the slope of trends in streamflow volume, precipitation adjustment did not change the direction or significance of most trends in streamflow volume at this station.

Whereas, LOESS plots supported the statistical results for station 29, stations with plots in which LOESS lines increased around the period of 1980 and decreased on or after the year 2000 did not consistently correspond to statistically significant trends in unadjusted base-flow or total-flow volumes that became insignificant after precipitation adjustment. This inconsistency may indicate a poor or complex relation between annual precipitation and annual streamflow volume that is not accounted for by a simple LOESS relation, or indicate that other factors in addition to the increase in precipitation from 1980–2000 may have caused significant upward trends in streamflow volume.

For the summer-autumn period, all stations that had significant upward trends in total-flow volume did not have significant trends after precipitation adjustment was calculated. This result indicated that significant upward trends in total-flow volume during the summer-autumn period most likely are caused by changes in precipitation.

Factors other than changes in annual or seasonal precipitation may have caused significant upward trends in precipitation-adjusted streamflow volume. Significant upward trends in precipitation-adjusted streamflow volume may be related to long-term changes in climate. For example, recharge of aquifers that contribute to surface-water flow in the drainage basin as a result of increases in precipitation over a long-term period may result in upward trends in precipitation-adjusted streamflow volume (see section titled “Kendall’s Tau Test for Streamflow Volume Adjusted for Annual Precipitation”). Several anthropogenic factors that may cause upward trends in precipitation-adjusted streamflow volume include recharge as a result of return flows from irrigation or other changes in water management practices (see section titled “Water-Use and Water Management Practices” for further discussion). Further evaluation of groundwater-level trends and water-management practices in these basins may reveal if upward trends were caused by anthropogenic or climate-related factors.

Several stations had downward trends in precipitation-adjusted streamflow volume where significant trends in unadjusted streamflow volume were not observed. Two stations, Arkansas River near Arkansas City, Kansas, and Spavinaw Creek near Sycamore, Oklahoma, (stations 1 and 15, respectively) had significant downward trends in annual base-flow volume after precipitation adjustment. Four stations—North Canadian River near Seiling, Oklahoma, Salt Fork Red River near Mangum, Oklahoma, North Fork Red River near Carter, Oklahoma and Kiamichi River near Big Cedar, Oklahoma; stations 22, 26, 27, and 35, respectively)—had significant downward trends in total-flow volume (annually or seasonally) that were not significant prior to precipitation adjustment. Downward trends in precipitation-adjusted streamflow volume are likely caused by local or regional-scale anthropogenic alteration such as changes in water use, water-management practices, and in urban or agricultural development.

Groundwater-Level Trends

In general, wells with significant trends in groundwater levels corresponded to trends in streamflow volume at many stations in the Oklahoma Panhandle and western and south-central Oklahoma. Water-level trends cannot easily be compared to trends in streamflow volume because winter groundwater data do not reflect seasonal changes in groundwater levels and the period of record for many wells was short (less than 40 years).

Downward trends in groundwater levels were detected at 7 of 35 wells analyzed (table 13, fig. 97). Five of these (wells 1–5) completed in the High Plains aquifer were located in the Oklahoma Panhandle region near stations that had downward trends in streamflow volume (fig. 97). Declining groundwater levels are likely contributing to downward trends in streamflow in the Oklahoma Panhandle. The two other wells with significant downward trends (well 20 completed in the Lower Canadian Basin and Central Oklahoma aquifer and well 25 completed in the Red-Washita Basin and Edwards Trinity aquifer) were not located near any stations with significant downward trends in streamflow volume. These wells may be in areas with isolated declining groundwater levels that are not well connected to surface-water sources (Shana Mashburn and Marvin Abbott, U.S. Geological Survey, oral and written commun., June 2009).

Upward trends in groundwater levels were detected for 18 of the 35 wells analyzed (table 13, fig. 97) These wells were mostly located in south-central and western Oklahoma (excluding the Oklahoma Panhandle), which is the same region where many surface-water stations also had significant upward trends in base-flow volume and base-flow index (figs. 48–53 and 60–62). Most LOESS plots for these wells indicate that the start of the rising groundwater levels corresponded to the start of the wet period, around 1980 (figs. 89–96). This observation indicates that increases in precipitation are a likely cause of upward trends in groundwater levels (from either short-term or long-term recharge) and upward trends in streamflow volume for many stations near those wells.

Many stations with significant upward trends in base-flow volume after precipitation adjustment were located in or near principal aquifers where wells had significant upward trends in groundwater levels. Thirteen stations had significant upward trends in precipitation-adjusted base-flow volume for annual or seasonal water years (all of which also had significant upward trends in base-flow index annually or seasonally). Eleven of these stations (stations 2, 10, 18, 20, 23, 26, 27, 30, 31, 32, and 33) were located on or near principal aquifers—alluvial and terrace aquifers along the Salt Fork Arkansas, Cimarron, Canadian, North Canadian, North Fork Red, and Washita Rivers; Central Oklahoma; Blaine; Edwards-Trinity; Rush Springs; and Arbuckle-Simpson (fig. 98). All four stations (stations 10, 23, 32, and 33) that had significant upward trends in annual or seasonal precipitation-adjusted total-flow volume were located near aquifer boundaries (alluvial and terrace aquifers for the Cimarron, North Canadian, and Washita Rivers, and Blaine and Arbuckle-Simpson aquifers) and were not near wells with significant downward trends. Most wells in these aquifers had significant upward trends in groundwater levels, with the exception of one well in the Edwards-Trinity aquifer and one well in the Central Oklahoma aquifer (the two wells with significant downward trends that were not located near any stations with significant upward trends in streamflow volume). This observation indicates that long-term recharge of principle aquifers, as a result of natural recharge from precipitation or artificial recharge from irrigation activities or other water-management practices, may have caused significant upward trends in streamflow volume, especially base-flow volume, after precipitation adjustment. More detailed analysis of local groundwater and surface-water interaction would be helpful in determining if the rate and magnitude of recharge of principle aquifers has affected streamflow.

Water-Use and Water-Management Practices

Water use could not be treated directly as a variable in the analysis because of a lack of reliable historic records (Tortorelli and others, 2005). Estimates of total freshwater withdrawals in Oklahoma available on a 5-year basis from calendar year 1950 through 2005 are shown in table 14. Estimated total freshwater withdrawals increased by about 400 percent from 1950 through 1975 and then decreased by about 25 percent from 1975 to 2005 (Tortorelli, 2009). Surface-water sources of withdrawal (mainly for public supply) were more dominant in the eastern half of Oklahoma and groundwater sources of withdrawal (mainly for irrigation) were more dominant in the western half of Oklahoma, including the Oklahoma Panhandle (Tortorelli, 2009).

Withdrawals for irrigation increased by about 500 percent from 1950 through 1975 and then decreased by about 55 percent from 1975 to 2005. The same pattern can be observed in the groundwater-source category (where irrigation is the largest percentage of groundwater use in Oklahoma), which increased from 1950 to 1975 by about 650 percent and then decreased by about 55 percent from 1975 to 2005. The decrease in irrigation withdrawals on a statewide basis since 1975 may have been caused by adoption of more efficient irrigation practices such as sprinkler irrigation systems and less reliance on surface or flood application to irrigated land (Tortorelli, 2009). Decreases in groundwater withdrawal and irrigation water use may explain some upward trends in base-flow volume and base-flow index in many stations in western Oklahoma, excluding the Oklahoma Panhandle, where downward trends in streamflow volume for stations are not explained by this water-use trend.

A likely cause of downward trends in streamflow is from long-term declines in groundwater levels from groundwater use (Sophocleous, 1998). Large declines in groundwater levels because of irrigation in the Oklahoma Panhandle (Upper Cimarron RiverBasin and upper part of the North Canadian River Basin) probably have contributed to decreases in streamflow in this area. Decreases in streamflows in the Beaver/North Canadian River Basin (the upper part of the North Canadian River Basin) have been attributed to depletion of groundwater in the High Plains aquifer (Wahl and Tortorelli, 1997; McGuire, 2009). Increases in streambed infiltration may have developed as a result of declines in groundwater levels, which cause the regional water table to decline below the streambed (Angelo, 1994; Wahl and Tortorelli, 1997), and may reduce base flow and total flow.

The Upper Cimarron Basin has the highest percentage of surface-water use for irrigation (Tortorelli, 2009). Surface-water diversions for irrigation also have been noted in the historic station record for stations in the Upper Cimarron Basin, at Cimarron River near Kenton and Cimarron River near Forgan (stations 6 and 7) (Lewis and Esralew, 2009). Direct surface-water diversions can reduce base flow, total flow, and peak flows, and possibly increase the number of extreme low-flow days as determined by the time of year when these occur. Downward annual and seasonal trends in these parameters were detected for these two stations in the Upper Cimarron Basin. A significant downward trend in annual base-flow index was observed at station 6, which indicated that total flow was decreasing more rapidly than base flow, and streamflow may have been more affected by surface-water diversions than groundwater withdrawals.

Water use for irrigation can affect base flow and runoff characteristics and in turn, affect streamflow trends depending upon how irrigation is applied. Irrigation returns in the river

Table 14. Estimated total freshwater withdrawals in Oklahoma by water-use category, 1950-2005.

Water-use category	Estimated total freshwater withdrawals (million gallons per day)[1,2]											
	1950	1955	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005
Total withdrawal	422	890	778	1,225	1,473	2,108	1,719	1,268	1,418	1,775	1,769	1,589
Public supply	140	185	206	224	262	340	306	520	515	567	675	646
Rural domestic and livestock	70	50	59	72	81	99	93	31	171	176	193	187
Irrigation	180	225	274	364	819	1,160	870	445	601	864	717	495
Industrial, commercial[3]	32	430	239	565	311	509	450	272	131	168	184	75
Source of water												
Ground	165	280	299	380	859	1,234	954	561	659	954	771	570
Surface	257	610	479	845	614	874	765	707	760	821	997	1,019

[1] Estimates of total freshwater withdrawals from Tortorelli and others (2005).

[2] 2005 estimates of total freshwater withdrawals from Tortorelli (2009).

[3] Includes thermoelectric power except 1950.

basin can increase recharge and result in upward trends in streamflow (Luckey and Becker, 1999). Irrigation diversions and reduction in groundwater supply can reduce streamflow volume and potentially reduce the magnitude of peak flows in the basin (Wahl and Tortorelli, 1997; Tortorelli, 2005).

Surface-flow characteristics for stations in the Red Headwaters Basin, which supplies water to Lugert-Altus Irrigation District, has shifted from streamflow dominated by runoff to streamflow dominated by base flow (annual base-flow index over 0.5). This shift is indicated by the upward trends in base-flow volume, base-flow index, and the number of extreme low-flow days, and by the downward trends in total-flow volume after precipitation adjustment and peak flow. Irrigation makes up 83 percent of all surface-water use in this basin (Tortorelli, 2009). The observed shift in surface-flow characteristics may be a result of increases in application of irrigation water from surface-water sources, which can reduce total-flow volume and peak flow but increase base-flow volume because of an increase in artificial recharge from irrigation returns (Luckey and Becker, 1999).

A similar observation also can be noted at station 31, Washita River near Cheyenne, which is located in the Red-Washita Basin, but has a large percentage of drainage area overlying the High Plains aquifer (fig. 1) and is dominated by base flow (fig. 41). This station had upward trends in base-flow index and streamflow volume (base flow increased faster than total flow), an upward trend in extreme low flow, and a downward trend in peak flow. The primary source of irrigation water in the High Plains aquifer is from groundwater (and groundwater is the dominant source for irrigation water use), although recent data indicate that groundwater withdrawals for irrigation may have declined from this aquifer since 1995 (Tortorelli, 2009, p. 26). Local groundwater levels mostly have remained stable or risen in this aquifer upgradient from this station since before 1950 (McGuire, 2009). Increases in total flow and greater percentages of base flow as a part of total flow (increases in base-flow index) at this station may be attributed to an increase in efficient agricultural practices that tend to artificially enhance recharge from precipitation and irrigation returns, and decrease the amount of withdrawals required for irrigation (Luckey and Becker, 1999; Smith and Wahl, 2003; Tortorelli, 2009). Artificial recharge from irrigation returns and a reduction in the rate of groundwater withdrawal also may contribute to an upward trend in base-flow volume and base-flow index at this station.

Surface-water supply for livestock may affect streamflow trends because livestock water supply serves to reduce surface runoff and reduces peak flows (Wahl and Tortorelli, 1997), and may induce recharge and increase base flow and base-flow index (Luckey and Becker, 1999; Smith and Wahl, 2003). Water use for livestock has been steadily increasing throughout Oklahoma since 1950 (table 14). The Red-Washita Basin has the largest total withdrawals for livestock operations and the largest increase in the amount of withdrawal for livestock (from 1990–2005) for any major river basin in the State (Tortorelli, 2009). Upward trends in base-flow volume and base-flow index were detected for many stations in this basin. For the upper part of the North Canadian River Basin (located in the Oklahoma Panhandle), documentation has been made of increases in the number of livestock ponds (Wahl and Tortorelli, 1997), which may be one of several factors that resulted in reduced streamflow and downward trends in streamflow volume and peak flow for station 31.

Surface-water sources for public supply (including commercial and industrial uses) are less likely to affect long-term trends in streamflow because these sources mostly are reservoirs in which releases are managed. Most surface-water withdrawals for public supply have increased, especially in river basins in central and eastern Oklahoma, which may correspond to an increase in population in Oklahoma (Tortorelli, 2009). No substantial correlation could be identified between significant trends in streamflow and trends in surface-water withdrawals for public supply.

Other types of water-management practices may have an effect on streamflow trends. Many stations used in this report were affected by floodwater retarding (FWR) structures. FWR structures tend to have the most substantial effect on streamflow by reducing flood peak discharge (Tortorelli, 1997). Similar to livestock ponds, these structures may have an effect on low flow as infiltration is increased as runoff is held behind the retention dam. This retention and infiltration may result in artificial recharge, which can augment base flow for stations affected by these conditions (Tortorelli and Bergman, 1985; R.L. Tortorelli, oral and written commun., August 2009). Increases in recharge from long-term increases in precipitation during the wet period (1980–2000) artificially enhanced by the presence of FWR structures may explain some upward trends in streamflow volume that are still significant after adjustment for annual or seasonal precipitation, and may explain some significant upward trends in base-flow index.

A spatial correlation was observed between the location of stations in southwestern and central Oklahoma that had significant upward trends in annual and winter-spring base-flow volume (before and after precipitation adjustment) and the location of floodwater retarding structures. Figure 98 highlights 8-digit hydrologic units (HU) where more than 10 percent of the drainage area was affected by FWR structures. This highlighted region is similar to the spatial pattern in stations with significant upward precipitation-adjusted base-flow trends observed for central and southwestern Oklahoma (fig. 63), especially in the Red-Washita Basin. Streamflow at some stations with large drainage basins that were not substantially affected by FWR structures (as a total percent of the drainage area) may be influenced by FWR structures that are near the station (fig. 98). These stations included Cimarron River near Ripley, Oklahoma, (station 10), North Canadian River near Wetumka, Oklahoma, (station 23), and Canadian River at Calvin, Oklahoma, (station 20). Significant upward trends in base-flow index and upward trends in annual or seasonal precipitation-adjusted streamflow volume were detected at all three stations.

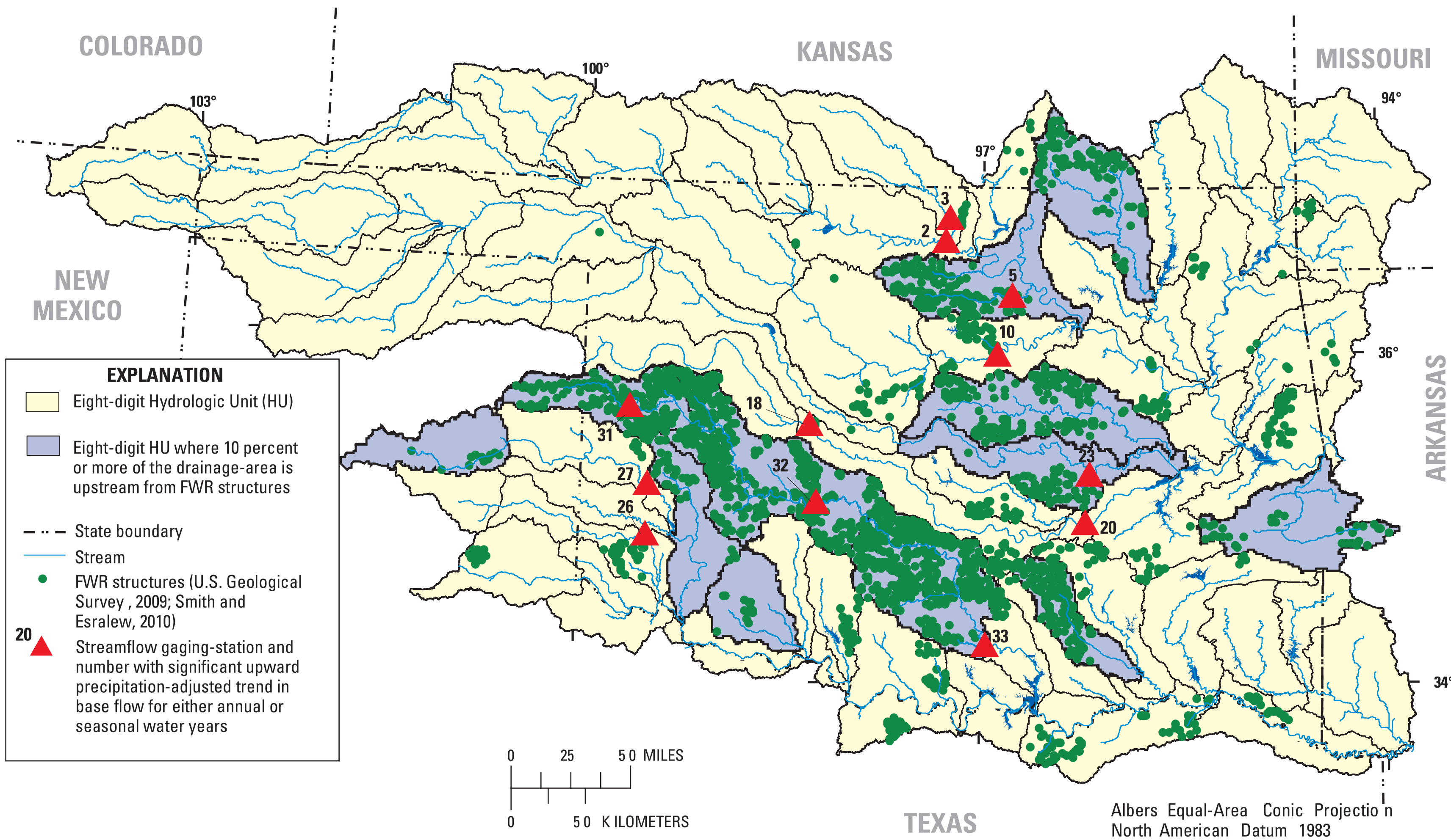

Figure 98. Locations of floodwater retarding (FWR) structures relative to eight-digit hydrologic unit boundaries and streamflow-gaging stations with significant upeard trends in precipitation-adjusted base-flow volume.

Even though a spatial correlation was observed between areas affected by FWR structures and regions where many stations had significant upward trends in base-flow index and streamflow volume, significant upward trends in annual or seasonal precipitation-adjusted base-flow volume were only detected for four out of eight stations that were regulated by FWR structures (table 1): Black Bear Creek at Pawnee, Oklahoma, (station 5), and Washita River near Cheyenne, at Anadarko, and near Dickson, Oklahoma, (stations 31, 32, and 33 respectively). Significant upward trends in annual or seasonal base-flow index also were detected for these stations in addition to Little River near Sasakwa, Oklahoma, (station 19). No significant upward trends in annual or seasonal precipitation-adjusted base-flow volume were detected for 4 stations substantially affected by FWR structures: Caney River near Elgin, Oklahoma, (station 12), Little River near Sasakwa, Oklahoma, (station 19), Deep Fork near Beggs, Oklahoma (station 24), and Fourche Maline near Red Oak, Oklahoma, (station 25). No significant base-flow index trends were detected for stations 12, 24, and 25. Streamflow at station 24 is moderately regulated by a water-supply reservoir (table 1), which also may affect base-flow index trends.

The inconsistency in the results of the trend analysis for stations substantially affected by FWR structures indicates that FWR structures may not be the dominant or an important factor contributing to significant trends in precipitation-adjusted streamflow volume. Rates of artificial recharge as a result of FWR structures also may be affected by infiltration capacity, soil permeability, and other local geologic characteristics of the drainage basins. Further investigation into the effects of FWR structures and other regulation on base flow and base-flow index for stations with different drainage-basin characteristics may help to identify potential sources of natural and artificial recharge, but was beyond the scope of this report.

Summary

The U.S. Geological Survey, in cooperation with the Oklahoma Water Resources Board, investigated trends in base flow, total flow, and base-flow index at selected streams in and near Oklahoma on an annual and seasonal (winter-spring, and summer-autumn) basis. Also included in the statistical evaluation were trends in annual and seasonal precipitation for 12 climate divisions in the study area, annual peak flow for selected stations, the number of days where streamflow was zero or less than one 1 cubic foot per second, both annually and seasonally, and annual winter groundwater levels for wells throughout the study area. These parameters were selected because these parameters are useful for comprehensive water-resources management, especially for flood control, low-flow permitting, and wastewater management.

Thirty-seven stations were selected for trend analysis. Streamflow at most stations was unregulated or was affected by moderate regulation. Most stations had a minimum length of continuous daily-mean streamflow record of at least 40 years through water year 2008 without substantial record gaps. For stations with moderately regulated streamflow, the regulated period of record was analyzed.

To assist with visual identification of potential trends, bar charts and LOESS lines were developed for annual base-flow volume, total-flow volume, base-flow index, annual and seasonal precipitation, annual peak flow, and winter groundwater levels. Bar charts and LOESS lines also were developed for the number of days where streamflow was zero or less than 1 cubic foot per second for selected stations.

Kendall's tau trend analysis was used to evaluate statistical trends in precipitation, streamflow, and groundwater levels. Precipitation-adjusted trends using LOESS regressions and Kendall's tau were calculated for annual and seasonal base-flow and total-flow volumes to identify the presence of underlying trends in streamflow volume that were not associated with annual or seasonal variations in precipitation. Kendall's tau was used to test trends on error residuals from LOESS regressions of annual or seasonal precipitation and streamflow volume. Significant trends in precipitation-adjusted streamflow volume may be caused by withdrawals and diversions, irrigation returns, or long-term recharge from underlying aquifers.

In general, climate divisions with significant upward trends in precipitation (either annually or seasonally) were detected in central Oklahoma and central and southeastern Kansas. More climate divisions had statistically significant upward trends in total precipitation for annual water years than in winter-spring or summer-autumn water years.

Significant trends in annual or seasonal base-flow volume were detected for 22 stations, 19 of which had upward trends. Significant trends in annual or seasonal total-flow volume were detected for 14 stations, 9 of which had upward tends. Many stations that had significant upward trends in annual or seasonal total-flow volume also had significant upward trends in base-flow volume for the same period. Precipitation adjustment changed the results (significance only or significance and direction) of annual or seasonal trends in unadjusted base-flow volume for 12 stations and in unadjusted total-flow volume for 13 stations.

Significant trends in annual or seasonal base-flow index were detected for 25 stations, 23 of which had upward trends. Eighteen stations that had significant upward trends in annual or seasonal base-flow index also had significant upward trends in base-flow volume and no significant downward trends in total-flow volume during the same period, which indicated that upward trends in base-flow index were likely driven by increases in base-flow volume at these stations.

Maps were used to evaluate spatial patterns in stations with significant trends. Trend results were highly variable throughout the State. However, some recurring patterns in locations of stations with similar trend results were detected. In general, significant downward trends in base-flow and total-flow volume were detected for the three stations in the Oklahoma Panhandle (including stations in the Upper Cimarron River Basin and upper part of the North Canadian River

Basin). Significant upward trends in annual or seasonal base-flow volume before and after precipitation adjustment were detected for 12 stations in central, southwestern, and south-central Oklahoma (including stations in the Red Headwaters, Red-Washita, Lower Canadian, lower part of the North Canadian, and Arkansas-Keystone Basins). No clear regional patterns were detected for stations with trends in unadjusted or precipitation-adjusted total-flow volume in central and western Oklahoma (excluding the Oklahoma Panhandle).

Prior to precipitation adjustment, significant upward trends in annual or seasonal base-flow volume were detected for four stations in the eastern half of Oklahoma (including stations in the Neosho-Verdigris, Lower Arkansas, and Red-Sulphur Basins) and a significant upward trend in total-flow volume was detected for one station for the winter-spring period. After precipitation adjustment, no stations in this region had significant upward trends in base-flow or total-flow volume, one station had significant downward trends in annual base-flow volume, and one station had significant downward trends in winter-spring total-flow volume. Significant upward trends in annual or seasonal base-flow index were detected for three stations in this region.

The Kendall's tau analysis of annual peak flow indicated that less than one-third of stations evaluated in this report had significant trends. Significant downward trends in annual peak flow were detected for eight stations in or near western Oklahoma (near the Texas Panhandle or the Oklahoma Panhandle). Direction of significant trends in annual peak flow did not consistently correspond to trends in total-flow volume.

Most stations that had significant trends in the number of days where streamflow was zero or less than 1 cubic foot per second were downward in direction, which indicated increases in extreme low flow. A majority of stations could not be analyzed for trends because these stations did not have a significant number of days where streamflow stamet these criteria. Where analyzed, most stations that had significant trends in the number of zero-flow days also had significant trends in the number of days that were less than 1 cubinc foot per second for the same period. However, stations with significant trends in the number of days where streamflow was zero or less than 1 cubic foot per second did not always correspond to trends in streamflow volume.

Winter groundwater levels in 25 of 35 groundwater wells had significant trends. Eighteen groundwater wells with significant upward trends in groundwater levels were located in western and central Oklahoma. Five of seven wells with significant downward trends were located in the Oklahoma Panhandle. Two wells with significant downward trends in groundwater levels were located in central Oklahoma.

Increases in annual and seasonal precipitation, especially for the period of 1980–2000, may have caused significant upward trends in annual or seasonal base-flow and total-flow volumes at stations where precipitation-adjustment removed the significant upward trends in these parameters. Factors that may cause upward trends in precipitation-adjusted streamflow volume include anthropogenic factors such as return flows from irrigation or changes in water-management practices, and climate-related factors such as recharge of aquifers that contribute to surface-water flow in the drainage basin (as a result of increases in precipitation over a long-term period). Downward trends in unadjusted and precipitation-adjusted streamflow volume are likely caused by local or regional-scale anthropogenic alteration such as water use or water-management practices or increases in urban or agricultural development.

In general, trends in annual groundwater levels corresponded to trends in streamflow volume at many stations in the Oklahoma Panhandle and western and south-central Oklahoma. Two wells in central Oklahoma with significant downward trends were not located near any stations with significant downward trends in streamflow volume. These wells may be in areas with isolated declining groundwater levels that are not well-connected to surface-water sources. Eleven stations with significant upward trends in precipitation-adjusted annual and winter-spring base-flow volume were located in or near principal aquifers where many wells had significant upward trends in groundwater levels, indicating that increased recharge of underlying aquifers may have caused significant upward trends in base-flow volume and base-flow index at these stations.

A likely cause of downward trends in streamflow volume for many stations in the Oklahoma Panhandle is from long-term declines in groundwater levels from groundwater use. Surface-water diversions for irrigation also have been noted in the Upper Cimarron River Basin and likely contributed to significant downward trends in streamflow volume and annual peak flow for stations in this basin. A shift in streamflow characteristics from rivers dominated by runoff to rivers dominated by base flow has been observed for stations in the Red Headwaters Basin, possibly because of increases in artificial recharge from irrigation activities that can contribute to an upward trend in base-flow volume and base-flow index. Upward trends in base-flow volume, total-flow volume, and base-flow index for a station in the upper part of the Red Washita Basin may be attributed to more efficient agricultural practices, which can serve to reduce groundwater withdrawals upgradient from the drainage basin, or also may be attributed to an increase in irrigation returns.

Many stations used in this report were affected by floodwater-retarding structures, which may artificially recharge underlying aquifers and possibly augment base flow for stations affected by these conditions. A spatial correlation was observed between the location of stations in southwestern and central Oklahoma that had significant upward trends in annual and winter-spring base-flow volume (before and after precipitation adjustment) and the location of floodwater retarding structures, which indicated that these structures may be a contributing factor to recharge. However, only five stations that were substantially regulated by floodwater retarding structures also had significant upward trends in either annual or seasonal base-flow volume, total-flow volume, or base-flow index, which indicated that the local geology may influence recharge characteristics for drainage basins affected by floodwater-retarding structures.

Acknowledgments

The authors would like to thank Robert Tortorelli, U.S. Geological Survey, for providing knowledge and expertise regarding streamflow statistics, gaging-station history, and water-use information. The authors would like to thank all U.S. Geological Survey Hydrologic Technicians, past and present, who have collected and processed streamflow data. The authors would like to thank Shana Mashburn and Marvin Abbott, U.S. Geological Survey, for providing their knowledge and expertise to the interpretation of groundwater data analyzed in this report. Finally, the authors would like to thank David K. Mueller, U.S. Geological Survey, for providing his knowledge and expertise toward selection of the methods used in the trend analysis.

References Cited

Angelo, R.T., 1994, Impacts of declining streamflow on surface water quality: Manhattan, Kansas, 11th Annual Water and the Future of Kansas Conference, Proceedings, p. 1–2.

Arndt, D., 2007, Unusual rainfall patterns of 2007: Norman, Oklahoma, U.S. Geological Survey "A Very Wet Year in Oklahoma" Conference, accessed in June, 2009, available at *http://ok.water.usgs.gov/projects/hurricane/Pdf%20 Files/04_Arndt_OkClimSurvey_Precipitation.pdf*

Beck, D.L., Miller, J.L., Hagny, M.P., 1998, Successful no-till on the Central and Northern Plains: Baltimore, Maryland, American Society of Agriculture Conference, Proceedings, p. 1-15, accessed in May, 2010, available at *http://www.dakotalakes.com/Publications/asa10_98.pdf*

Blazs, R.L., Coffey, T.L., Esralew, R.A., Paxton, S.T., Tortorelli, R.L., 2007, Streamflow and rating analysis of a very wet year: Norman, Oklahoma, U.S. Geological Survey "A Very Wet Year in Oklahoma" Conference, accessed in June, 2009, available at *http://ok.water.usgs.gov/projects/hurricane/Pdf%20Files/07_Esralew_USGS_Discharge.pdf*

Cleveland, W.S., and Devlin, S.J., 1988, Locally-weighted regression: An approach to regression analysis by local fitting: Journal of American Statistical Association, v. 83, p. 596-610.

Crawford, K., McManus, G., 2008, Statement on climate change and its implications for Oklahoma, 3 p., accessed June 2009, available at *http://climate.ok.gov/newsmedia/climate_statement.pdf*

Dietz, E.J., 1989, Teaching regression in a nonparametric statistics course: American Statistician, v.43, p. 35-40

Garbrecht, J.D., Van Liew, M.W., and Brown, G.O., 2004, Trends in precipitation, streamflow, and evapotranspiration in the Great Plains of the United States: Journal of Hydrologic Engineering, v. 9, no. 5, p. 360-367.

Garbrecht, J.D., and Schneider, J.M, 2007, 1895-2006 annual precipitation, long-term trends, persistent variations, and annual precipitation expectations for Oklahoma climate divisions: Grazinglands Research Laboratory Miscellaneous Publication, accessed June 2009, available at *http://ars.usda.gov/Main/docs.htm?docid=11617*.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: New York, Elsevier, 522 p.

Insightful Corporation, 2007, S-PLUS Version 6.1 for Windows Professional Edition, Release 1: Lucent Technologies, Inc.

Institute of Hydrology, 1980a, Low flow studies: Wallingford, Oxon, United Kingdom, Report No. 1, 41 p.

Institute of Hydrology, 1980b, Low flow studies: Wallingford, Oxon, United Kingdom, Report No. 3, p. 12- 19.

Karl, T.R., and Knight, R.W., 1998, Secular trends of precipitation amount, frequency, and intensity in the United States: Bulletin of the American Meteorological Society, v. 79, p. 231–241.

Kendall, Maurice, and Gibbons, J.D., 1990, Rank correlation methods (5th ed.): New York, Oxford University Press, 260 p.

Lewis, J.M., and Esralew, R.A., 2009, Statistical summaries of streamflow in and near Oklahoma through 2007: U.S. Geological Survey Scientific Investigations Report 2009-5135, 634 p.

Luckey, R.R., and Becker, M.F., 1999, Hydrogeology, water use, and simulation of flow in the High Plains aquifer in northwestern Oklahoma, southeastern Colorado, southwestern Kansas, northeastern New Mexico, and northwestern Texas: U.S. Geological Survey Water-Resources Investigations Report 99-4104, 68 p.

McGuire, V.L., 2009, Water-level changes in the High Plains aquifer, predevelopment to 2007, 2005–06, and 2006–07: U.S. Geological Survey Scientific Investigations Report 2009–5019, 9 p., accessed June 2009, available at: *http://pubs.usgs.gov/sir/2009/5019/*.

National Oceanic and Atmospheric Administration, 2009, Climate division: Temperature-precipitation drought-data: National Climatic Data Center, accessed May 28, 2009, available at *http://www.ncdc.noaa.gov/oa/climate/onlineprod/drought/ftppage.html*

Oklahoma Water Resources Board, 2006, Hydrologic drought of water year 2006, A Historical Context: Oklahoma Water Resources Board Circular, 4 p, accessed June 2009, available at: *http://www.owrb.ok.gov/studies/reports/reports_pdf/drought_of_wy2006.pdf*

Oklahoma Water Resources Board, 2009, Water well search with groundwater levels: accessed January 31, 2005, available at URL http:// *www.owrb.state.ok.us/wd/search/search.php?type=wl/*

Oklahoma Water Resources Board, 2010, Water Information Mapping System: accessed March 1st, 2009, available at *http://www.owrb.ok.gov/maps/server/wims.php*

Ott, R.L., and Longnecker, M., 1995, An introduction to statistical methods and data analysis, 5th edition: Belmont, California, Duxbury Press, 1,152 p.

Sen, P.K., 1968, On a class of aligned rank order tests in two-way layouts: Annals of Mathematical Statistics, v. 39, p. 1,115-1,124.

Smith, S. J.., Esralew, R.A., 2010, StreamStats in Oklahoma – Drainage-basin characteristics and peak-flow frequency statistics for ungaged Streams: U.S. Geological Survey Scientific Investigations Report 2009-5255, 58 p

Smith, S.J., and Wahl, K.L., 2003, 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: U.S. Geological Survey Water-Resources Investigations Report 03-4086, 36 p.

Sophocleous, Marios, 1998, On the elusive concept of safe yield and the response of interconnected stream-aquifer systems to development, *in* Sophocleous, Marios, ed., Perspectives on sustainable development of water resources in Kansas: Kansas Geological Survey Bulletin 239, p. 61–86.

Swan, D.R., and Condie, R., 1983, Computation of the base flow index: Water Resources Branch Inland Water Directorate, Environment Canada, Ottawa, Ontario, 21 p.

Tortorelli, R.L., 1991, Floods and droughts: Oklahoma, National Water Summary 1988-89: U.S. Geological Survey Water-Supply Paper 2375, p. 451-452.

Tortorelli, R.L., 1997, Techniques for estimating peak-streamflow frequency for unregulated streams and streams regulated by small floodwater retarding structures in Oklahoma: U.S. Geological Survey Water-Resources Investigations Report 97-4202, 39 p.

Tortorelli, R.L., 2002, Statistical summaries of streamflow in Oklahoma through 1999: *U.S. Geological Survey Water-Resources Investigations Report 02-4025*, 510 p.

Tortorelli, R.L., 2008, Hydrologic drought of water year 2006 compared with four major drought periods of the 20th century in Oklahoma: U.S. Geological Survey Scientific Investigations Report 2008–5199, 46 p.

Tortorelli, R.L., 2009, Water Use in Oklahoma 1950-2005: U.S. Geological Survey Scientific Investigations Report 2009-5212 50 p.

Tortorelli, R.L., and Bergman, D.L., 1985, Techniques for estimating flood peak discharges for unregulated streams and streams regulated by small floodwater retarding structures in Oklahoma: U.S. Geological Survey Water Resources Investigations Report 84-4358, 85 p.

Tortorelli, R.L., Rasmussen, T.J., and Perry, C.A., 2005, Trends in annual peak flows and mean annual flows of selected streams within and near Oklahoma: U.S. Geological Survey Scientific Investigations Report 2005-5192, p. 116.

U.S. Geological Survey, 2009, National Streamflow Statistics Program, available only online at *http://water.usgs.gov/osw/programs/nss/index.html*. (Accessed April 15, 2009.)

Wahl, K.L., and Tortorelli, R.L., 1997, Changes in flow in the Beaver-North Canadian River basin upstream from Canton Lake, western Oklahoma: U.S. Geological Survey Water-Resources Investigations Report 96-4304, 58 p.

Wahl, K.L., and Wahl, T.L., 1988, Effects of regional groundwater level declines on streamflow in the Oklahoma Panhandle, *in* Proceedings of the Symposium on Water-Use Data for Water Resources Management: American Water Resources Association, August 1988, Tuscon, Ariz., p. 239–249.

Wahl, K. L., and Wahl, T. L., 1995, Determining the flow of Comal Springs at New Braunfels, Texas: Texas Water ‘95, American Society of Civil Engineers Symposium, August 16-17, 1995, San Antonio, Texas, p. 77-86.

Figures

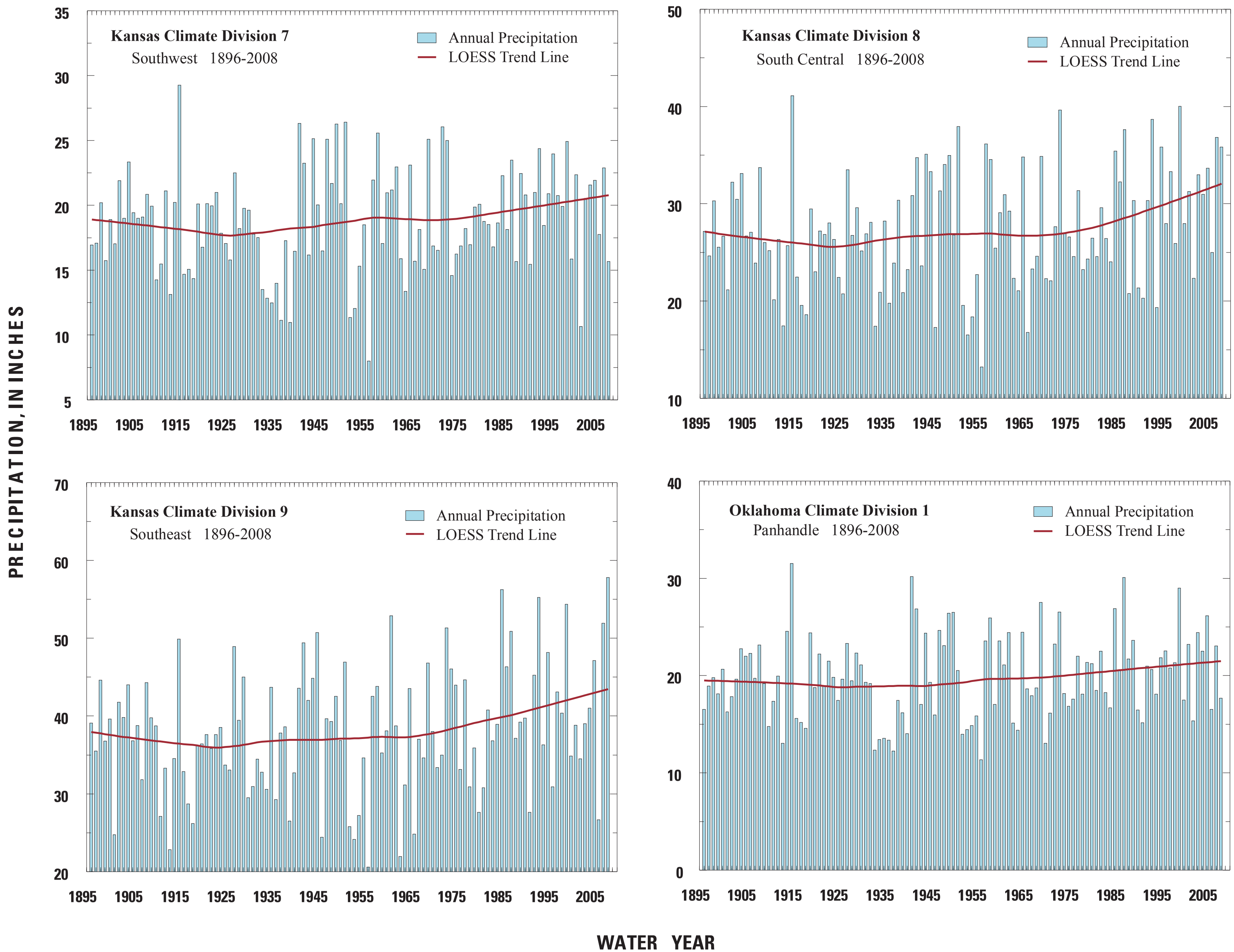

Figure 7. Annual precipitation and LOESS trend lines fro Kansas Climate Divisions 7–9 and Oklahoma Climate Division 1, water years 1896–2008 (National Oceanic and Atmospheric Administration, 2009).

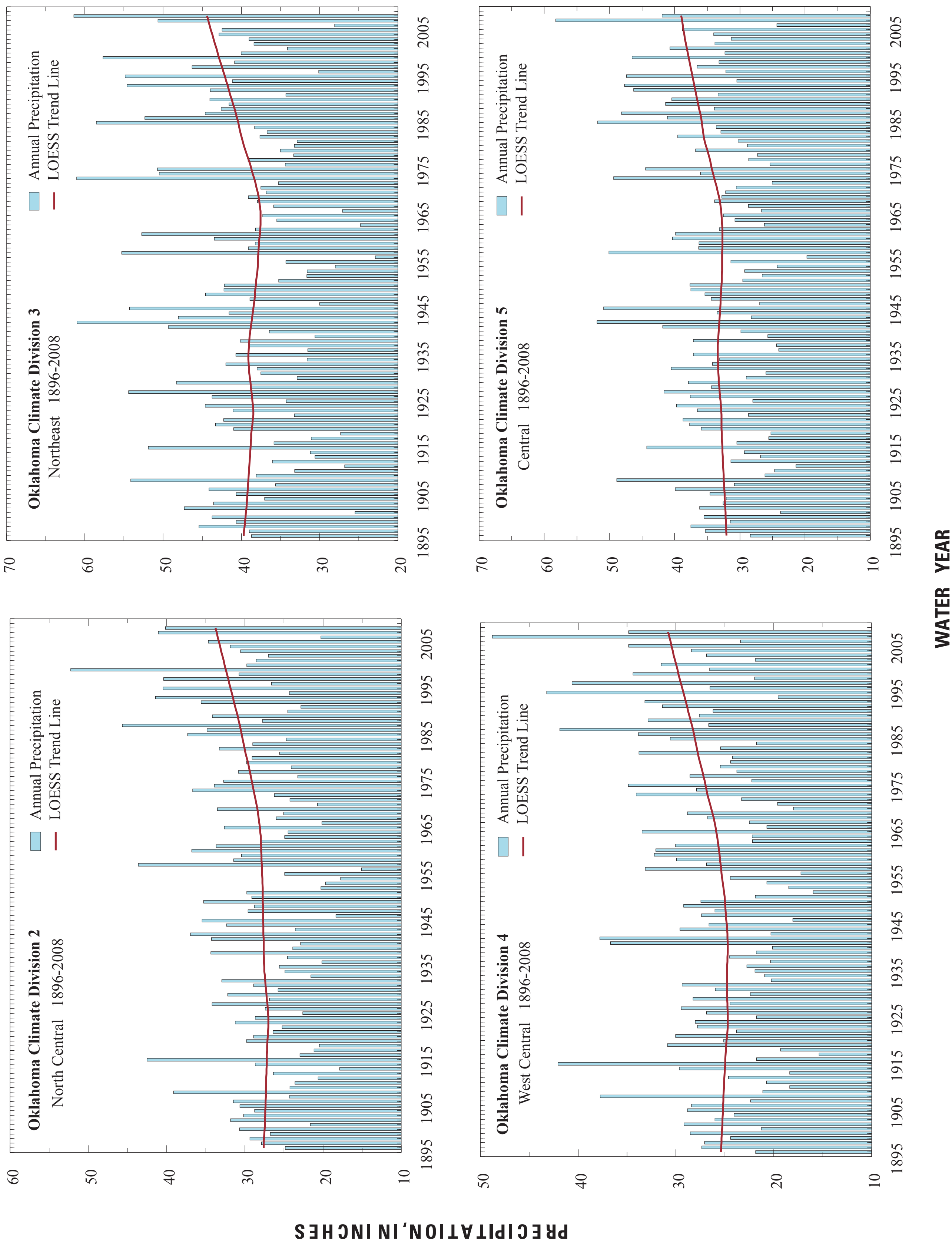

Figure 8. Annual precipitation and LOESS trend lines for Oklahoma Climate Divisions 2–5, water years 1896–2008 (National Oceanic and Atmospheric Administration, 2009).

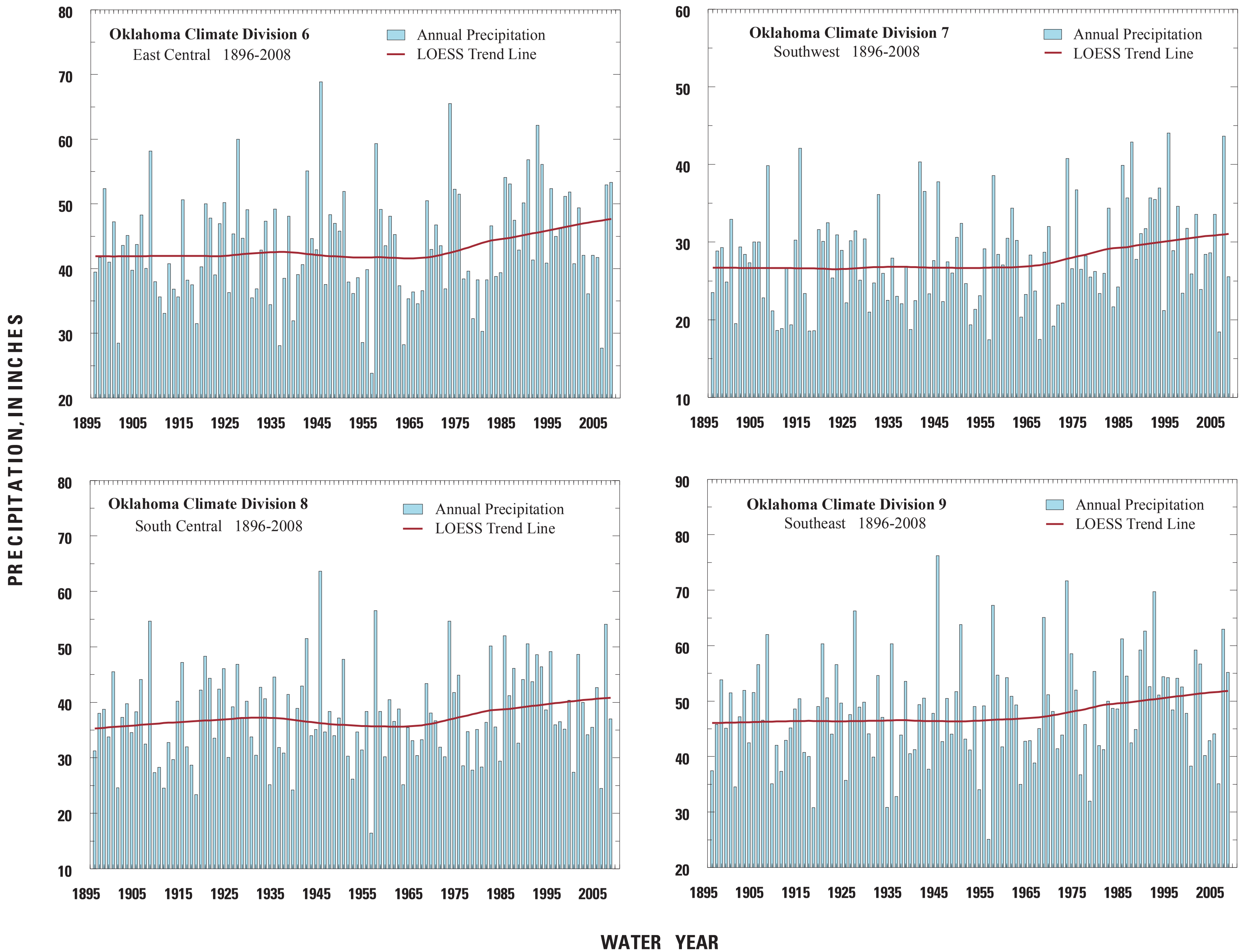

Figure 9. Annual precipitation and LOESS trend lines for Oklahoma Climate Divisions 6–9, water years 1896–2008 (National Oceanic and Atmospheric Administration, 2009).

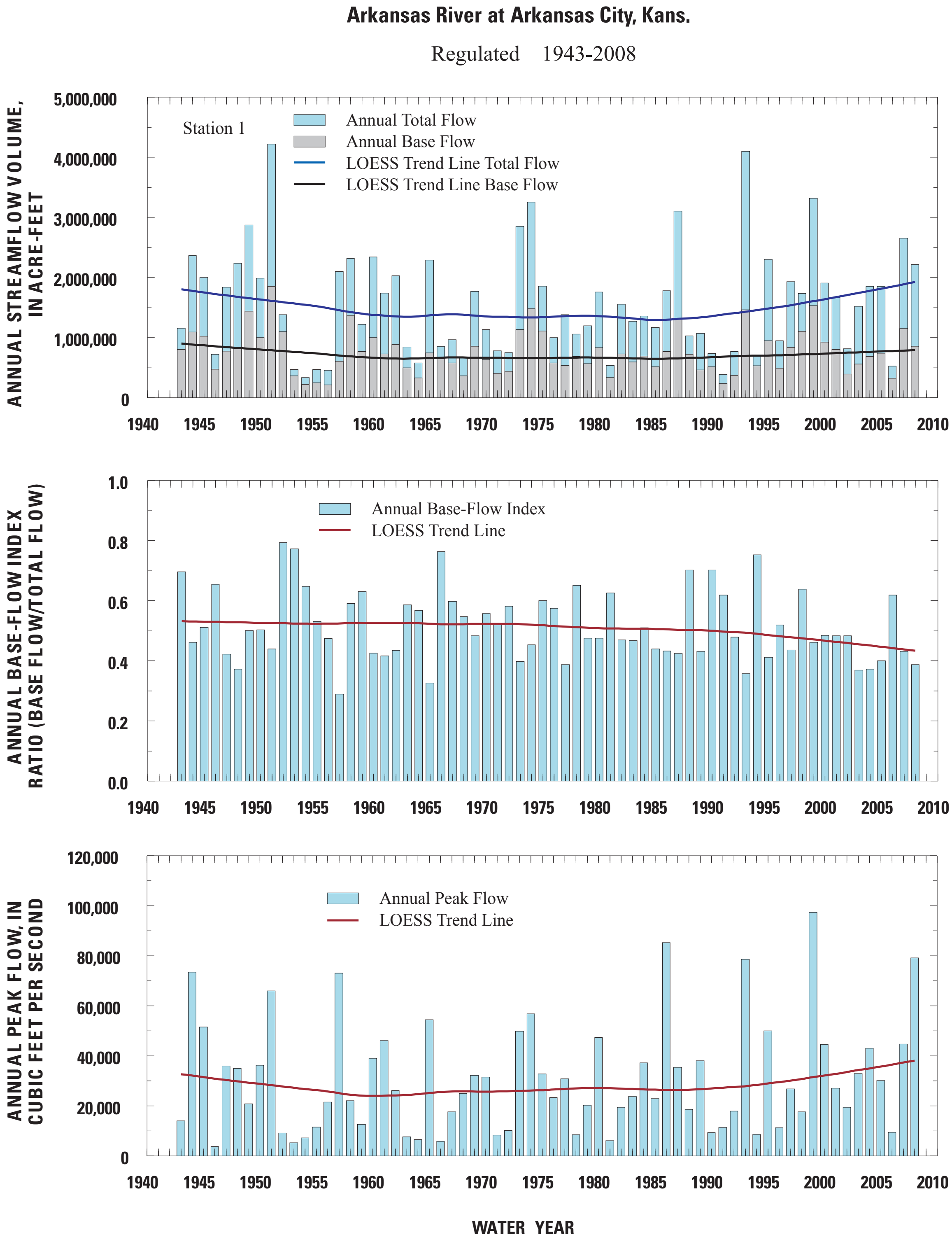

Figure 11. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Arkansas River at Arkansas City, Kansas, (U.S. Geological Survey station identifier 07146500, station 1 from table 1), water years 1943–2008.

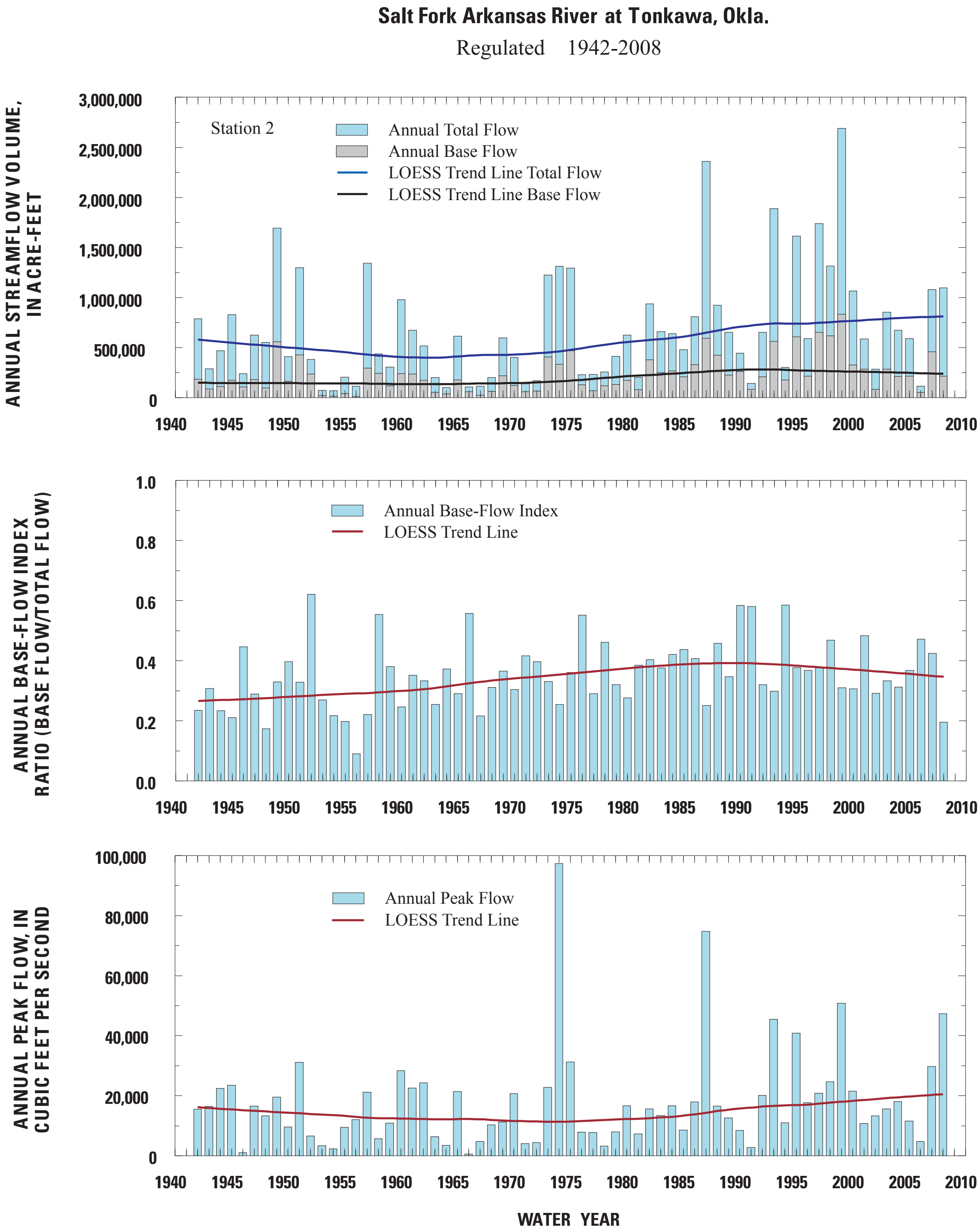

Figure 12. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Salt Fork Arkansas River at Tonkawa, Oklahoma, (U.S. Geological Survey station identifier 07151000, station 2 from table 1), water years 1942–2008.

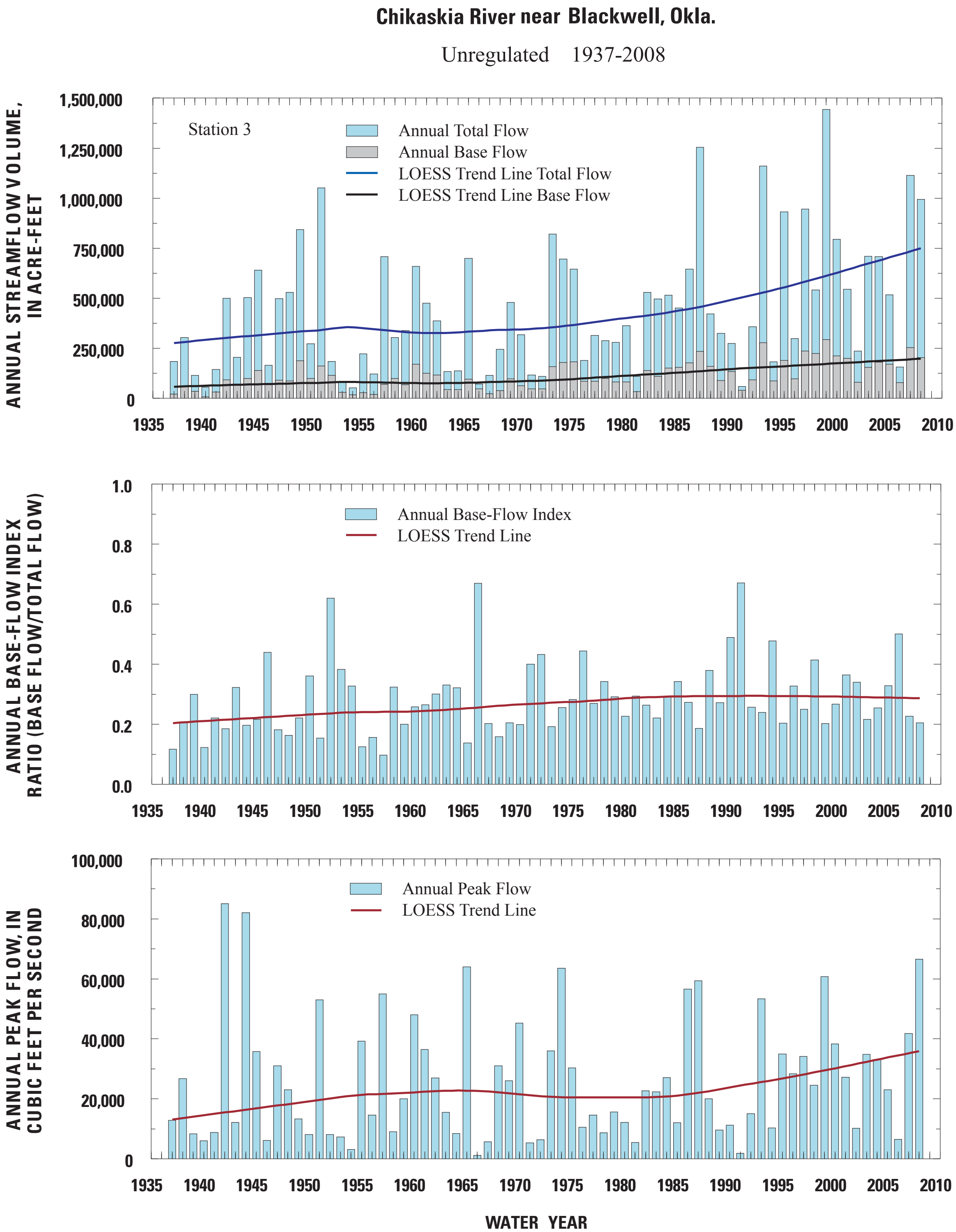

Figure 13. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Chikaskia River near Blackwell, Oklahoma, (U.S. Geological Survey station identifier 07152000, station 3 from table 1), water years 1937–2008.

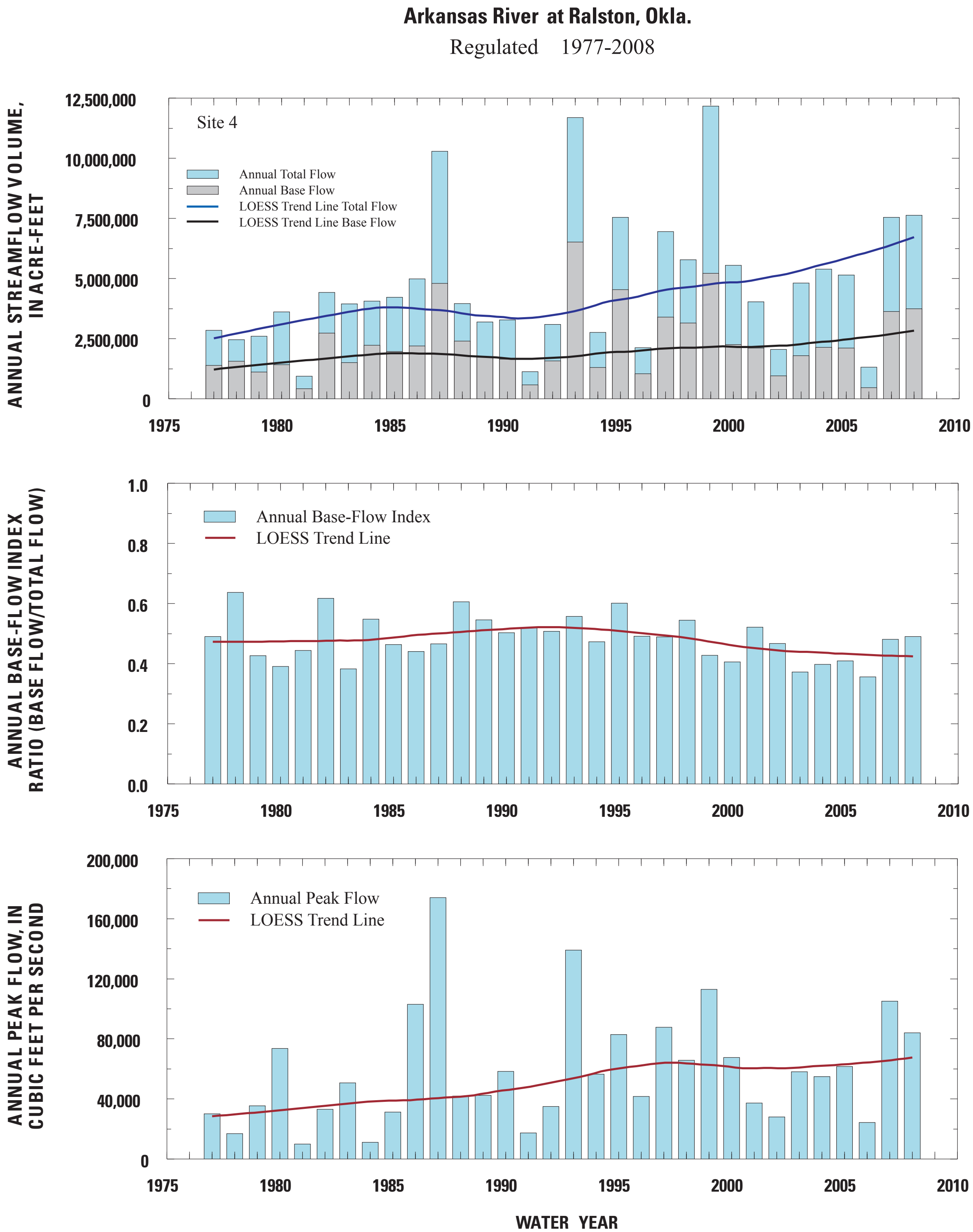

Figure 14. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Arkansas River at Ralston, Oklahoma, (U.S. Geological Survey station identifier 07152500, station 4 from table 1), water years 1977–2008.

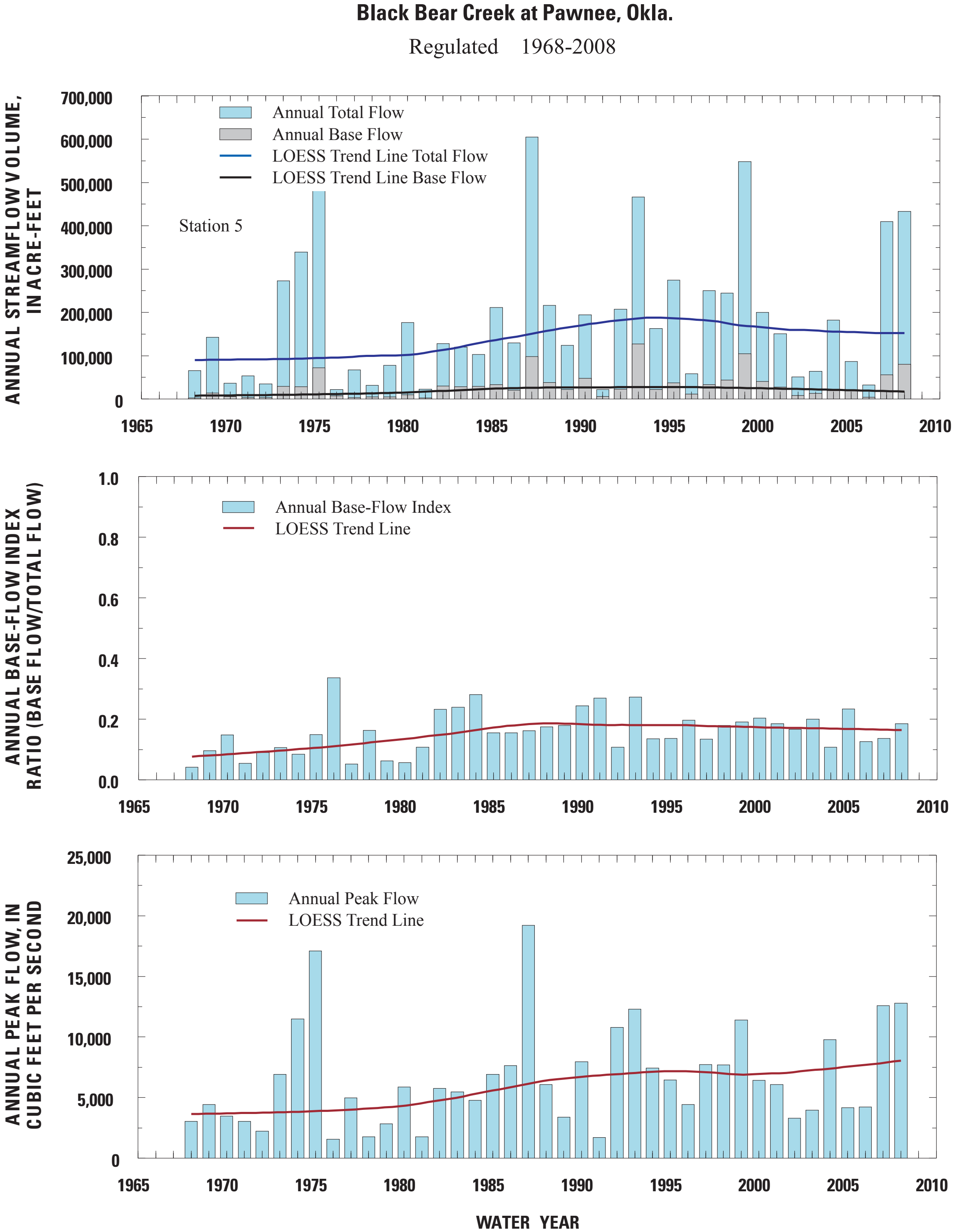

Figure 15. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Black Bear Creek at Pawnee, Oklahoma, (U.S. Geological Survey station identifier 07153000, station 5 from table 1), water years 1968–2008.

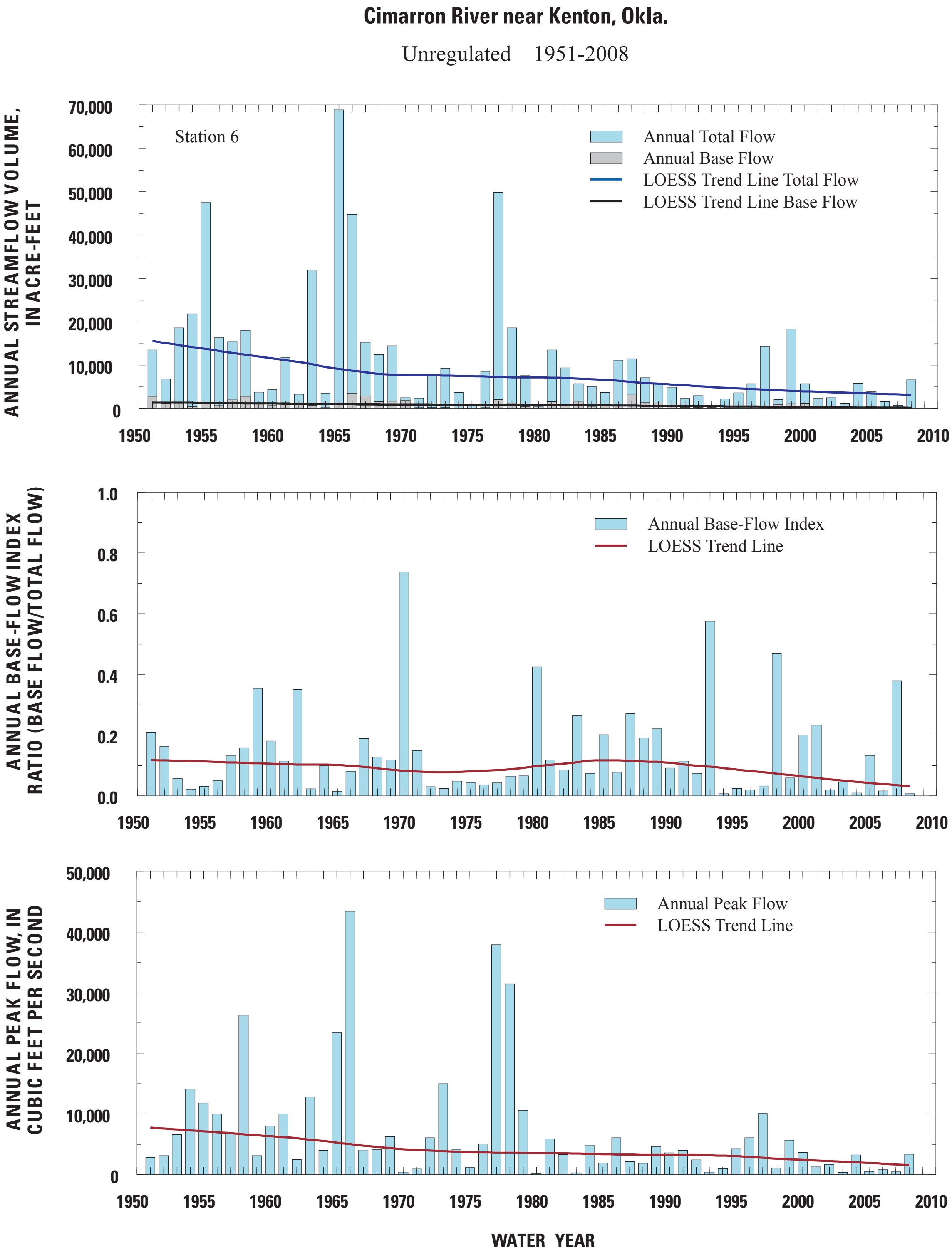

Figure 16. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Cimarron River near Kenton, Oklahoma, (U.S. Geological Survey station identifier 07154500, station 6 from table 1), water years 1951–2008.

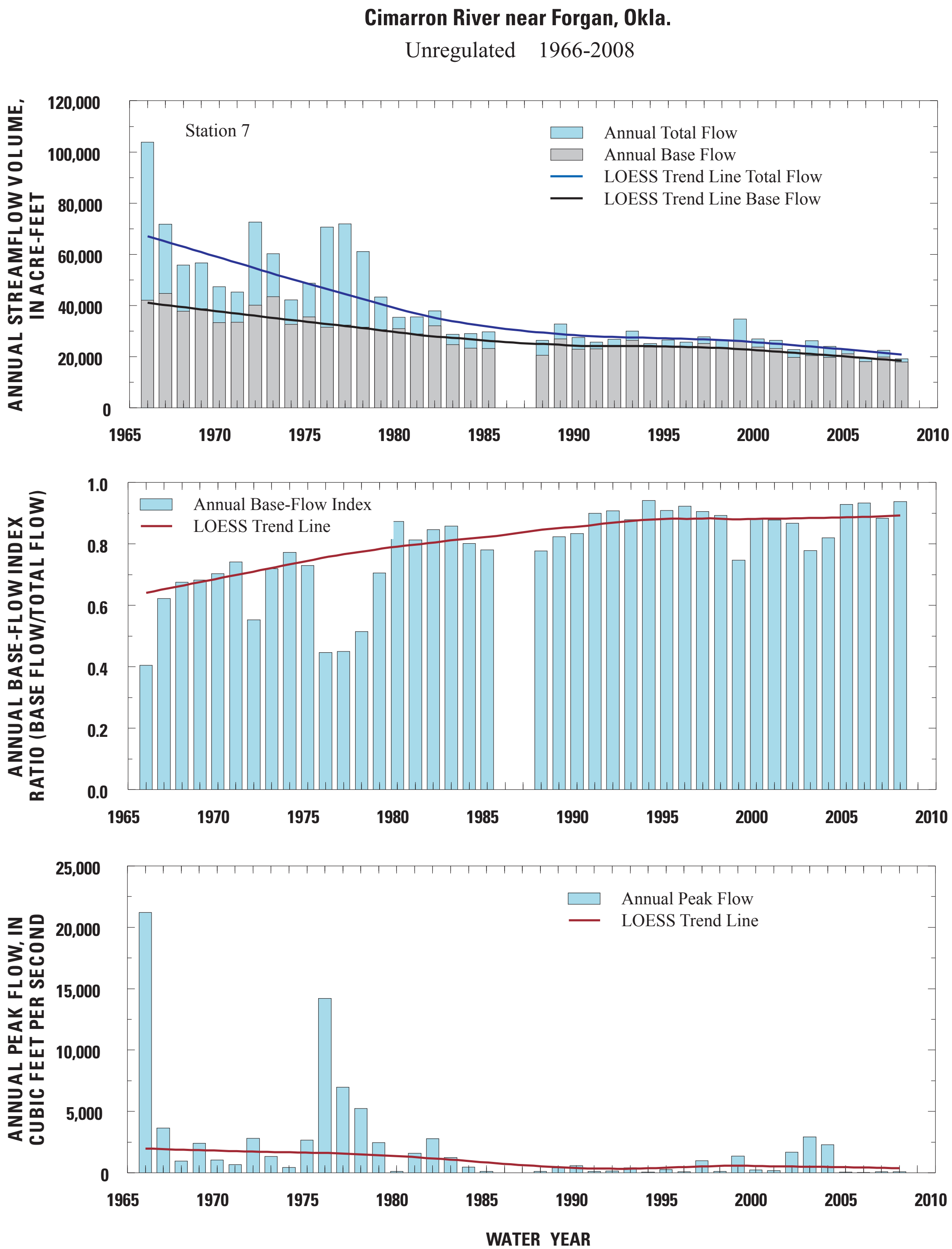

Figure 17. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Cimarron River near Forgan, Oklahoma, (U.S. Geological Survey station identifier 07156900, station 7 from table 1), water years 1966–2008.

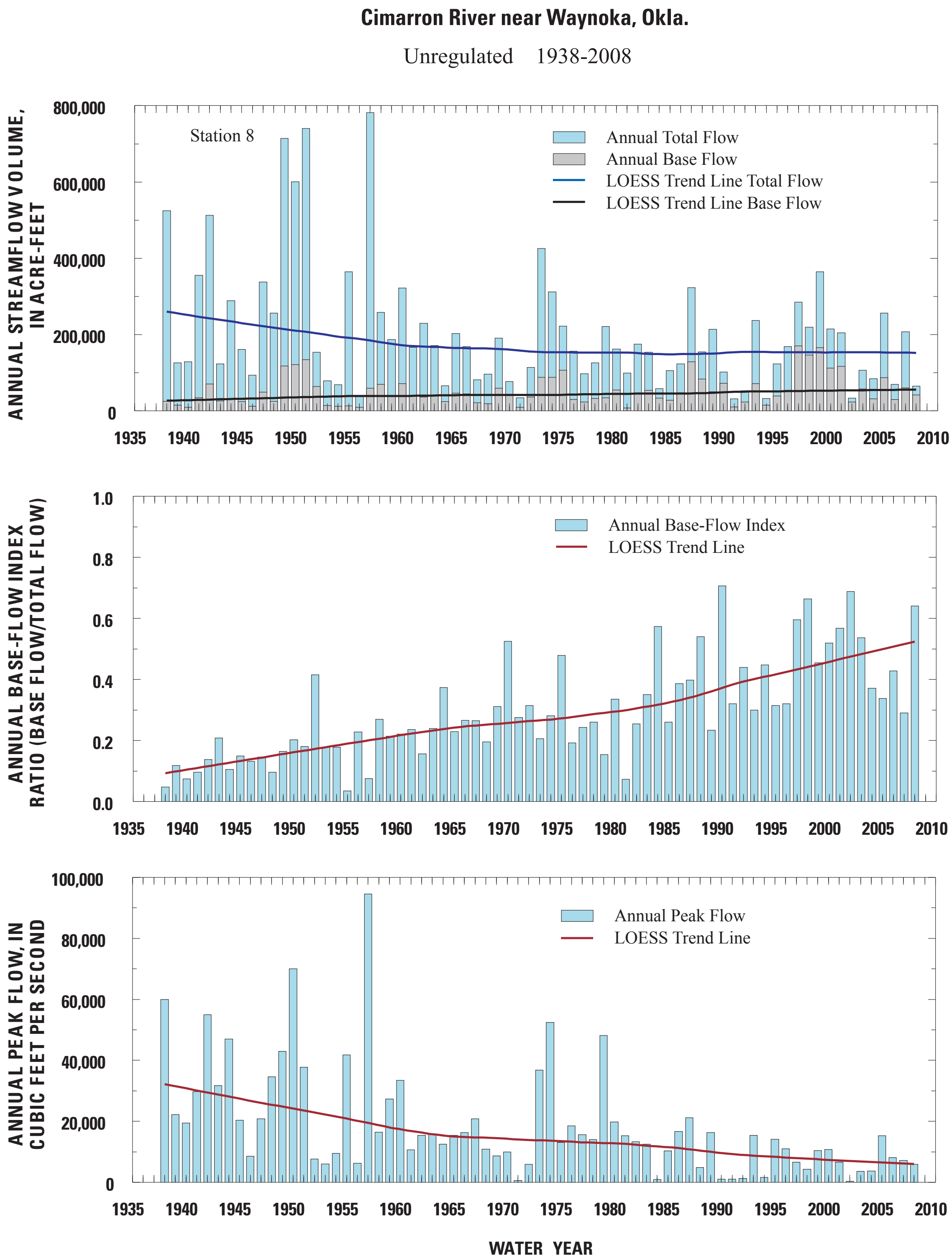

Figure 18. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Cimarron River near Waynoka, Oklahoma, (U.S. Geological Survey station identifier 07158000, station 8 from table 1), water years 1938–2008.

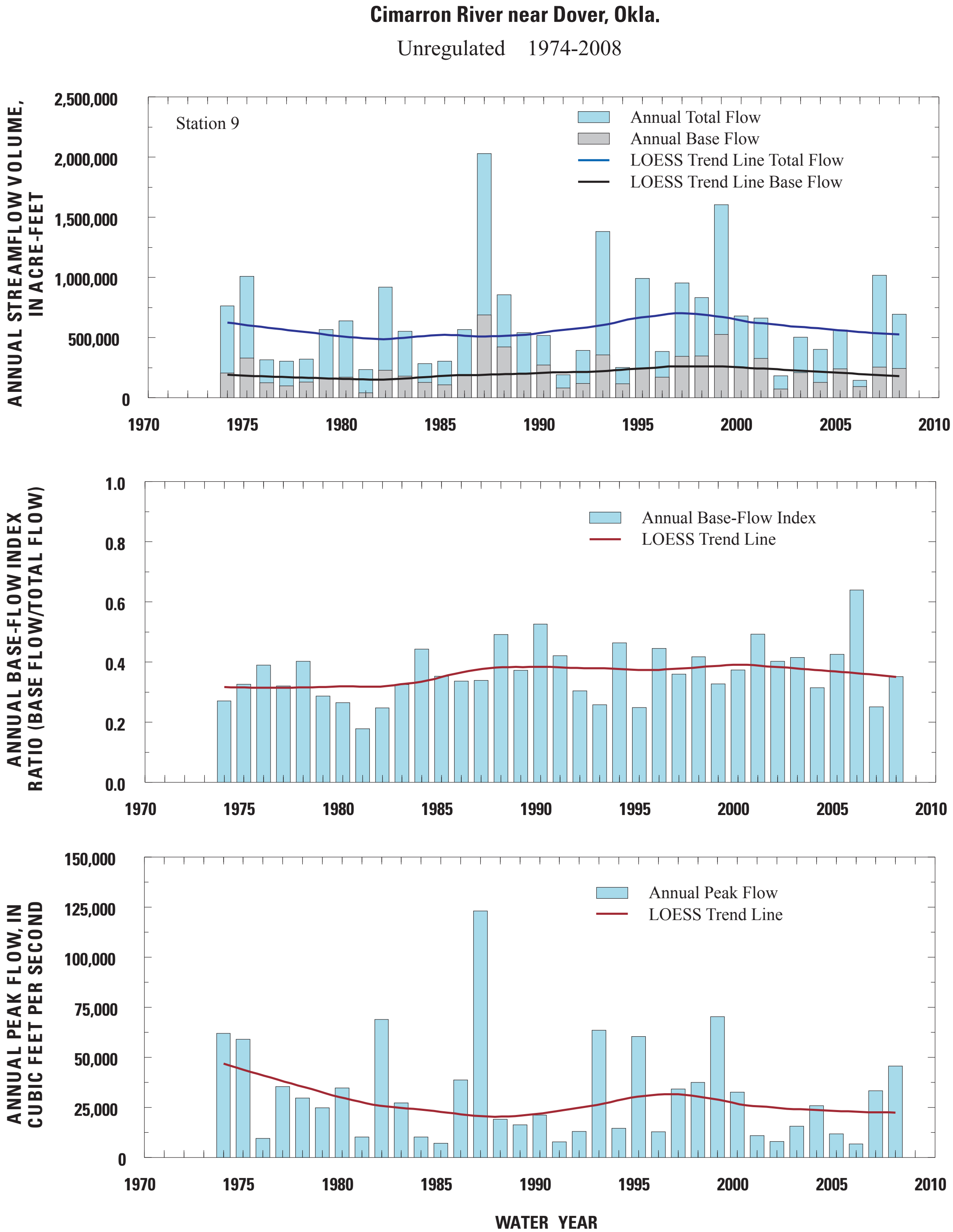

Figure 19. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Cimarron River near Dover, Oklahoma, (U.S. Geological Survey station identifier 07159100, station 9 from table 1), water years 1974–2008.

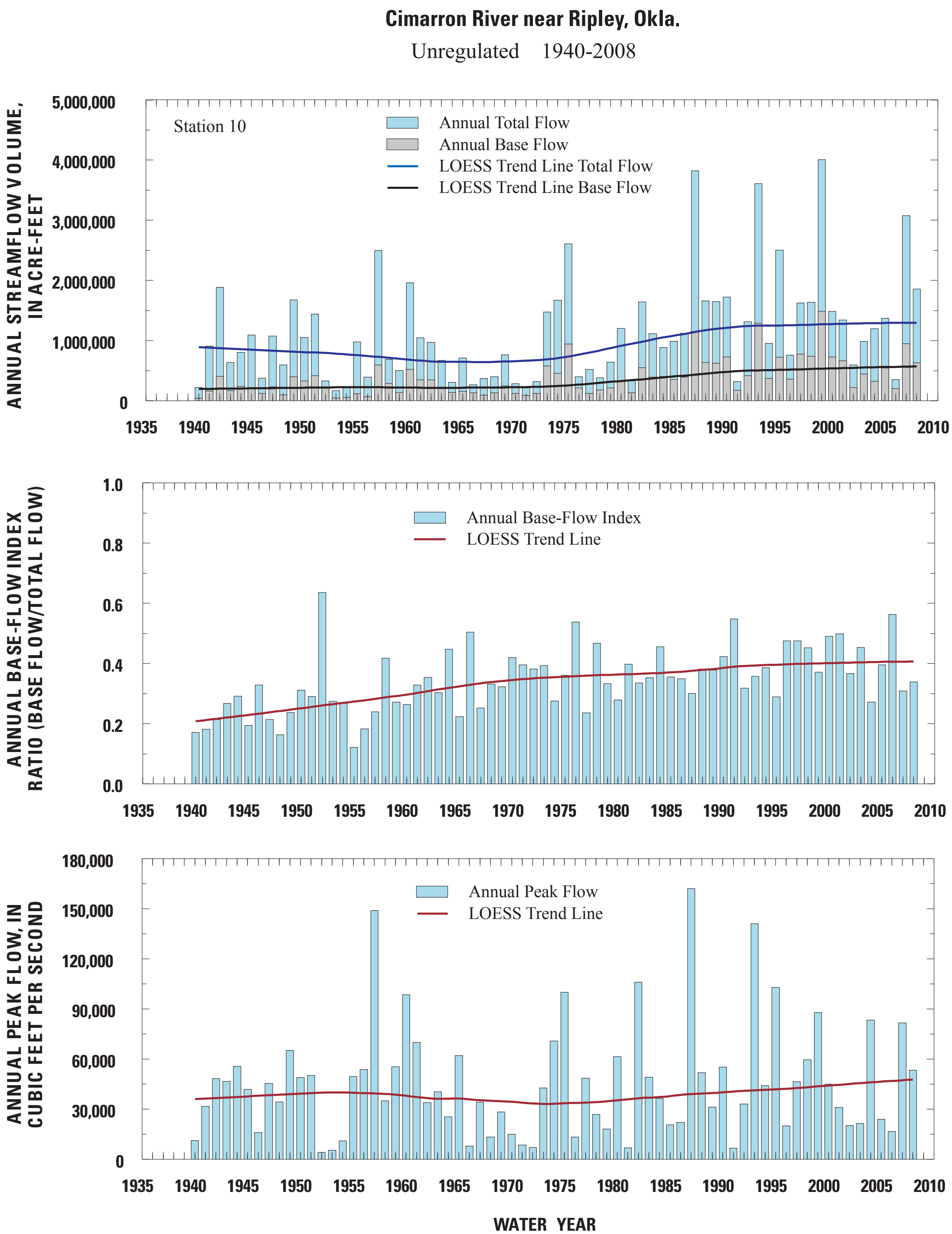

Figure 20. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Cimarron River near Ripley, Oklahoma, (U.S. Geological Survey station identifier 07161450, station 10 from table 1), water years 1940–2008.

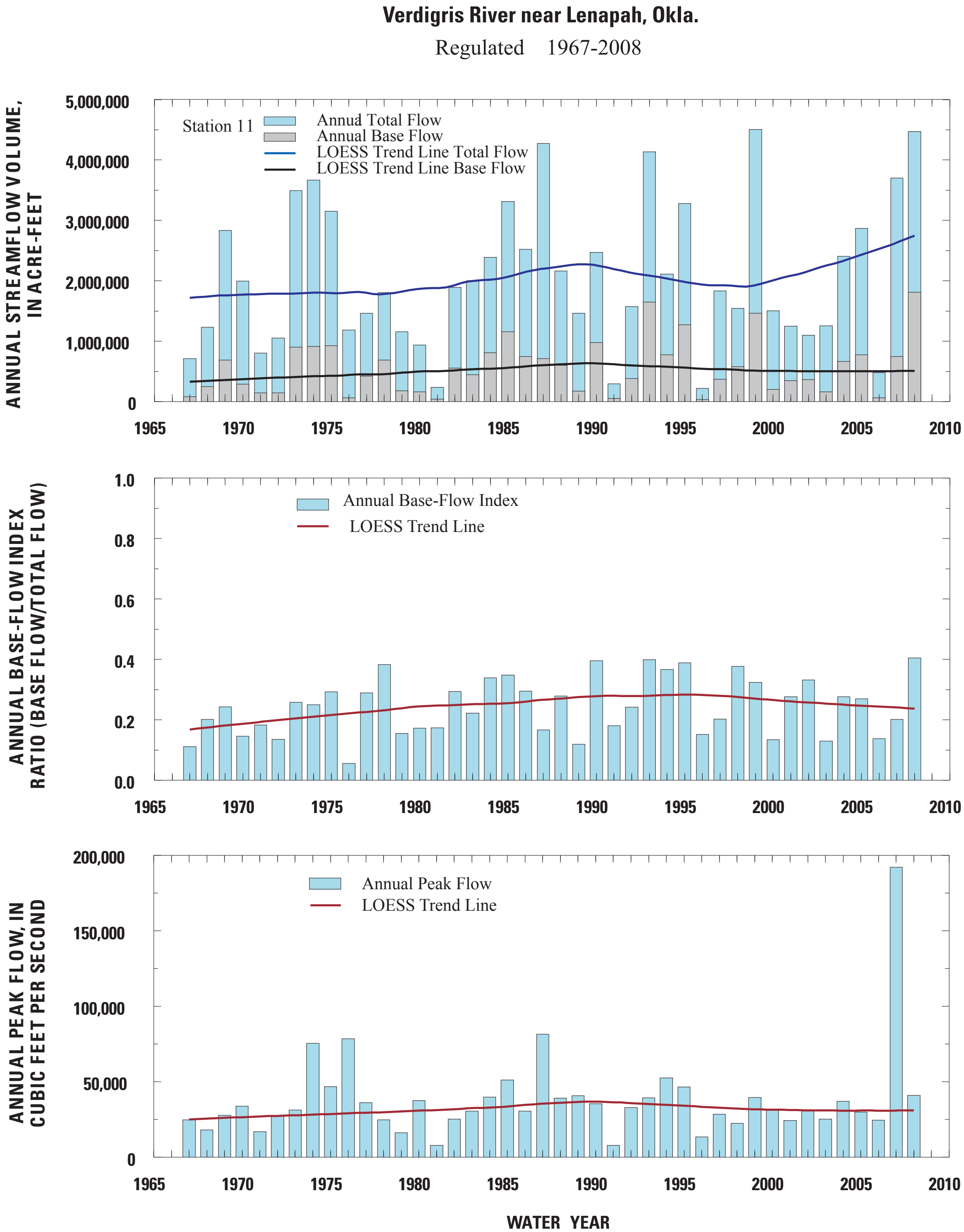

Figure 21. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Verdigris River near Lenapah, Oklahoma, (U.S. Geological Survey station identifier 07171000, station 11 from table 1), water years 1967–2008.

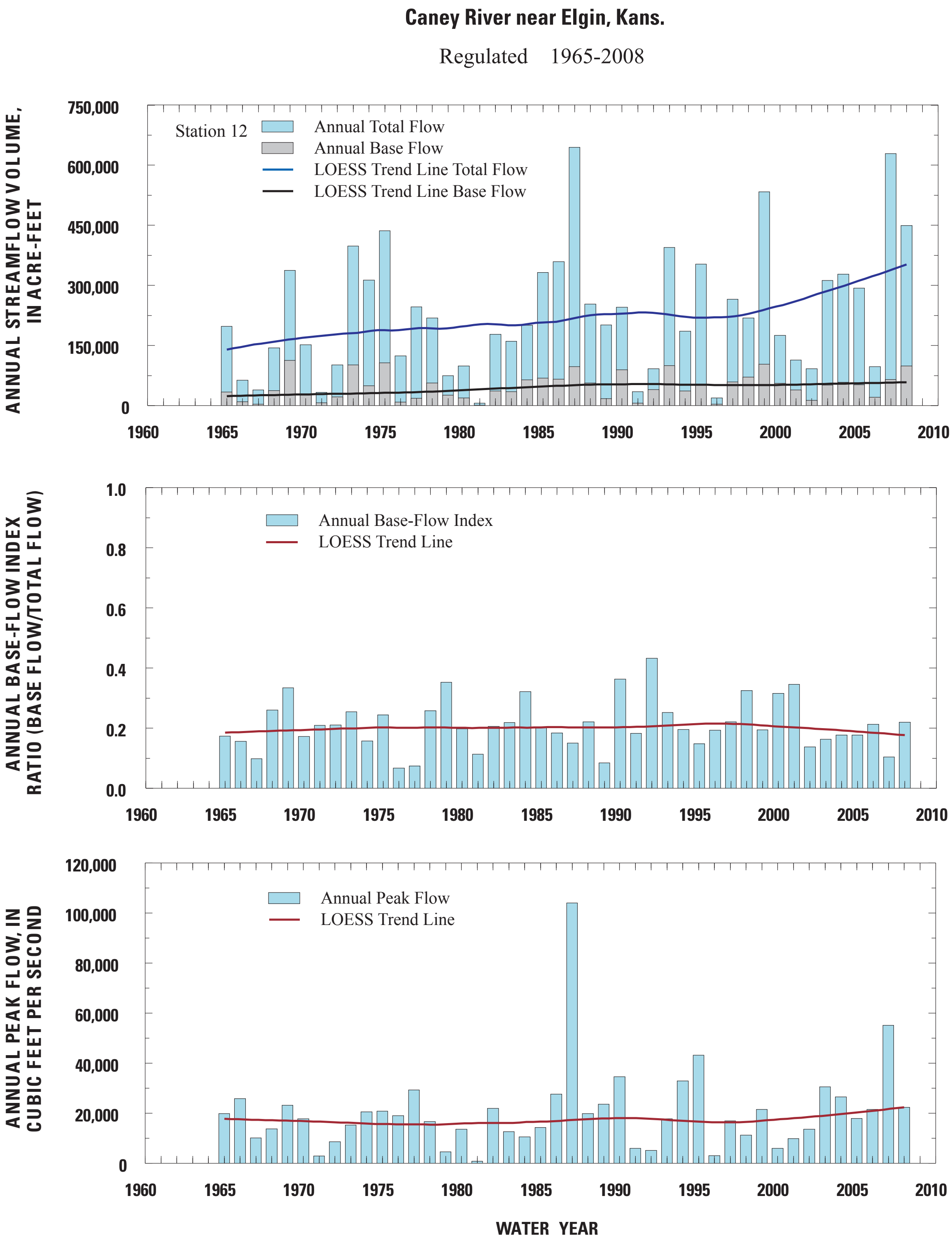

Figure 22. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Caney River near Elgin, Oklahoma, (U.S. Geological Survey station identifier 07172000, station 12 from table 1), water years 1965–2008.

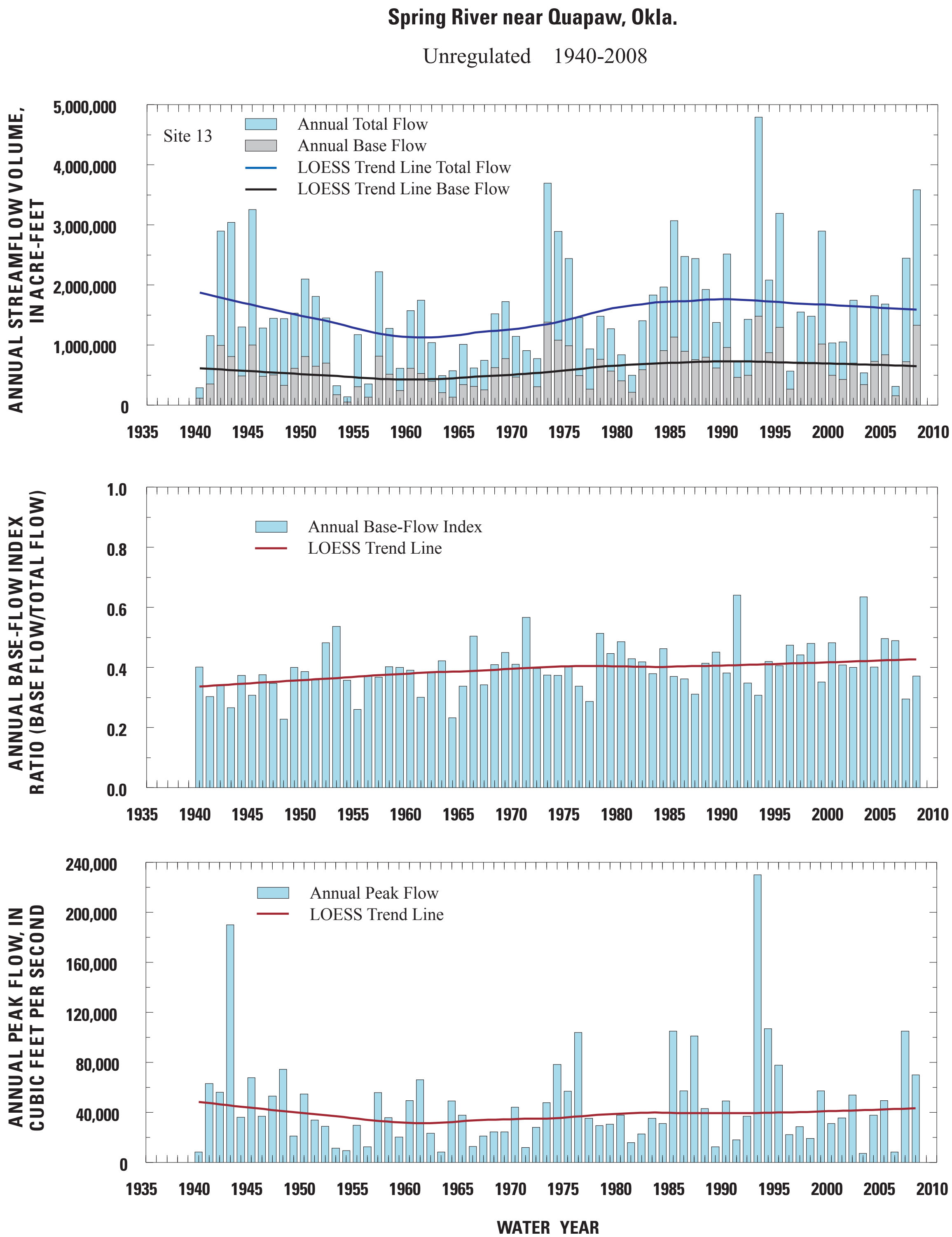

Figure 23. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Spring River near Quapaw, Oklahoma, (U.S. Geological Survey station identifier 07188000, station 13 from table 1), water years 1940–2008.

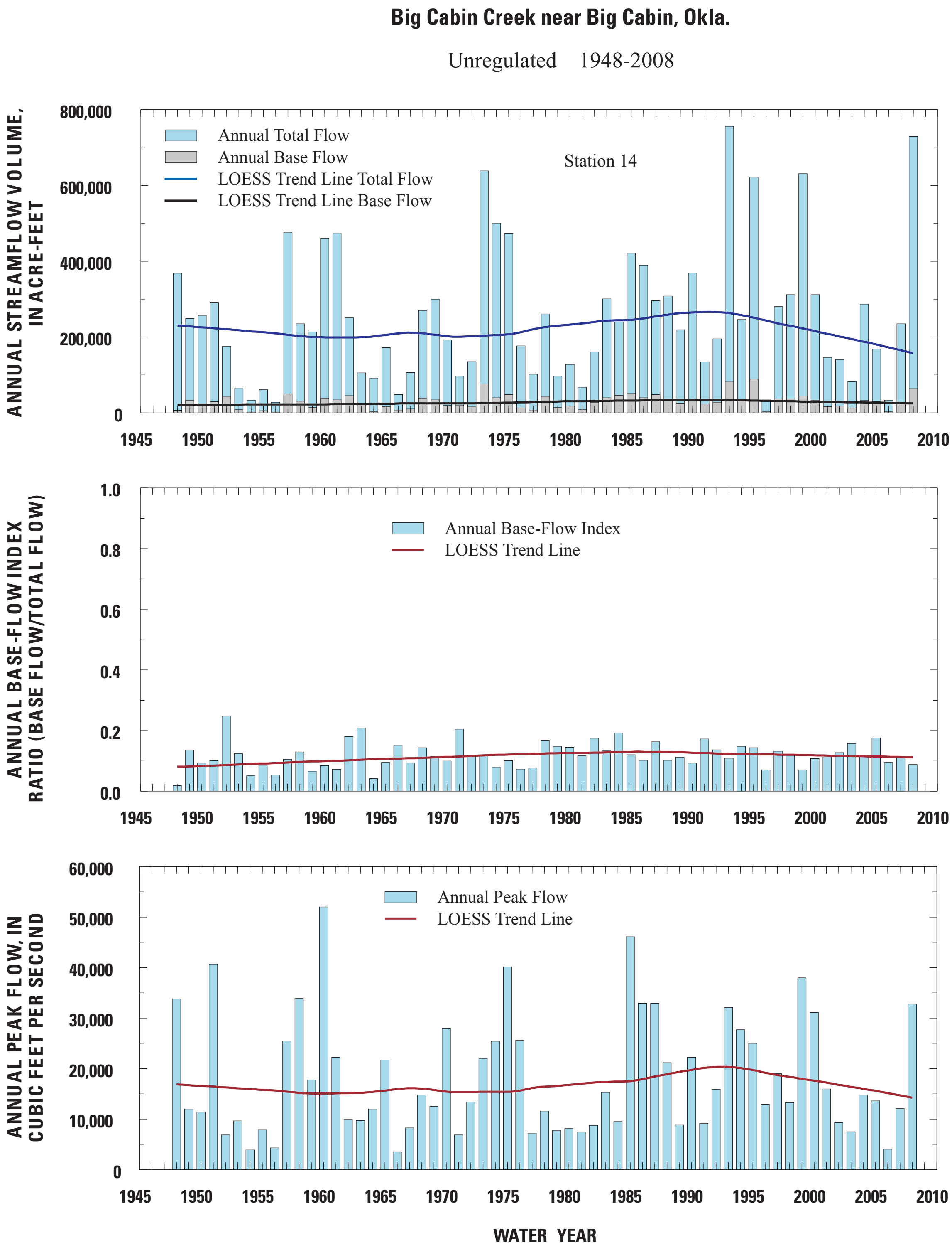

Figure 24. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Big Cabin Creek near Big Cabin, Oklahoma, (U.S. Geological Survey station identifier 07191000, station 14 from table 1), water years 1948–2008.

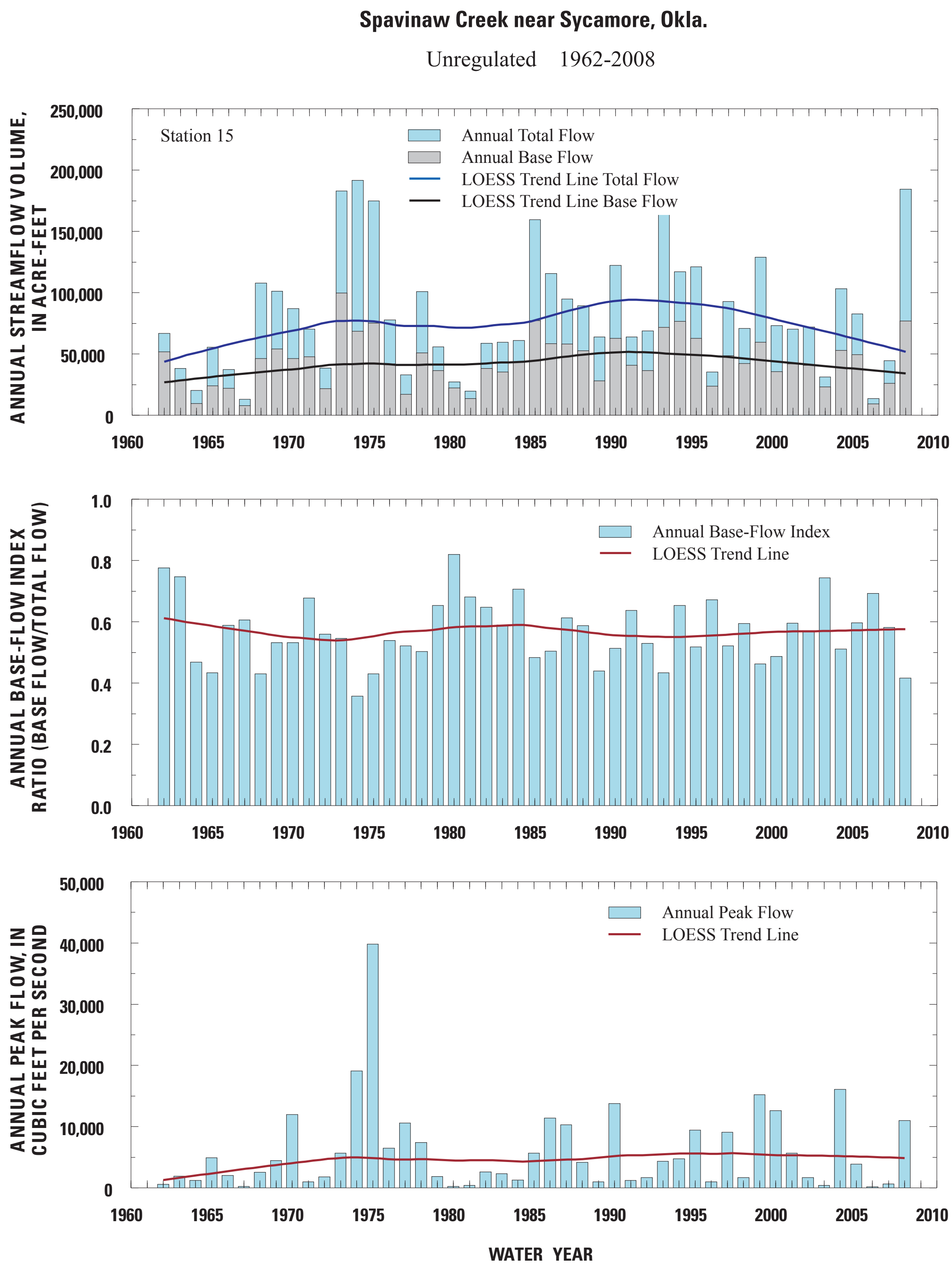

Figure 25. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Spavinaw Creek near Sycamore, Oklahoma, (U.S. Geological Survey station identifier 07191220, station 15 from table 1), water years 1962–2008.

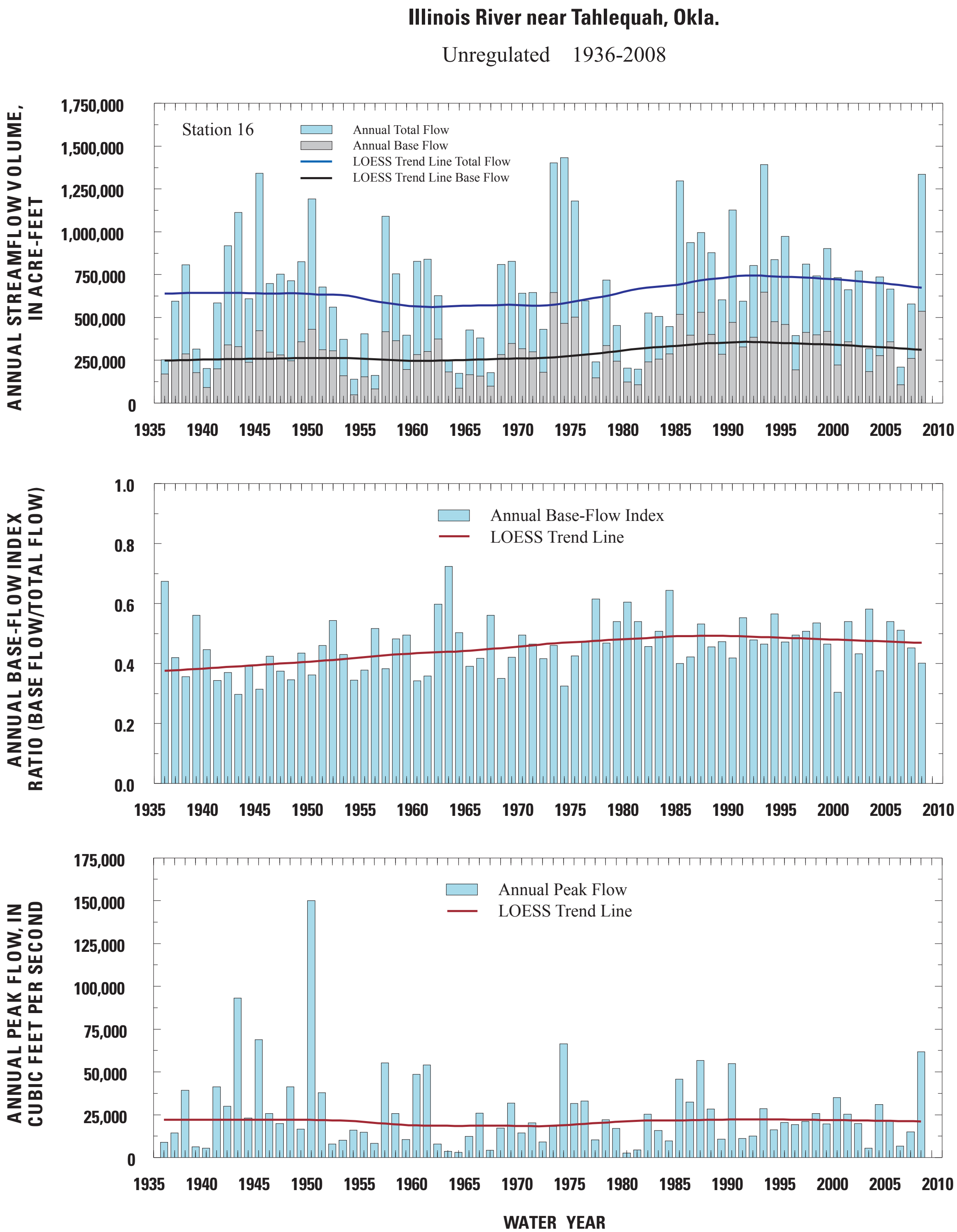

Figure 26. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Illinois River near Tahlequah, Oklahoma, (U.S. Geological Survey station identifier 07196500, station 16 from table 1), water years 1936–2008.

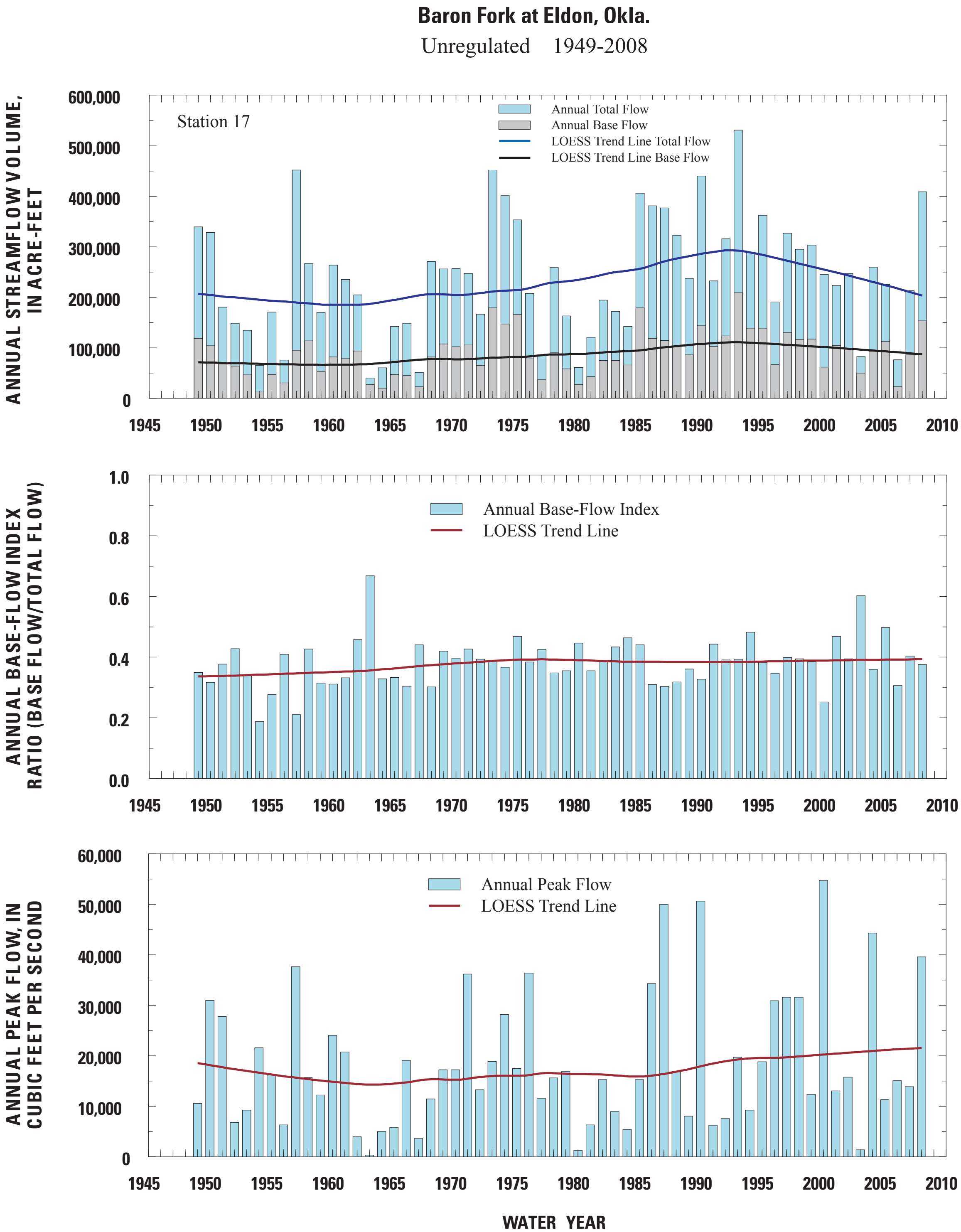

Figure 27. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Baron Fork at Eldon, Oklahoma, (U.S. Geological Survey station identifier 07197000, station 17 from table 1), water years 1949–2008.

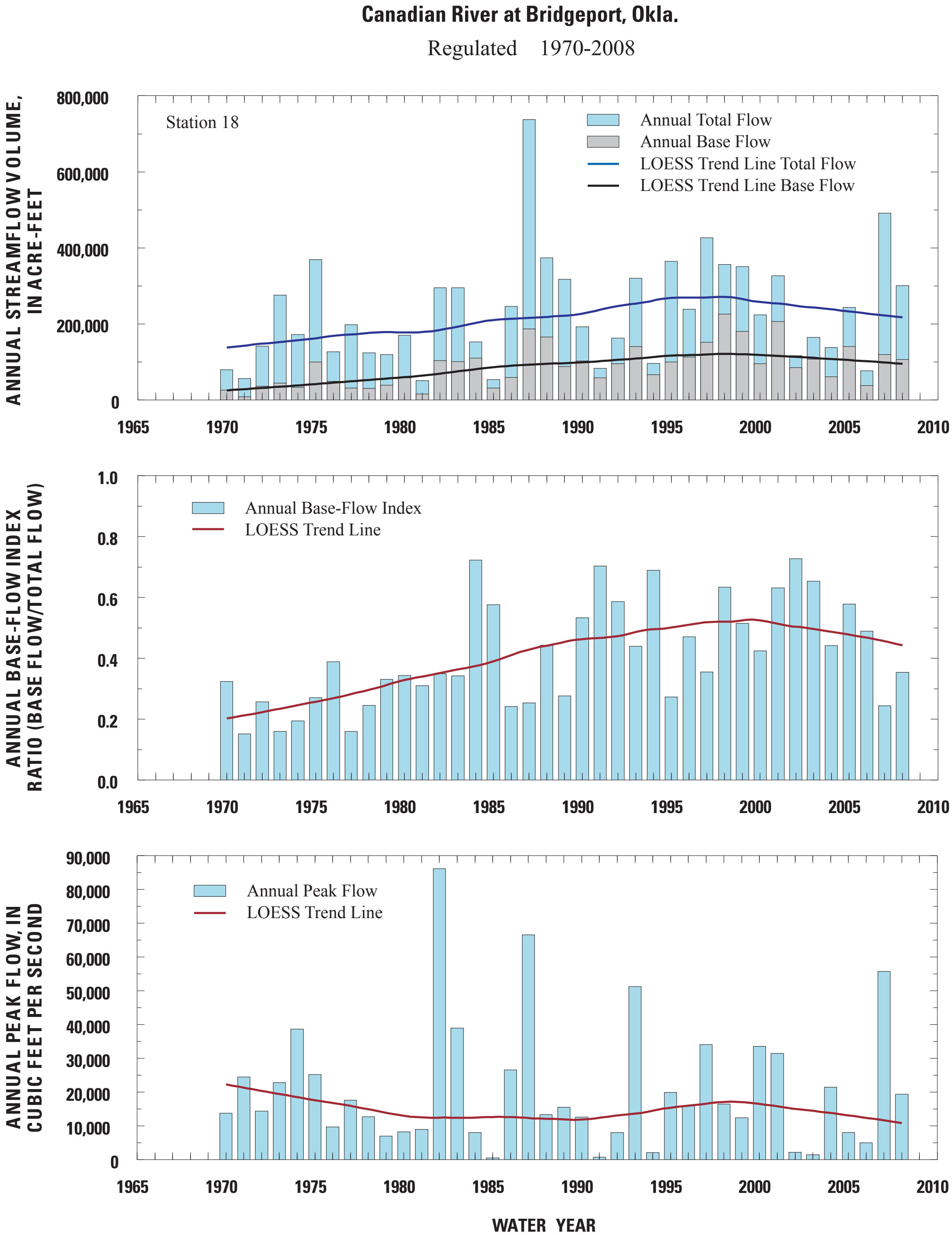

Figure 28. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Canadian River at Bridgeport, Oklahoma, (U.S. Geological Survey station identifier 07228500, station 18 from table 1), water years 1970–2008.

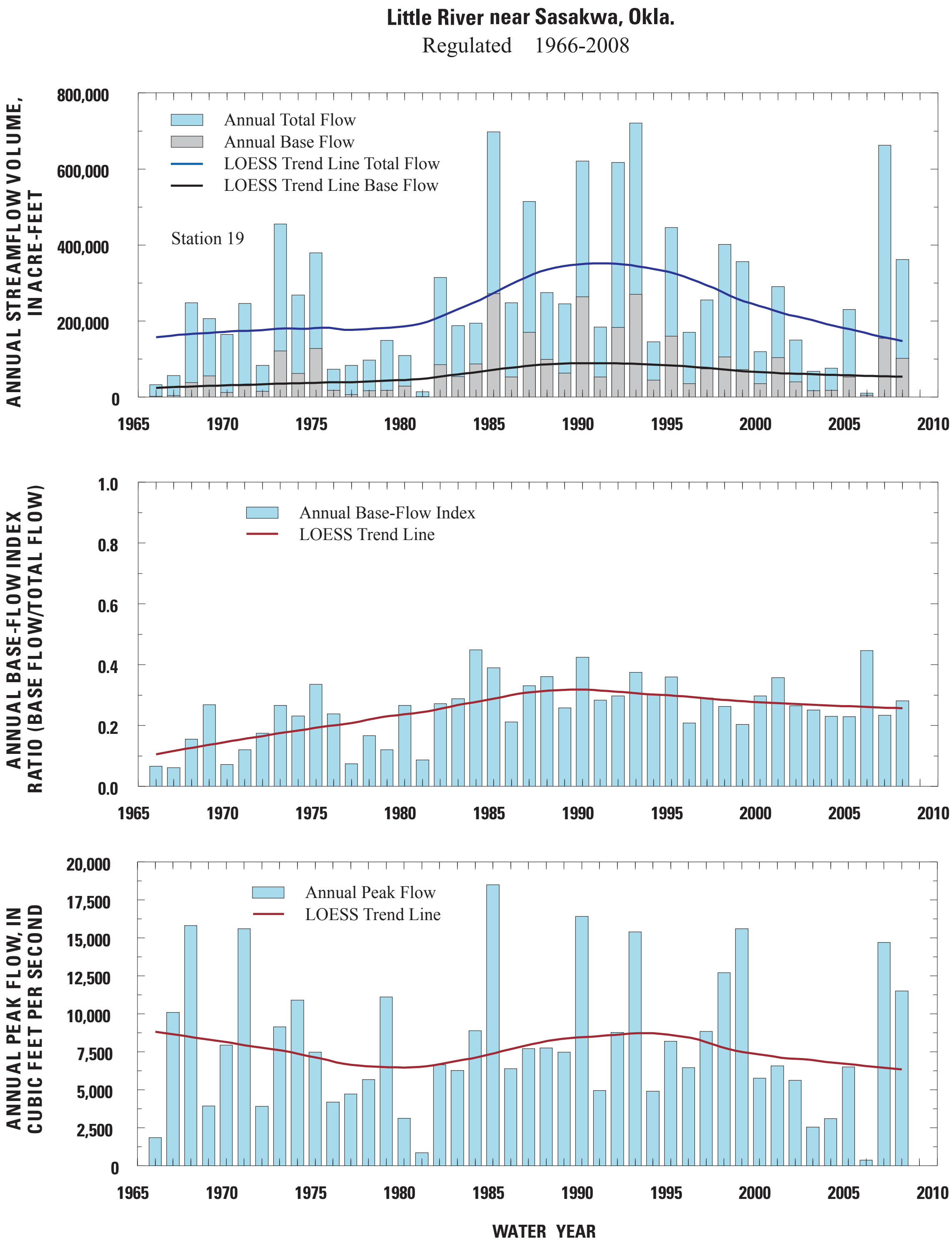

Figure 29. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Little River near Sasakwa, Oklahoma, (U.S. Geological Survey station identifier 07231000, station 19 from table 1), water years 1966–2008.

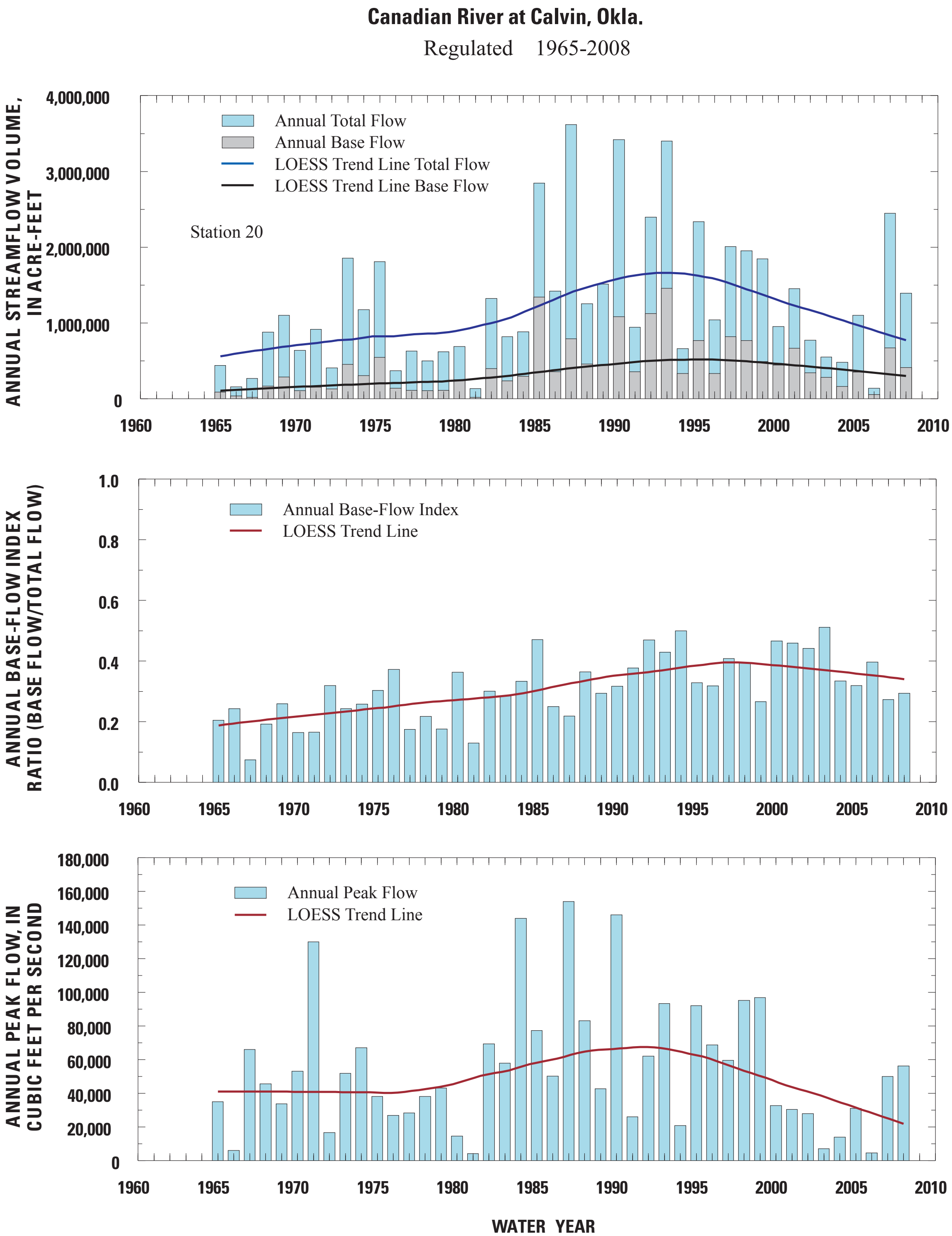

Figure 30. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Canadian River at Calvin, Oklahoma, (U.S. Geological Survey station identifier 07231500, station 20 from table 1), water years 1965–2008.

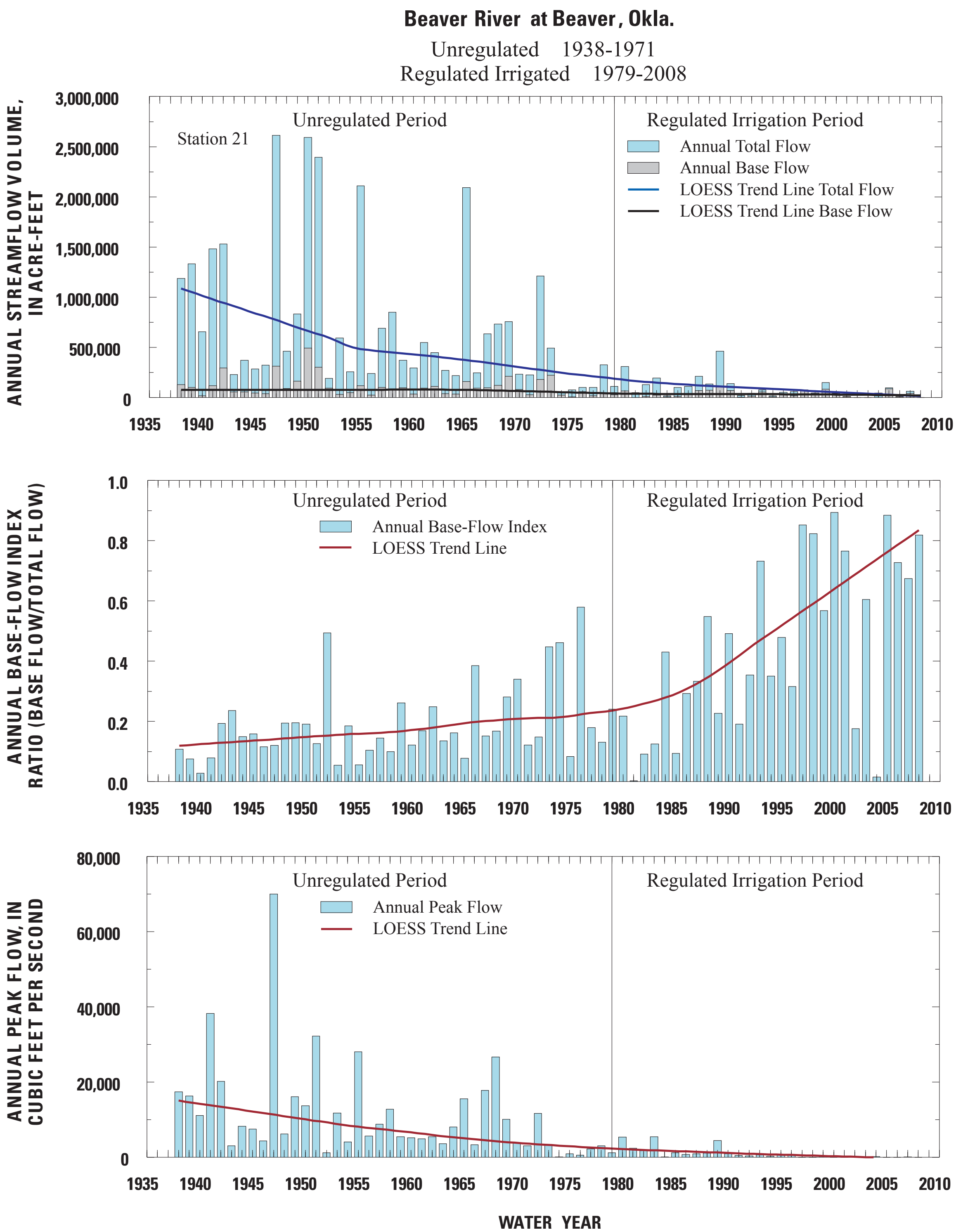

Figure 31. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Beaver River at Beaver, Oklahoma, (U.S. Geological Survey station identifier 07234000, station 21 from table 1), water years 1938–2008.

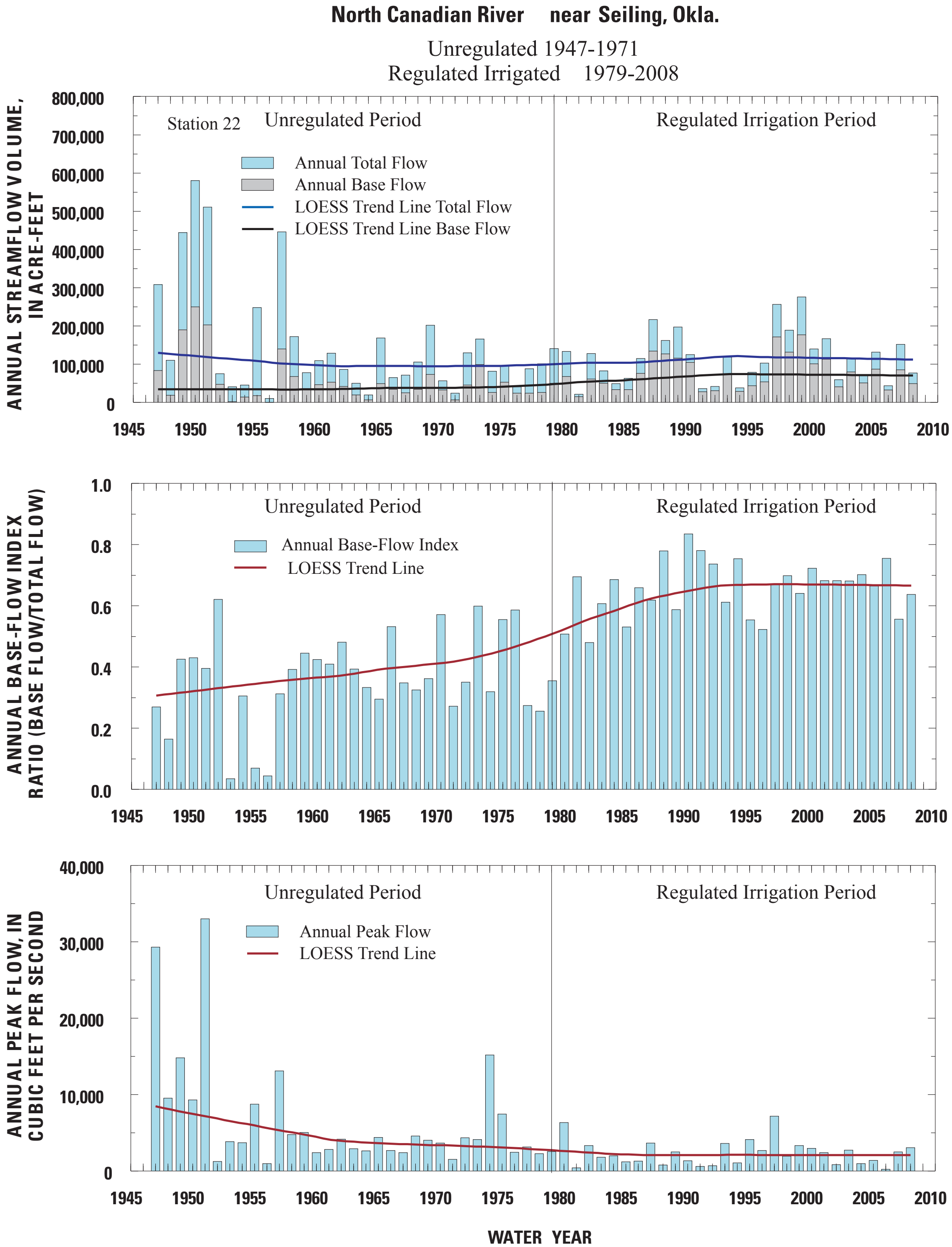

Figure 32. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for North Canadian River at Sailing, Oklahoma, (U.S. Geological Survey station identifier 07238000, station 22 from table 1), water years 1947–2008.

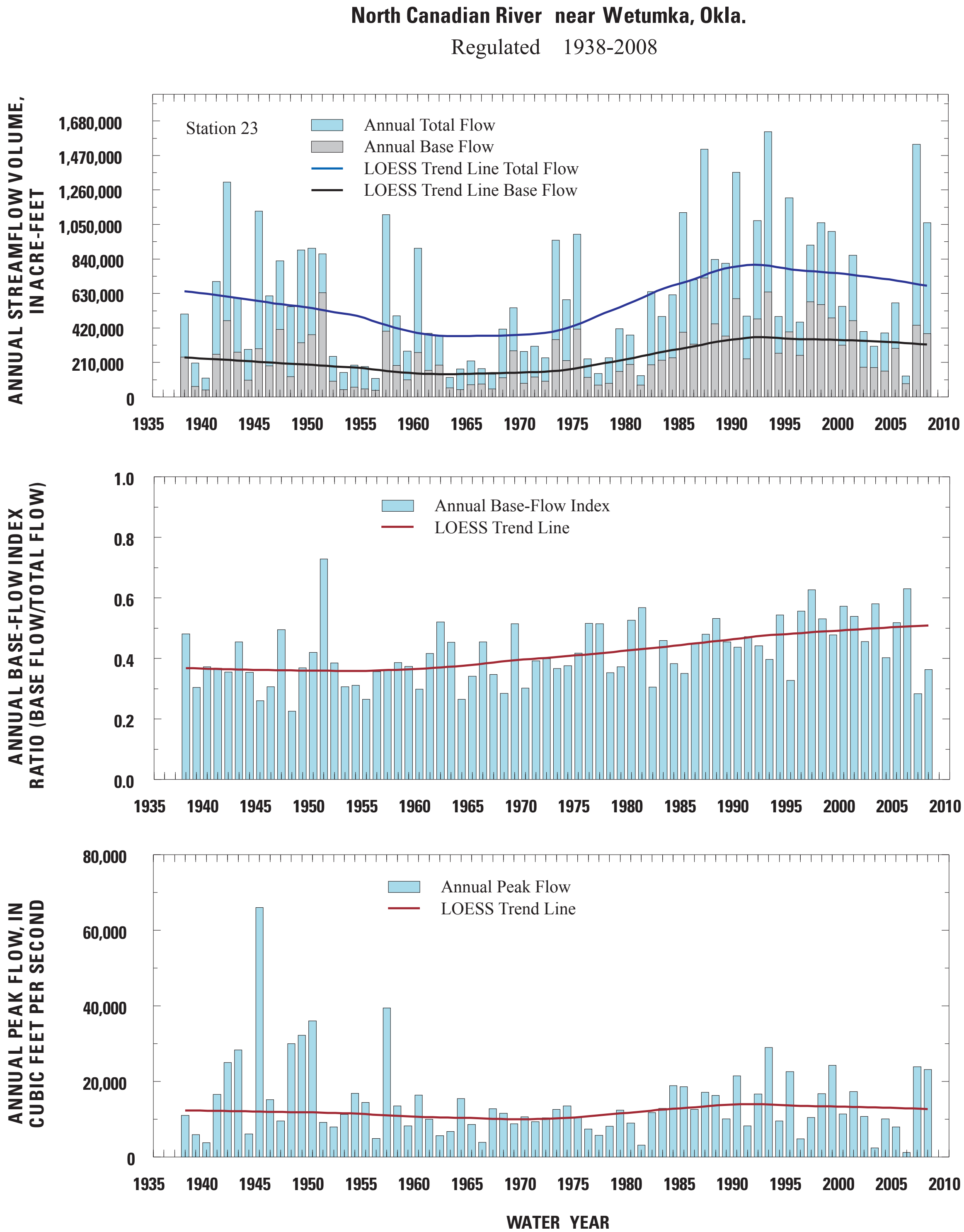

Figure 33. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for North Canadian River near Wetumka, Oklahoma, (U.S. Geological Survey station identifier 07242000, station 23 from table 1), water years 1938–2008.

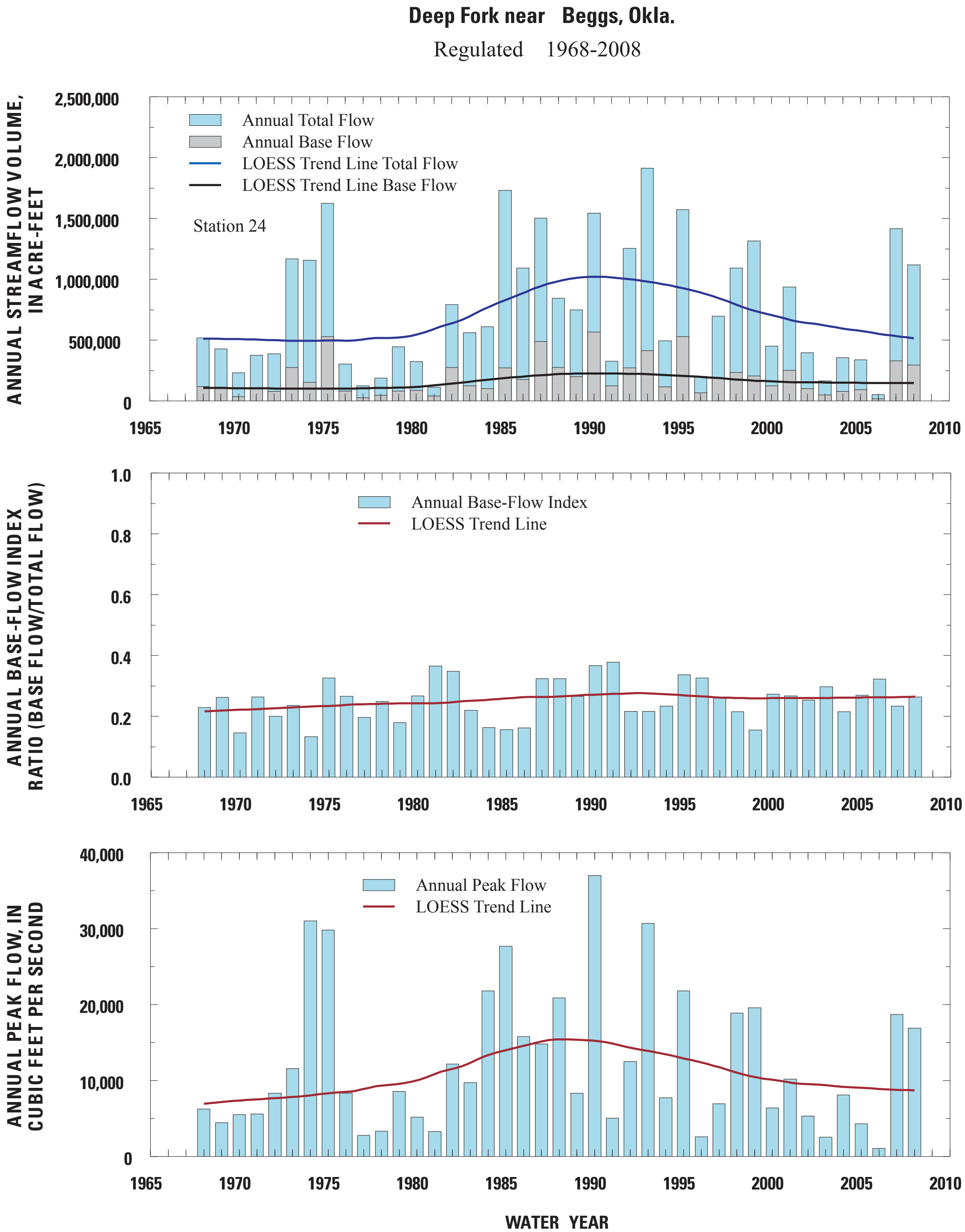

Figure 34. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Deep Fork near Beggs, Oklahoma, (U.S. Geological Survey station identifier 07243500, station 24 from table 1), water years 1968–2008.

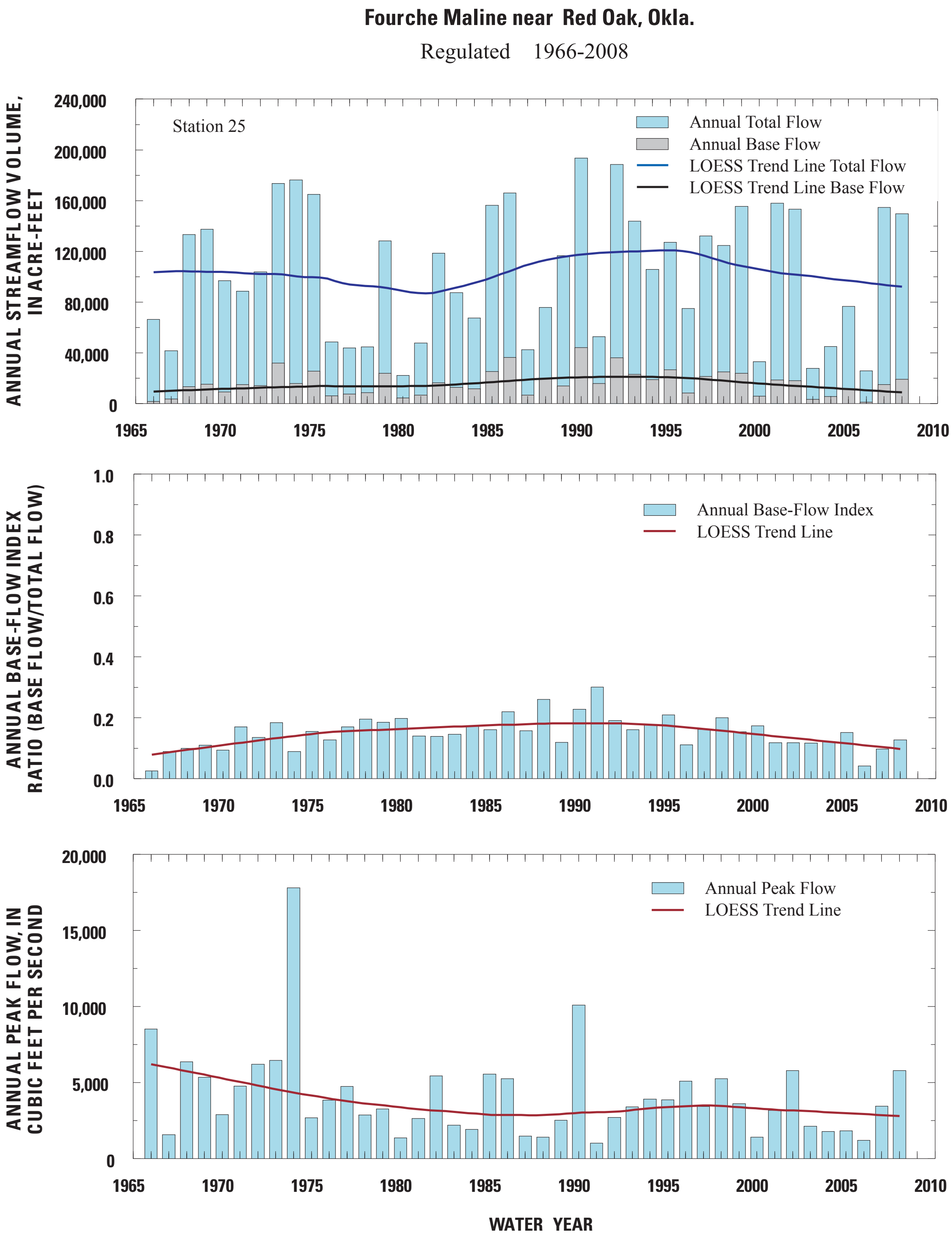

Figure 35. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Fourche Maline near Red Oak, Oklahoma, (U.S. Geological Survey station identifier 07247500, station 25 from table 1), water years 1966–2008.

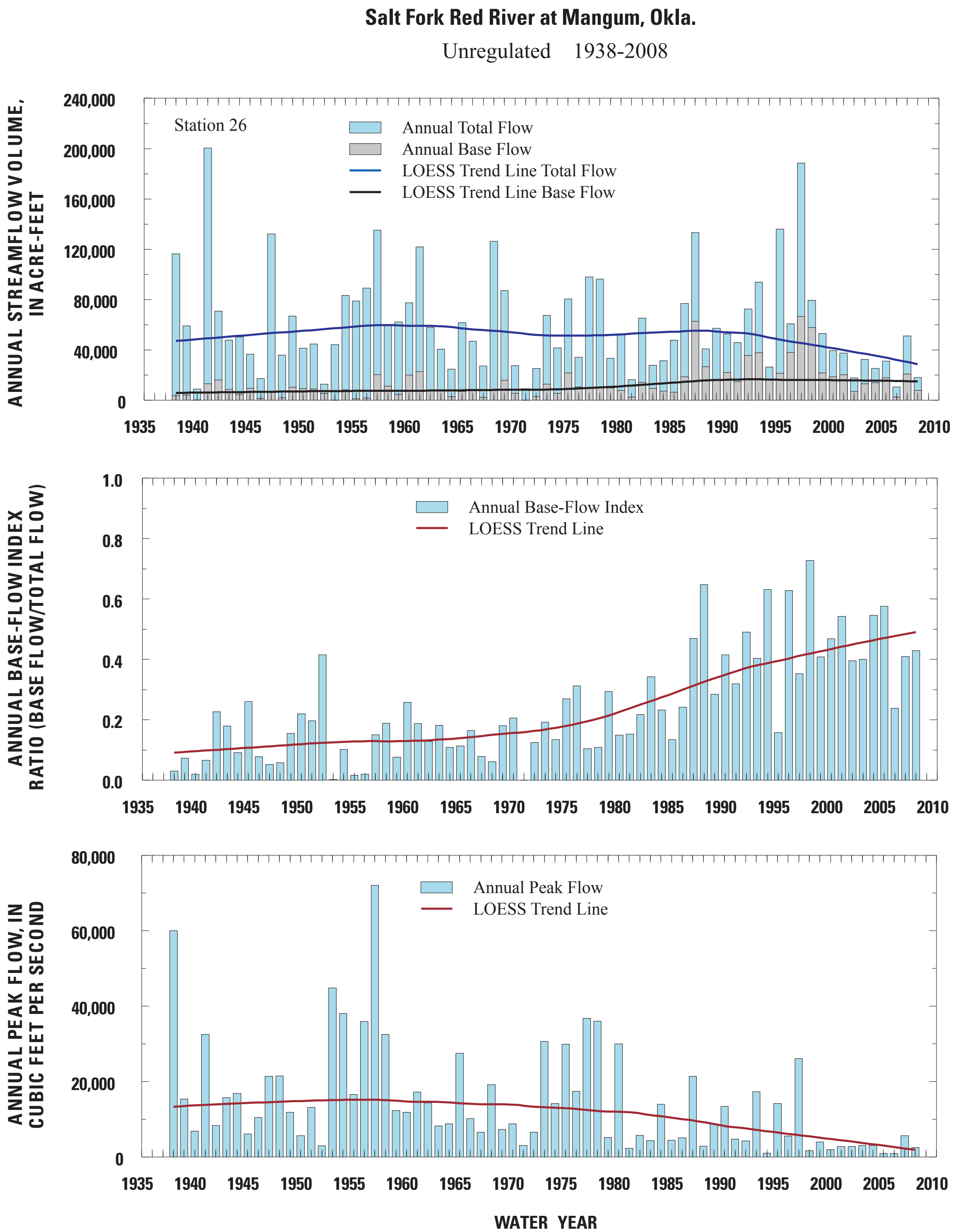

Figure 36. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Salt Fork Red River at Mangum, Oklahoma, (U.S. Geological Survey station identifier 07300500, station 26 from table 1), water years 1938–2008.

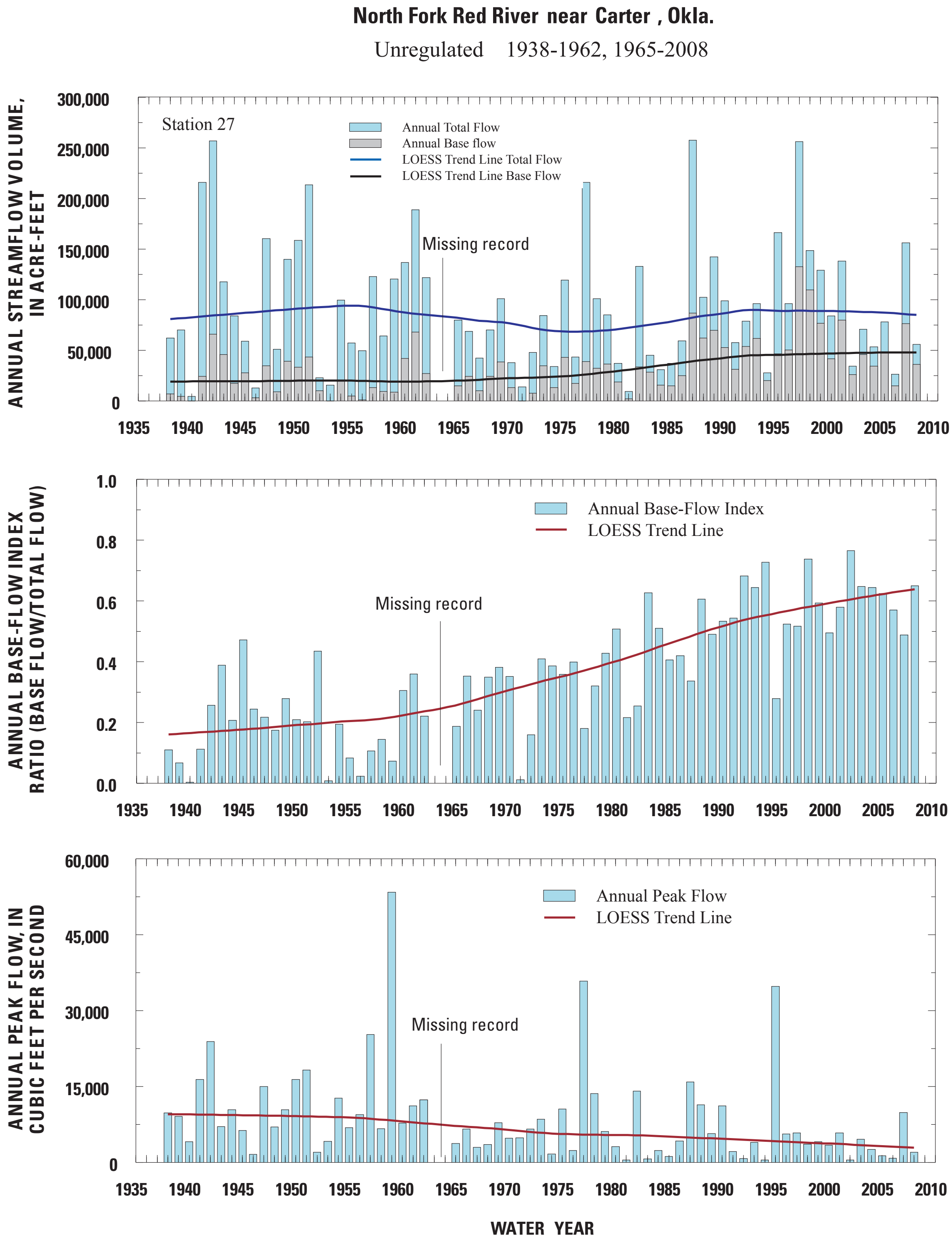

Figure 37. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for North Fork Red River near Carter, Oklahoma, (U.S. Geological Survey station identifier 07301500, station 27 from table 1), water years 1938–2008.

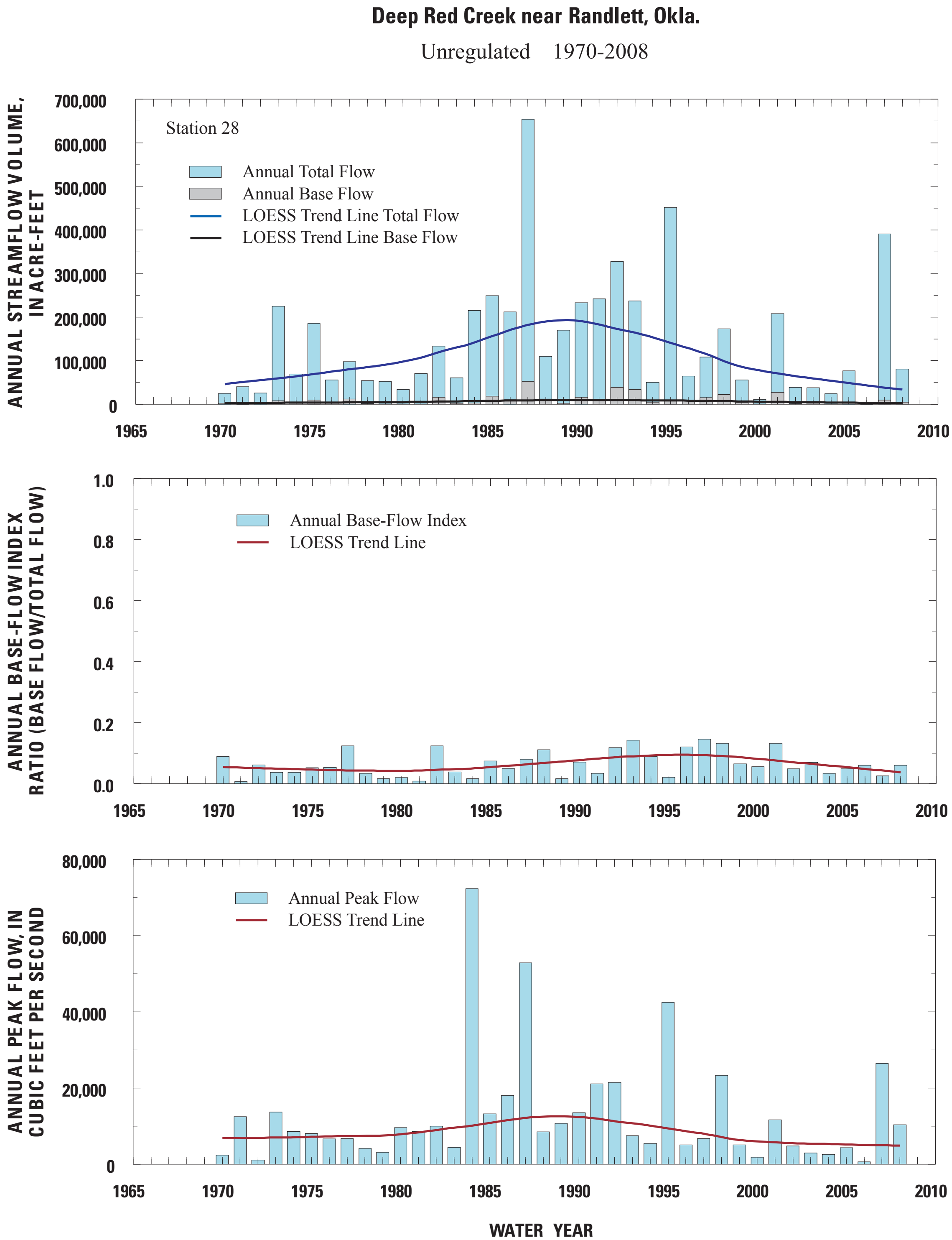

Figure 38. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Deep Red Creek near Randlett, Oklahoma, (U.S. Geological Survey station identifier 07311500, station 28 from table 1), water years 1970–2008.

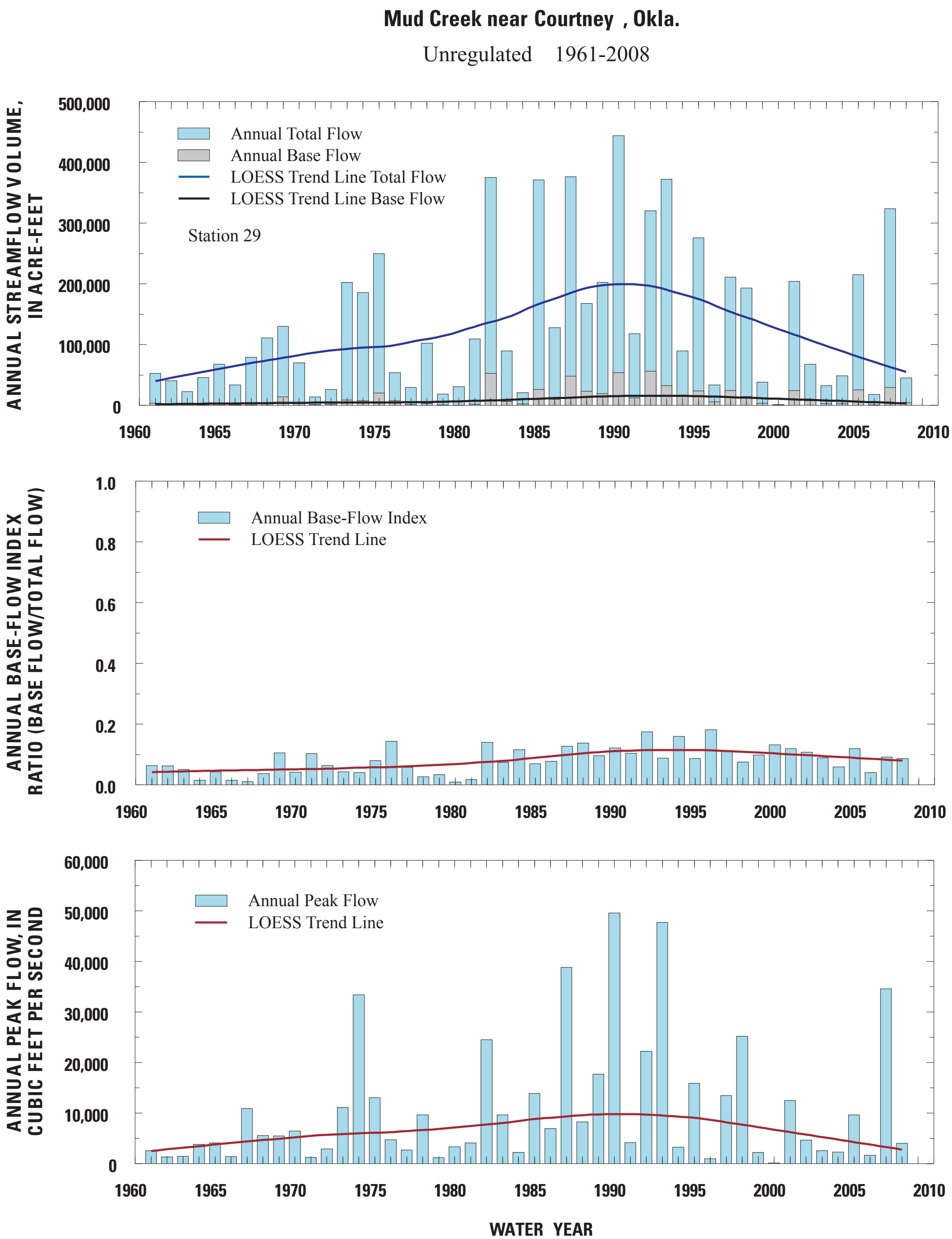

Figure 39. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Mud Creek near Courtney, Oklahoma, (U.S. Geological Survey station identifier 07315700, station 29 from table 1), water years 1961–2008.

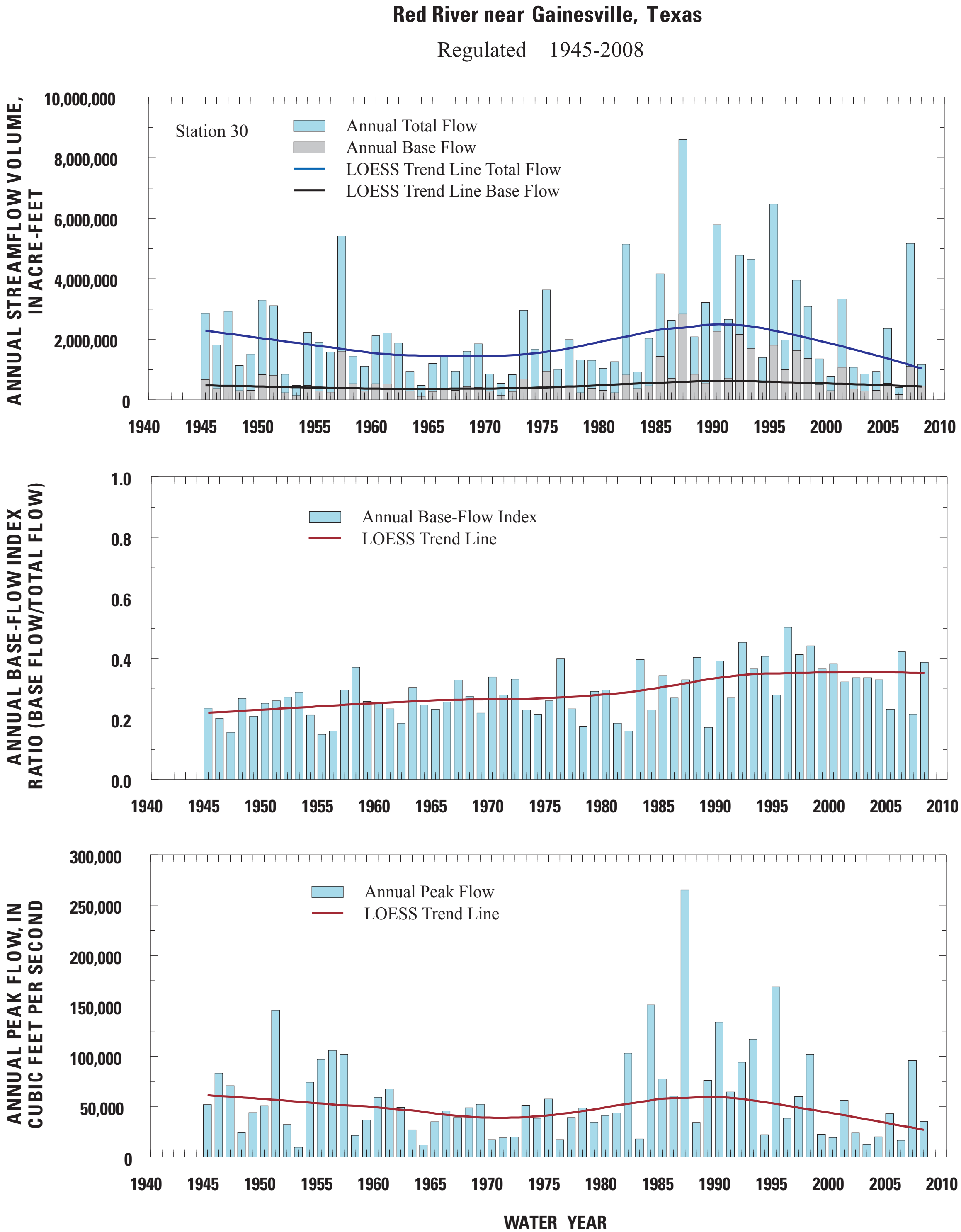

Figure 40. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Red River near Gainesville, Texas, (U.S. Geological Survey station identifier 07316000, station 30 from table 1), water years 1945–2008.

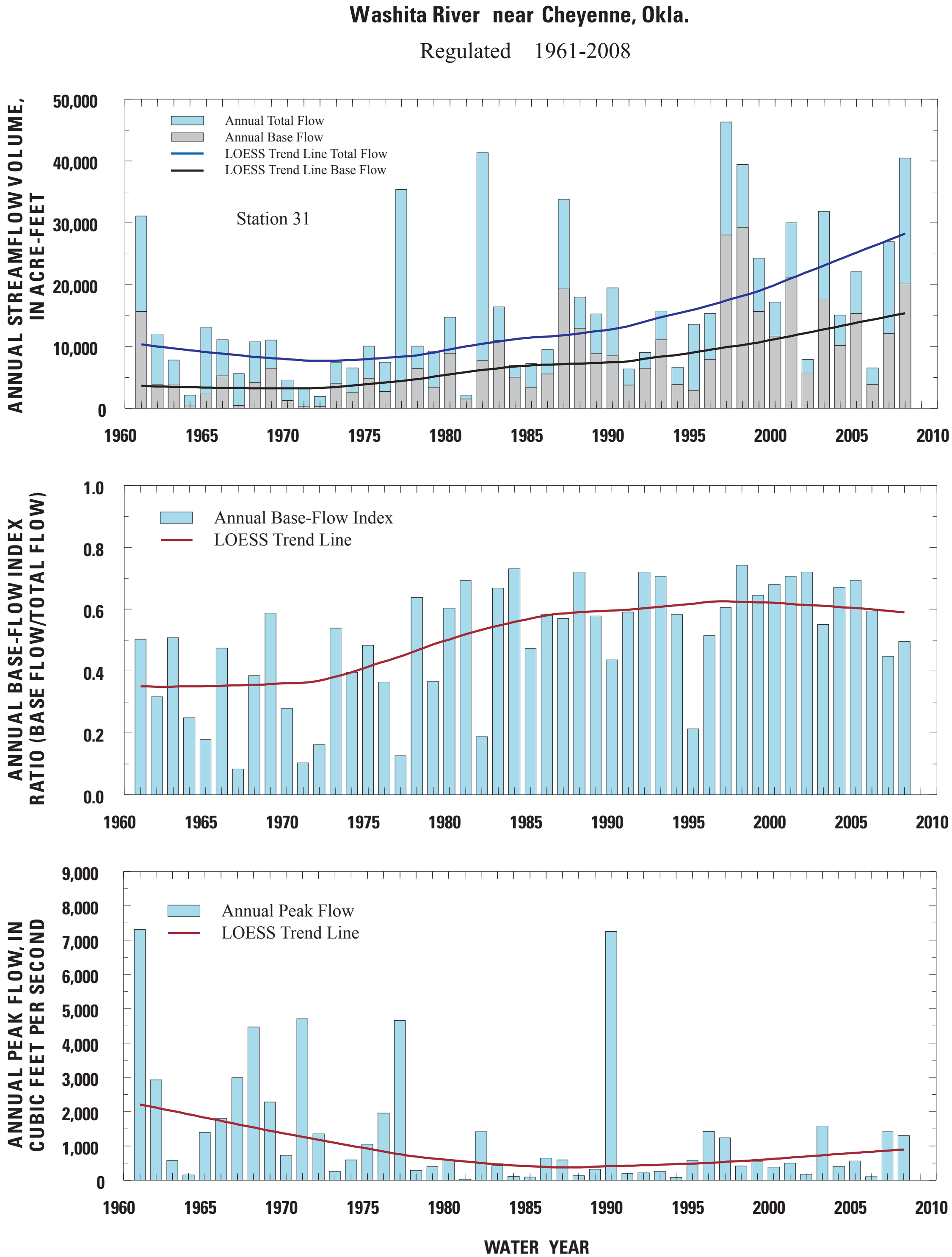

Figure 41. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Washita River near Cheyenne, Oklahoma, (U.S. Geological Survey station identifier 07316500, station 31 from table 1), water years 1961–2008.

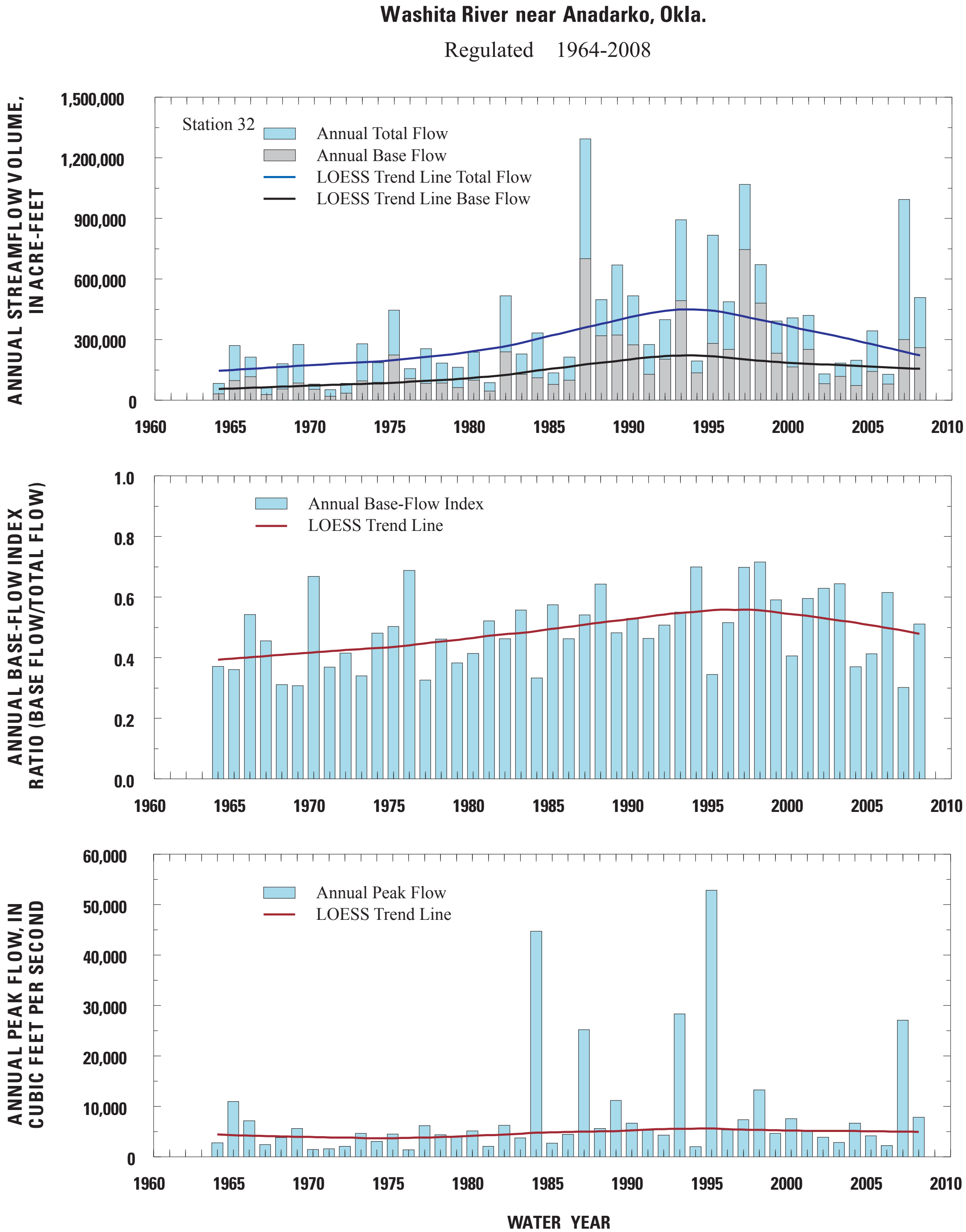

Figure 42. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Washita River near Anadarko, Oklahoma, (U.S. Geological Survey station identifier 07326500, station 32 from table 1), water years 1964–2008.

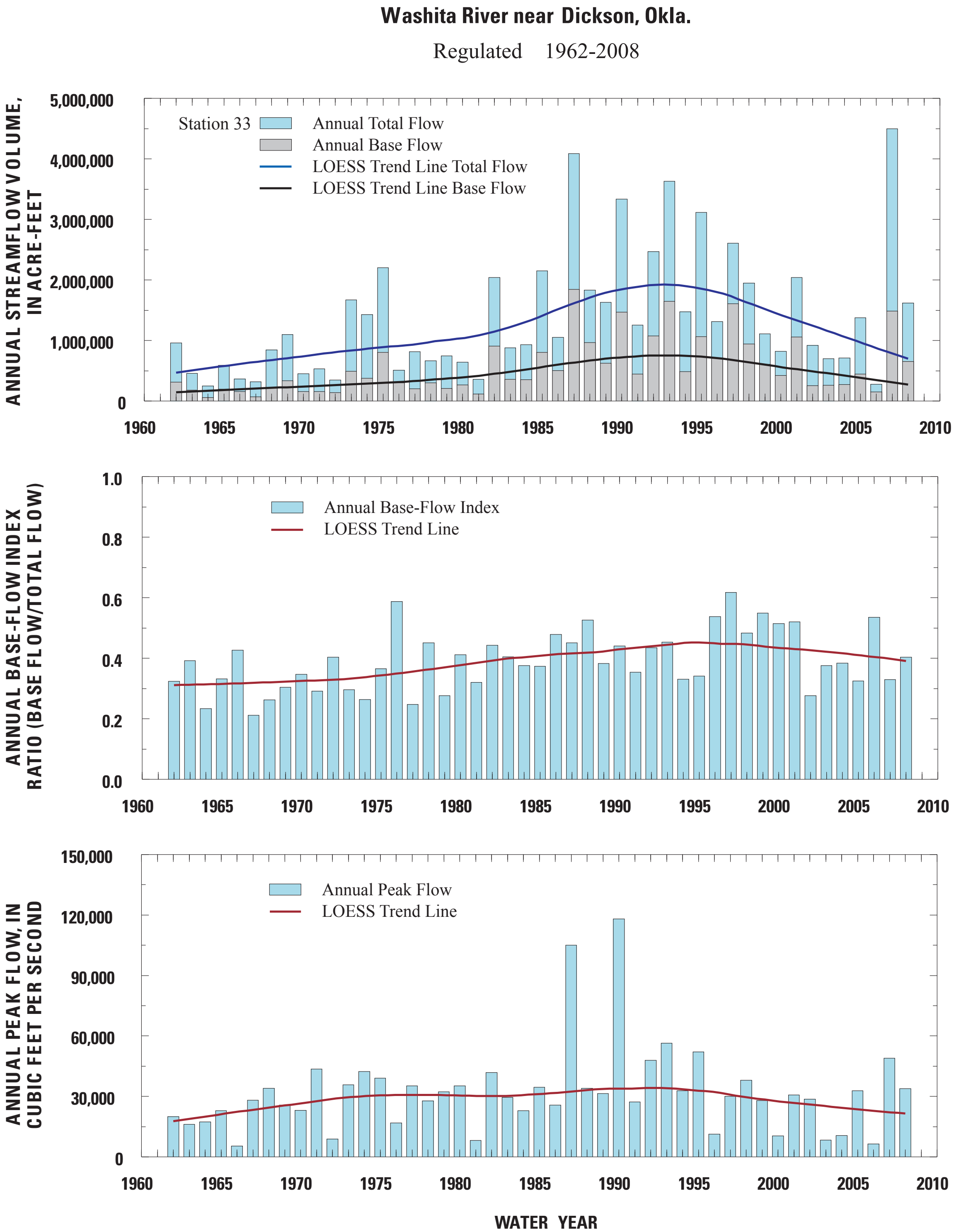

Figure 43. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Washita River near Dickson, Oklahoma, (U.S. Geological Survey station identifier 07331000, station 33 from table 1), water years 1962–2008.

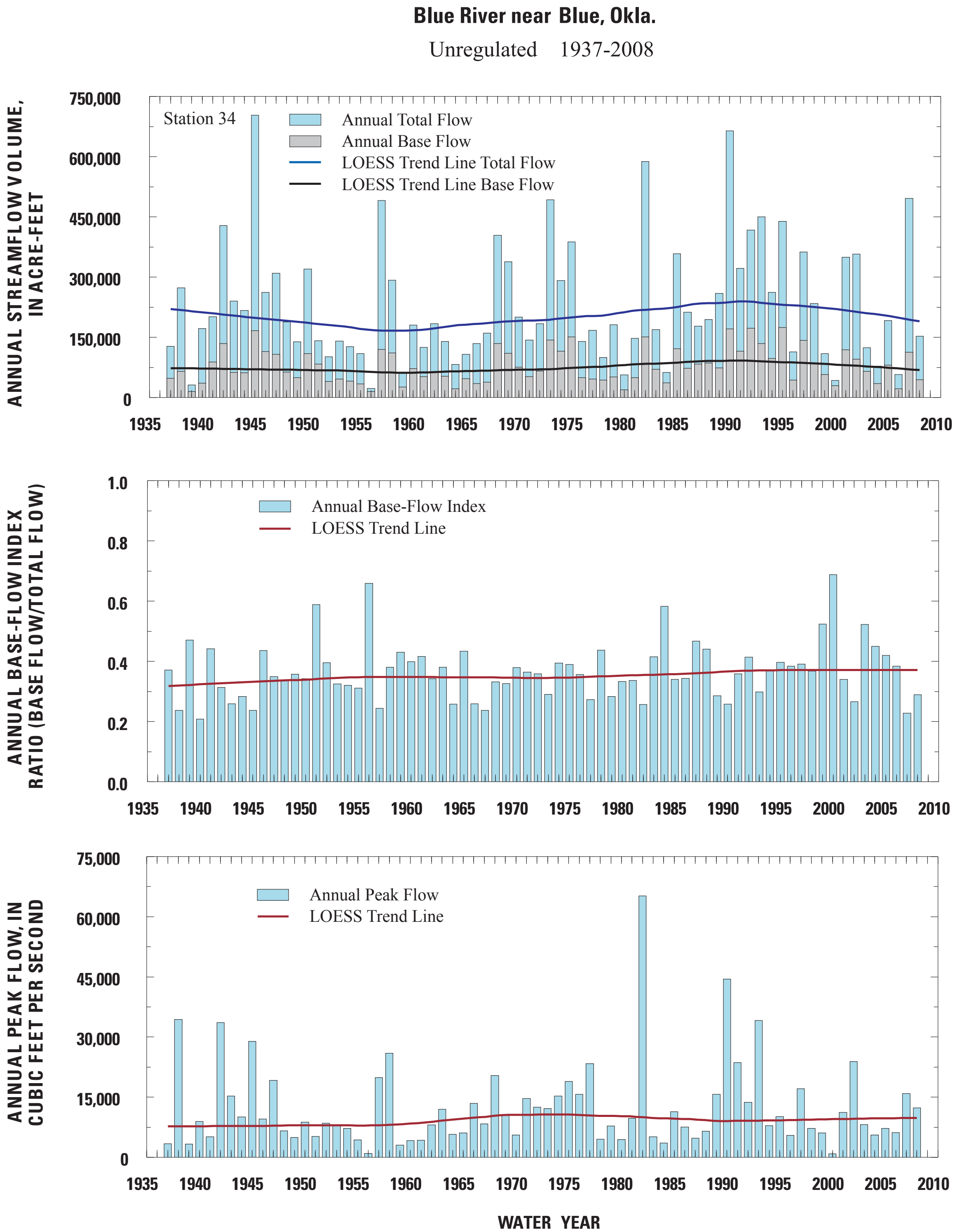

Figure 44. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Blue River near Blue, Oklahoma, (U.S. Geological Survey station identifier 07332500, station 34 from table 1), water years 1937–2008.

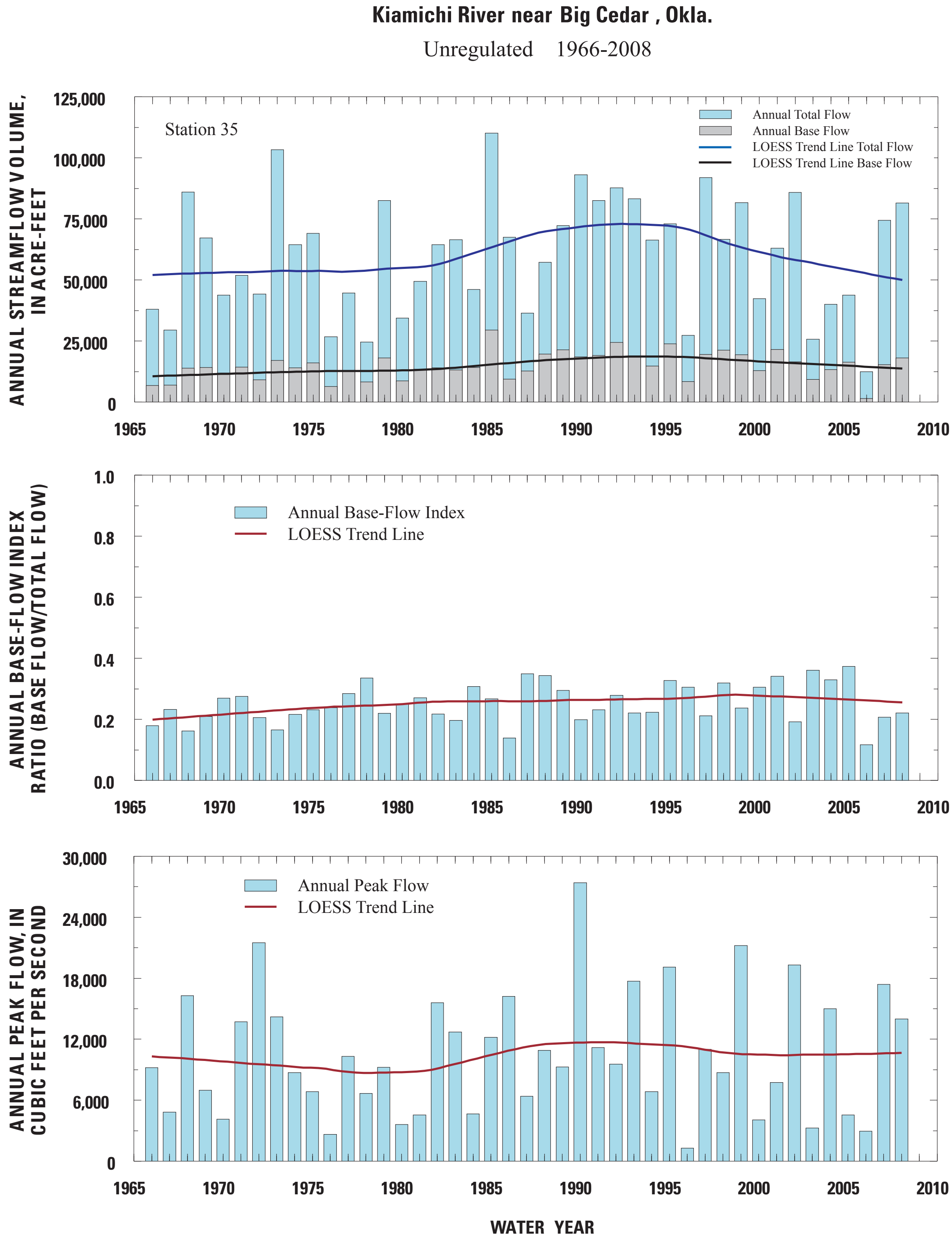

Figure 45. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Kiamichi River near Big Cedar, Oklahoma, (U.S. Geological Survey station identifier 07335700, station 35 from table 1), water years 1966–2008.

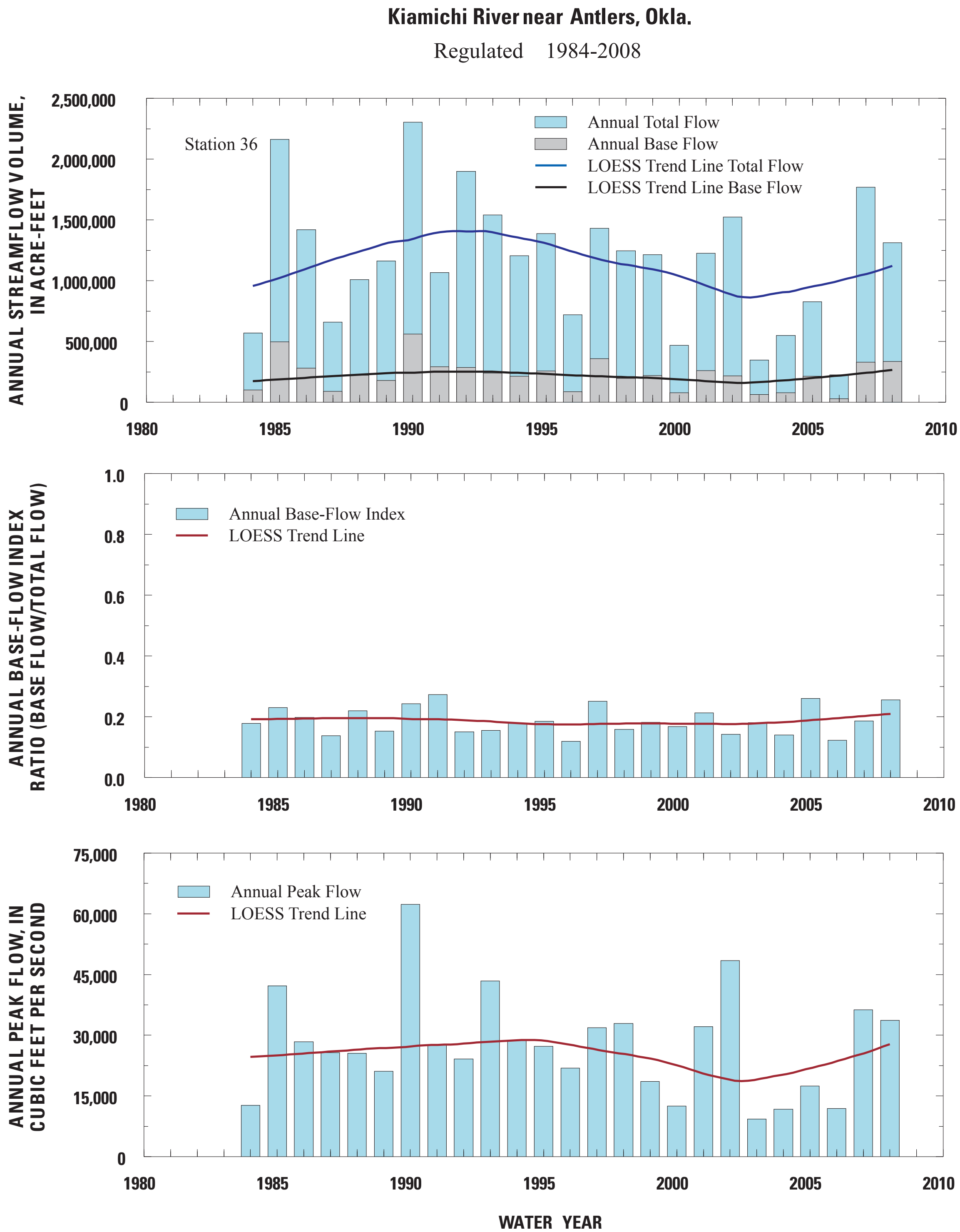

Figure 46. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Kiamichi River near Antlers, Oklahoma, (U.S. Geological Survey station identifier 07336200, station 36 from table 1), water years 1984–2008.

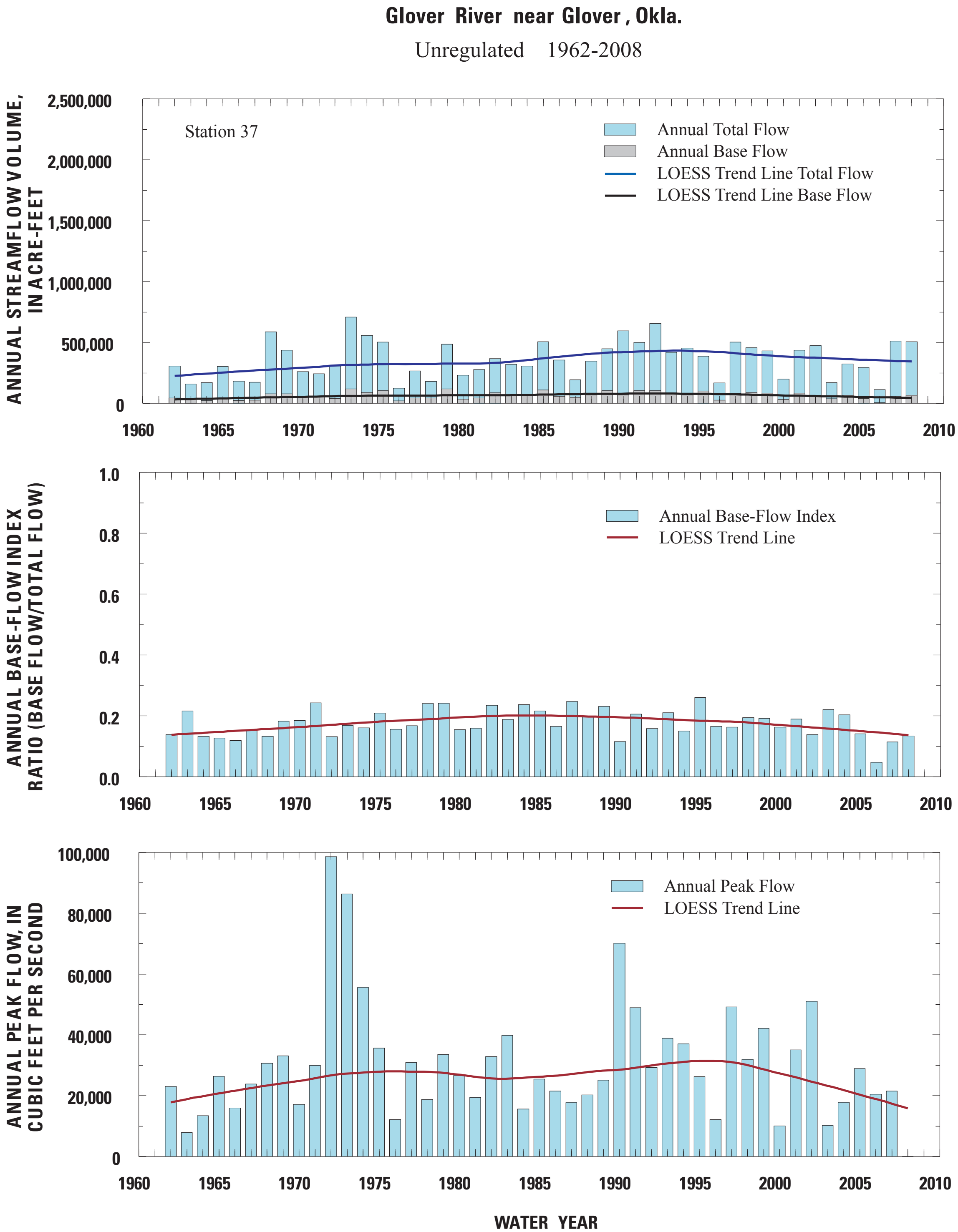

Figure 47. Annual base-flow volume, total-flow volume, base-flow index, and peak flow, and LOESS trend lines for Glover River near Glover, Oklahoma, (U.S. Geological Survey station identifier 07337900, station 37 from table 1), water years 1962–2008.

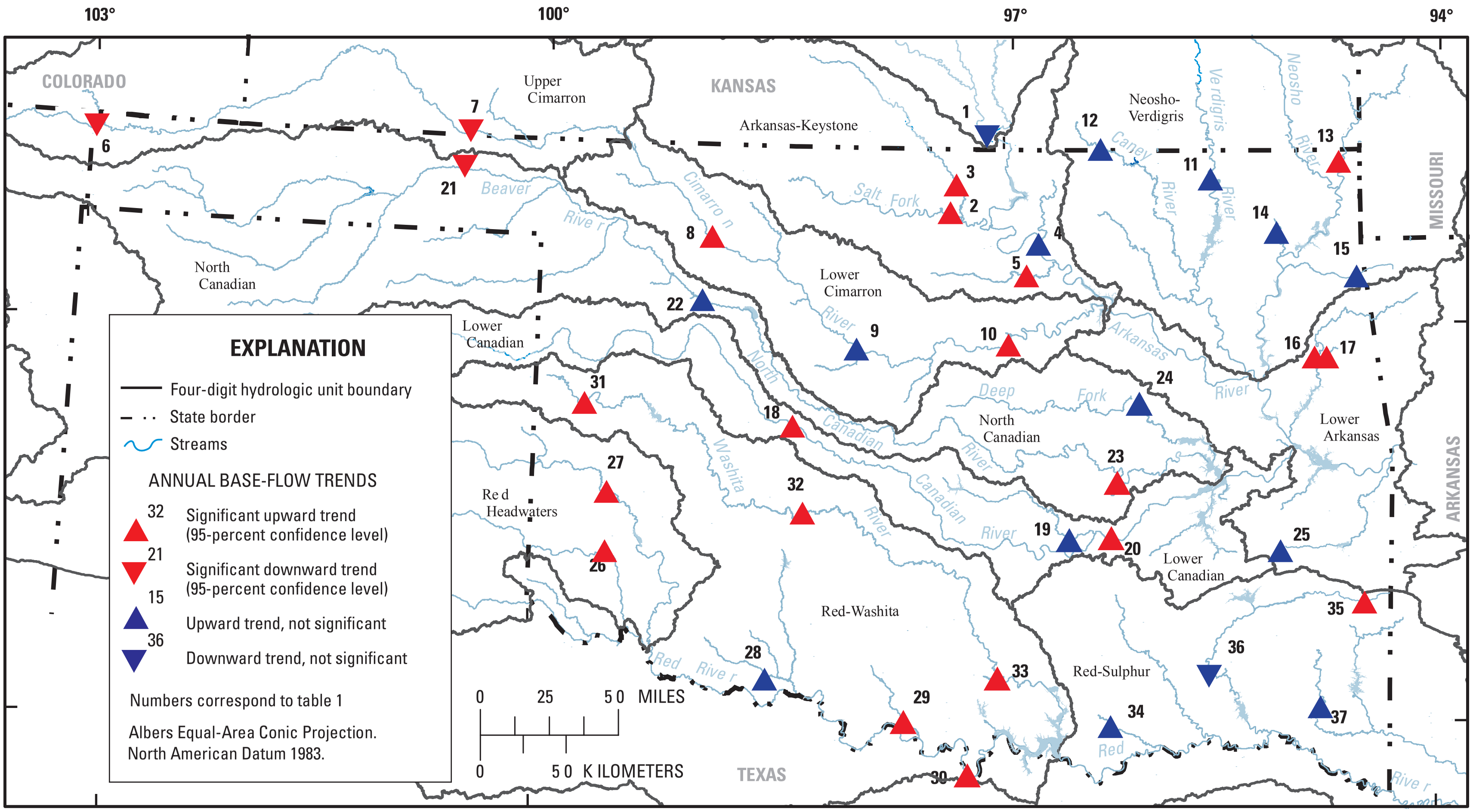

Figure 48. Results of Kendall's tau trend analyses of annual base-flow volume at selected streamflow-gaging stations in and near Oklahoma.

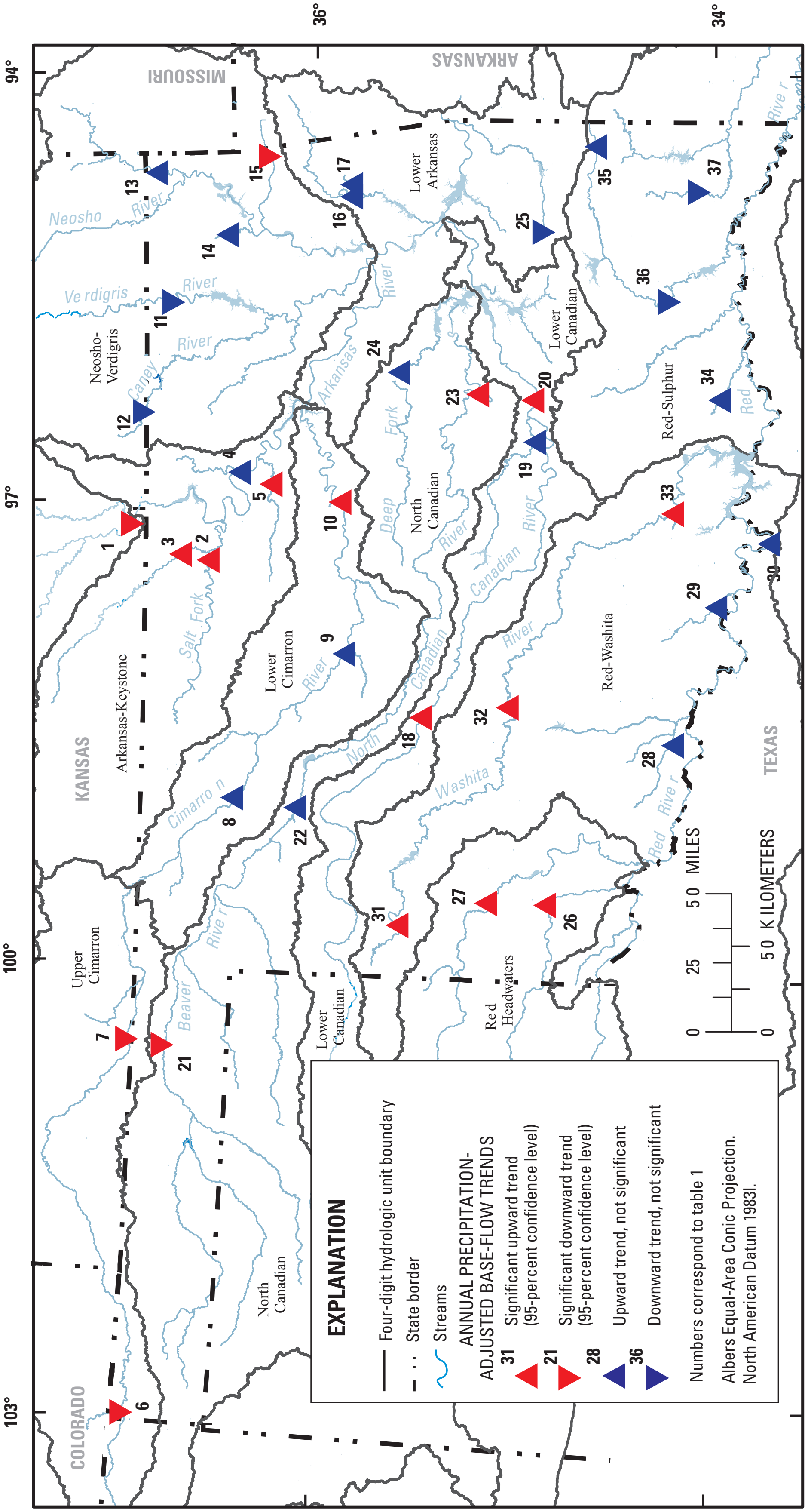

Figure 49. Results of Kendall's tau trend analyses of annual precipitation-adjusted base-flow volume at selected streamflow-gaging stations in and near Oklahoma.

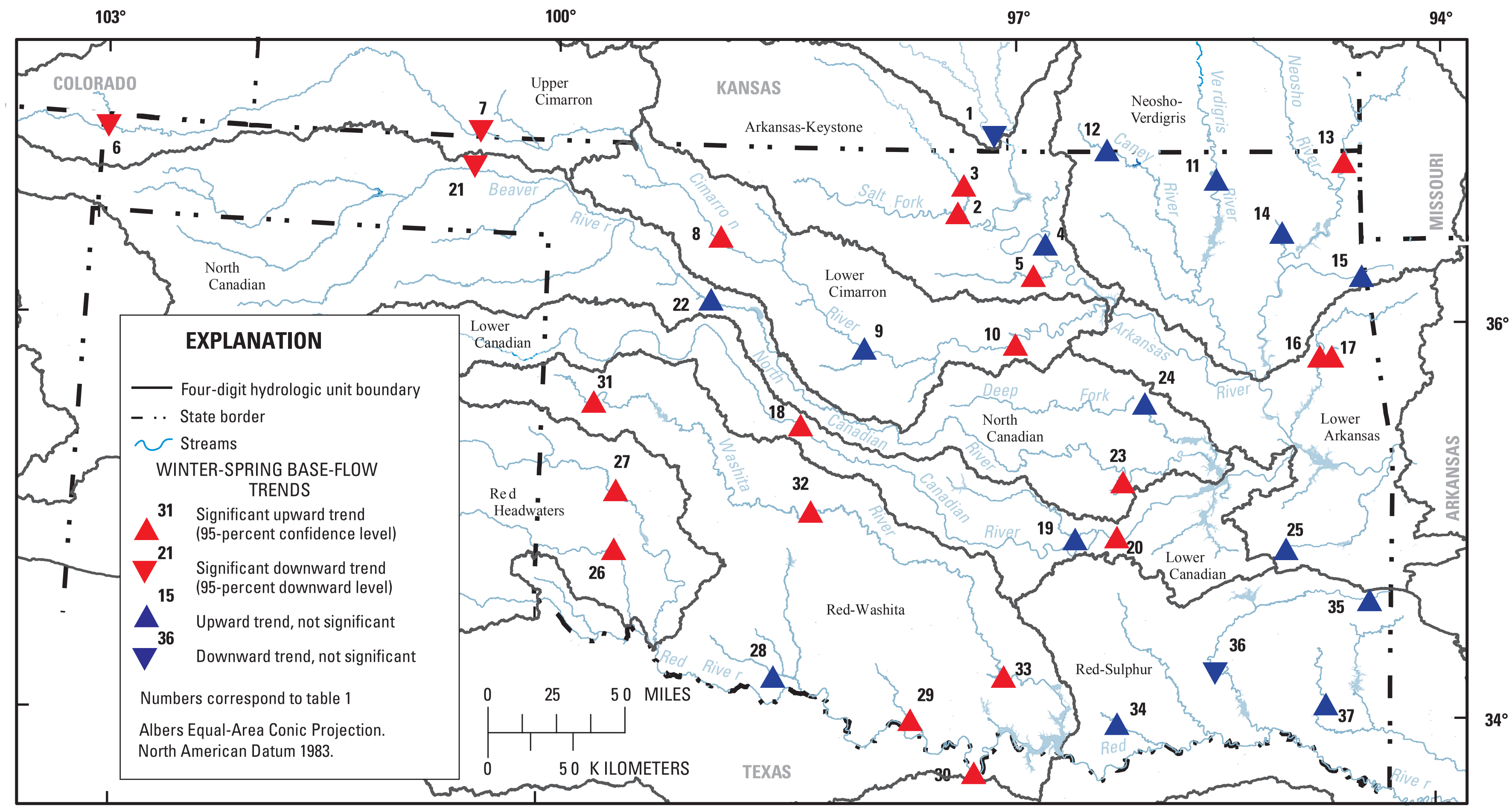

Figure 50. Results of Kendall’s tau trend analyses of winter-spring base-flow volume at selected streamflow-gaging stations in and near Oklahoma.

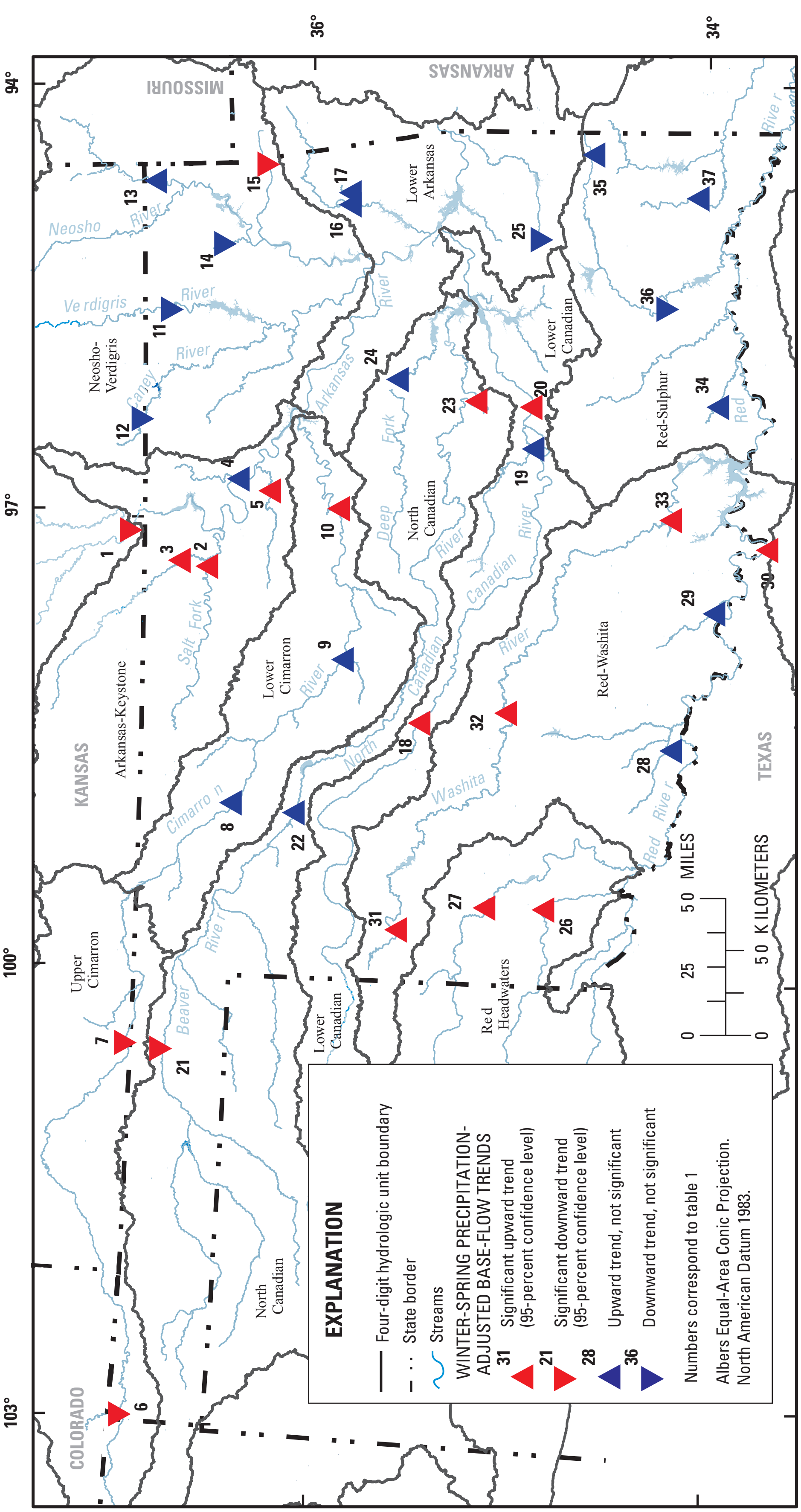

Figure 51. Results of Kendall's tau trend analyses of winter-spring precipitation-adjusted base-flow volume at selected streamflow-gaging stations in and near Oklahoma.

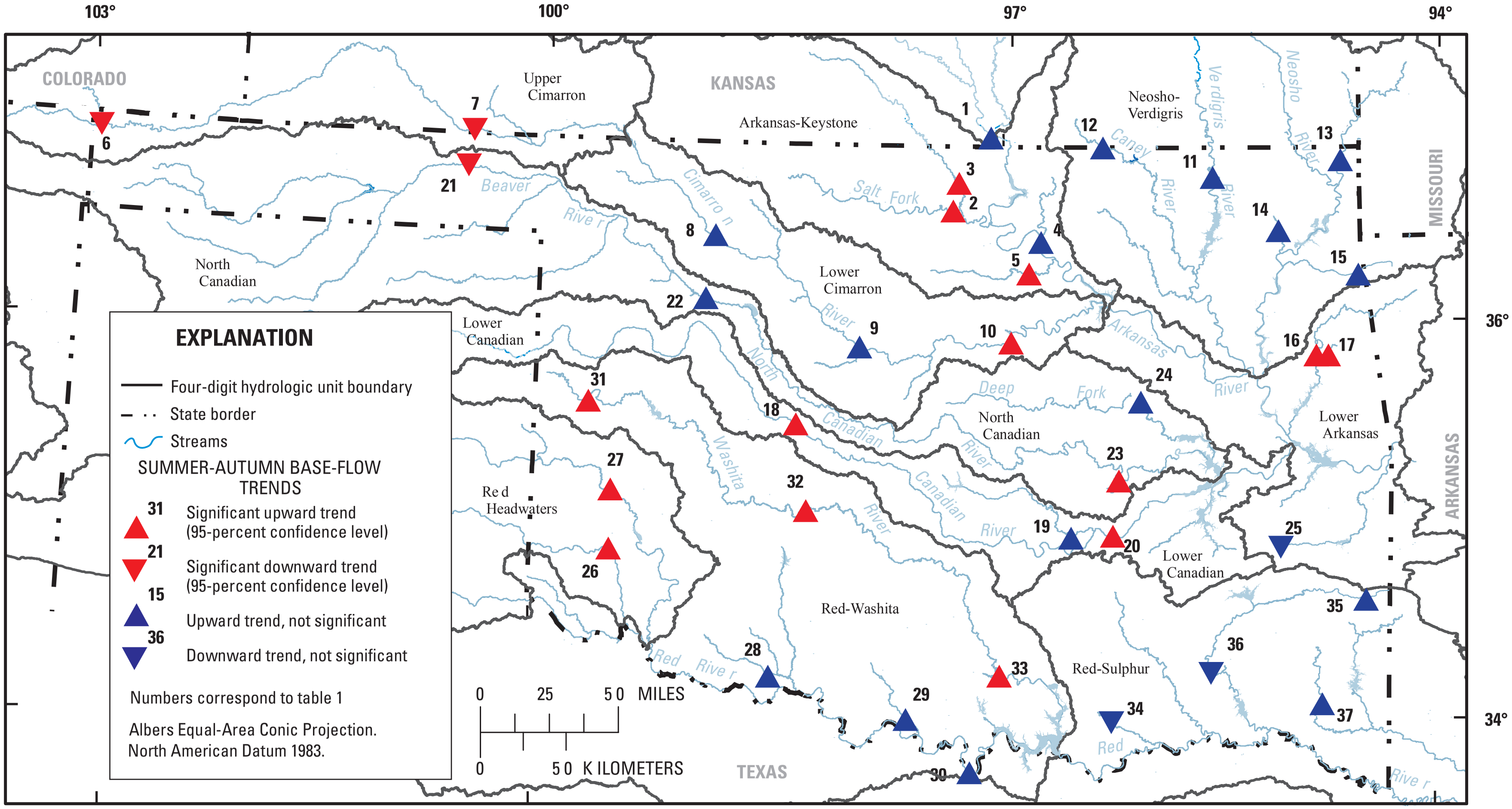

Figure 52. Results of Kendall's tau trend analyses of summer-autumn base-flow volume at selected streamflow-gaging stations in and near Oklahoma.

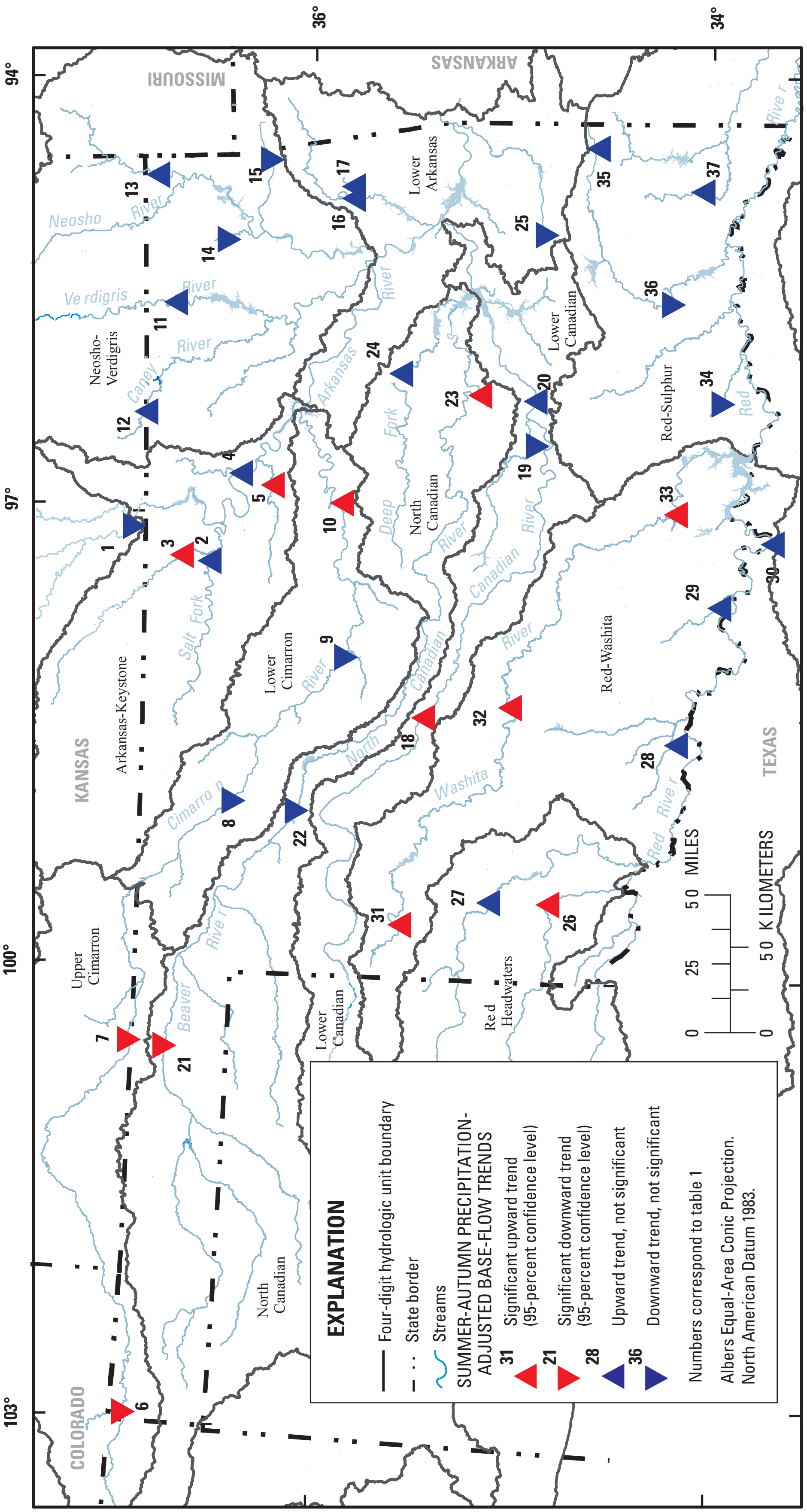

Figure 53. Results of Kendall's tau trend analyses of summer-autumn precipitation-adjusted base-flow volume at selected streamflow-gaging stations in and near Oklahoma.

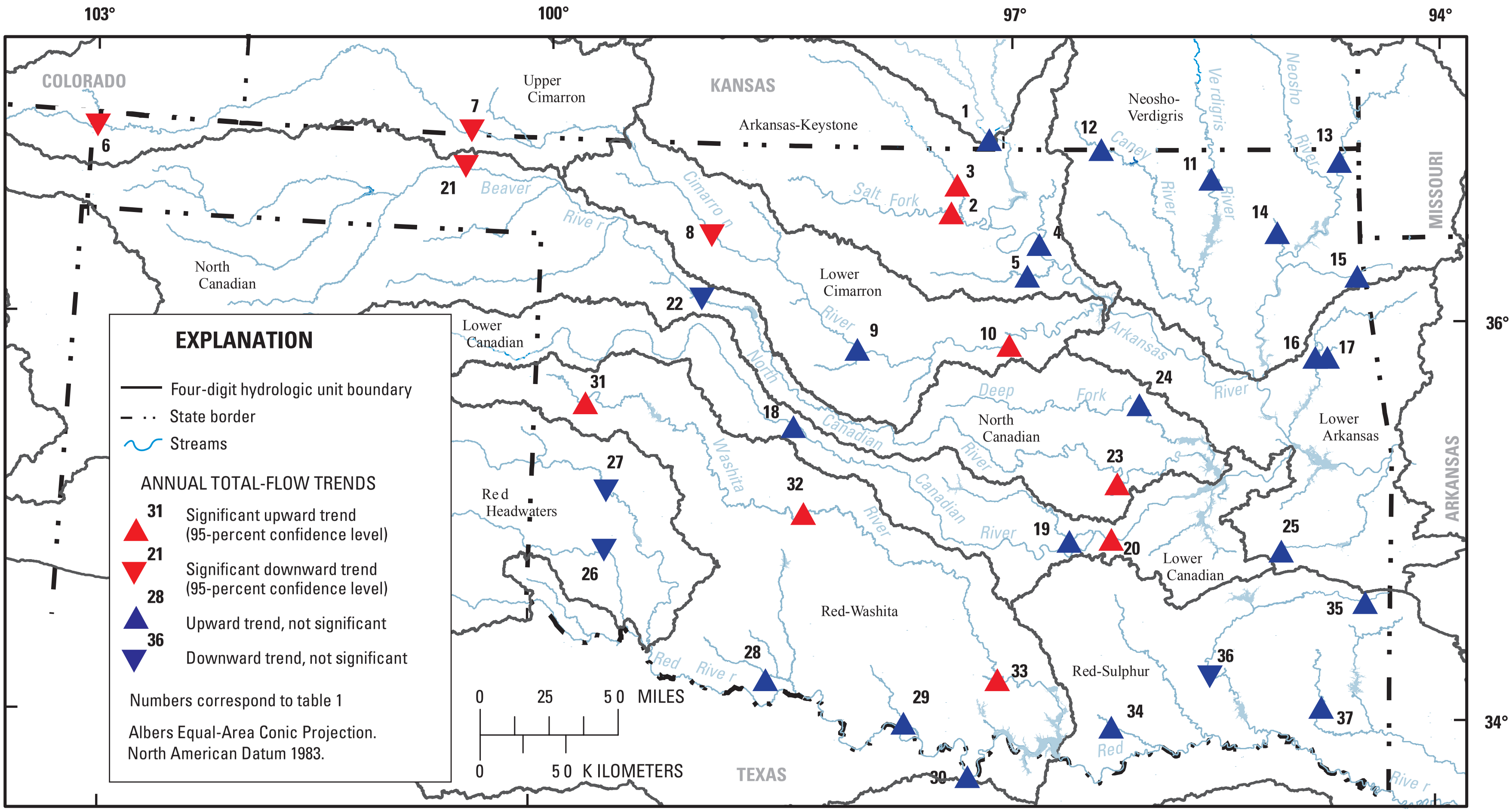

Figure 54. Results of Kendall's tau trend analyses of annual total-flow volume at selected streamflow-gaging stations in and near Oklahoma.

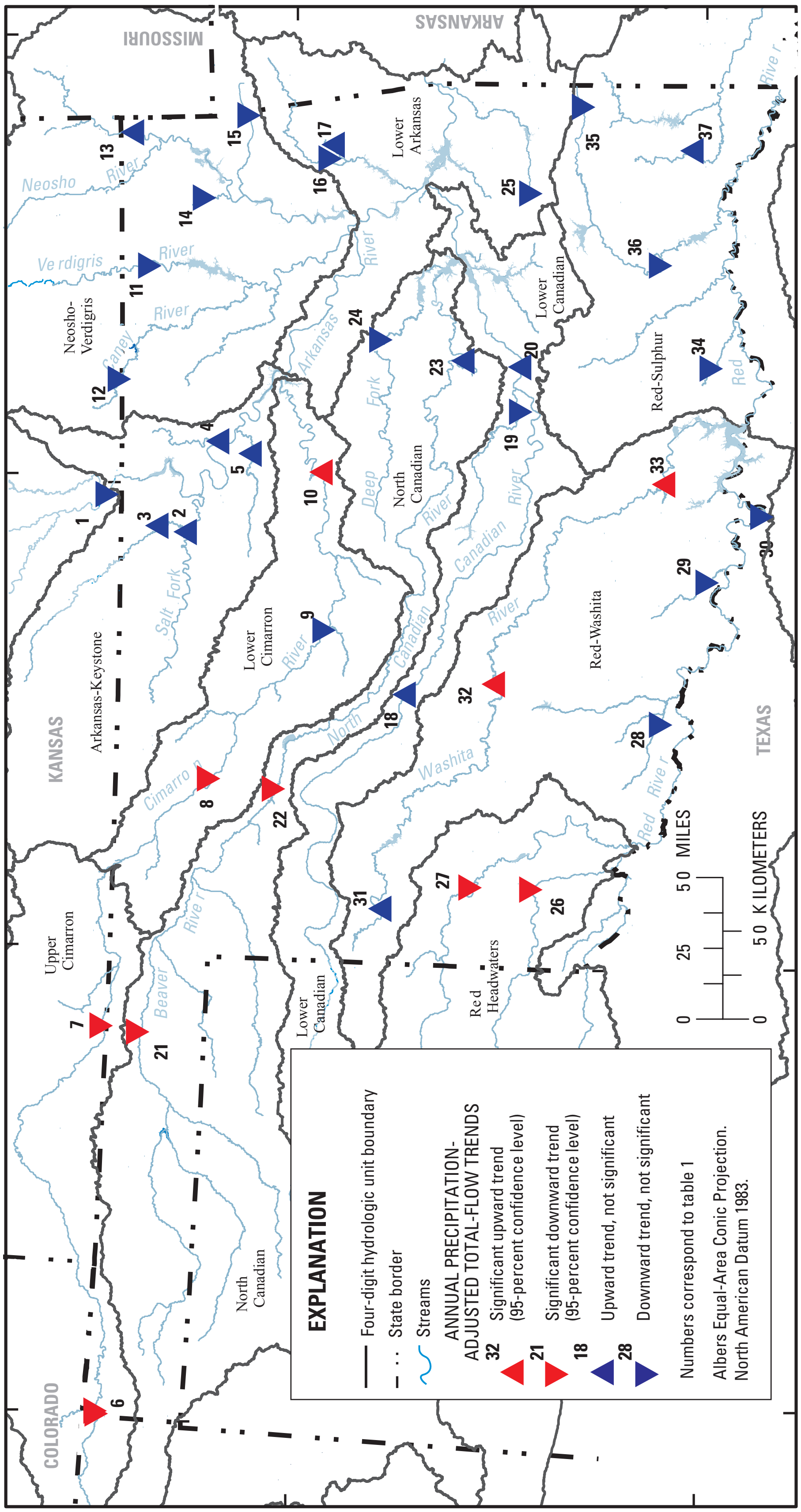

Figure 55. Results of Kendall's tau trend analyses of annual precipitation-adjusted total-flow volume at selected streamflow-gaging stations in and near Oklahoma.

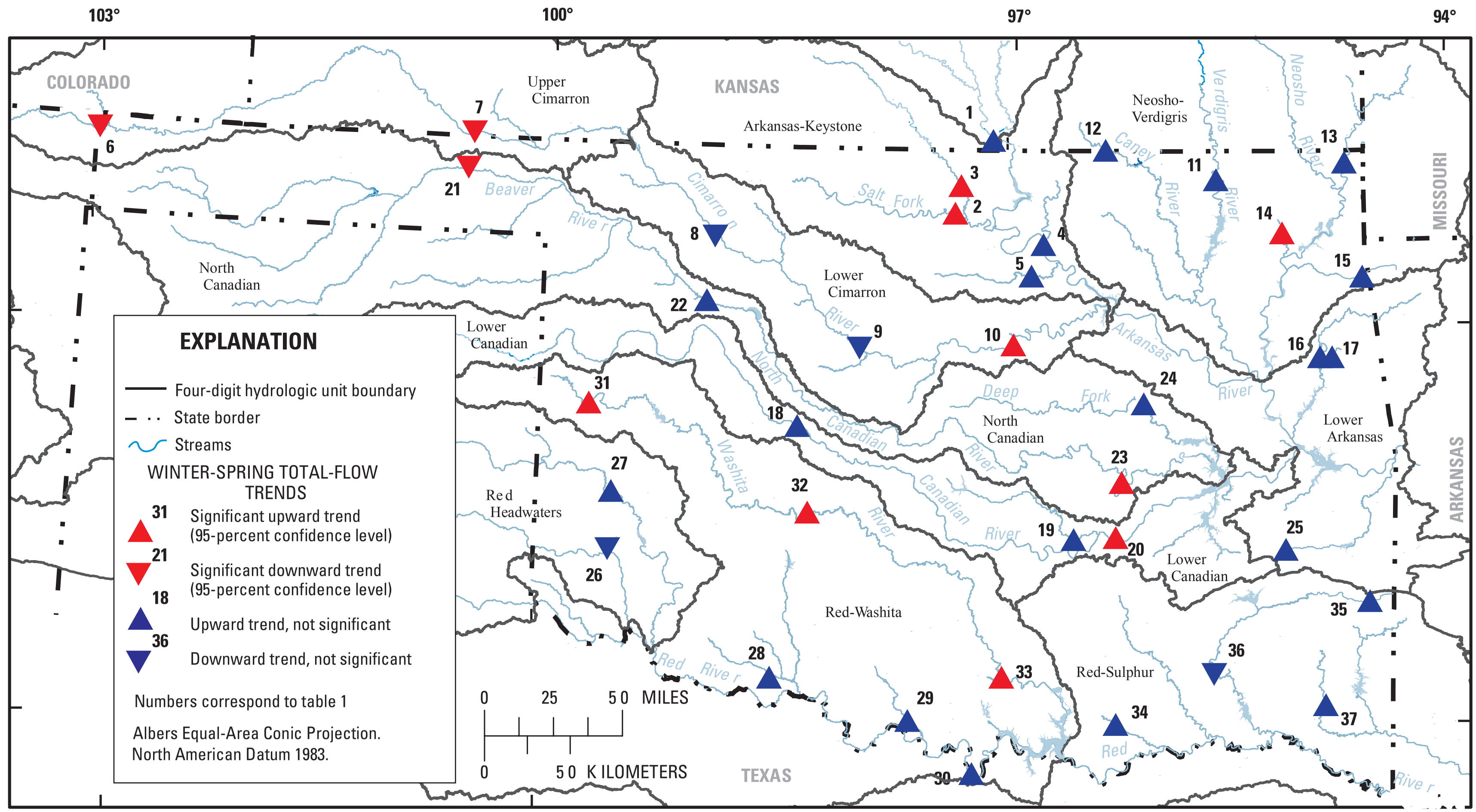

Figure 56. Results of Kendall's tau trend analyses of winter-spring total-flow volume at selected streamflow-gaging stations in and near Oklahoma.

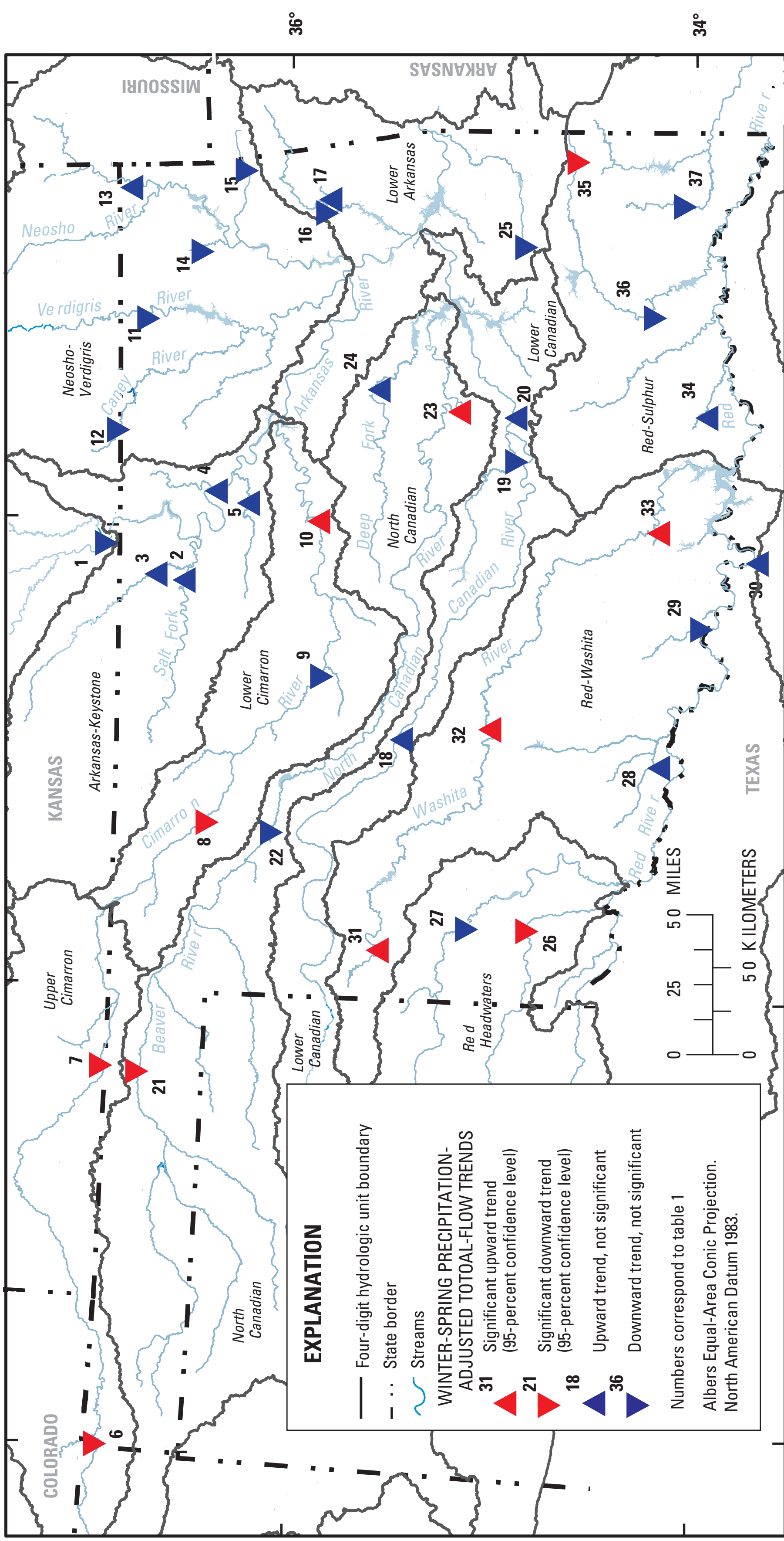

Figure 57. Results of Kendall's tau trend analyses of winter-spring precipitation-adjusted total-flow volume at selected streamflow-gaging stations in and near Oklahoma.

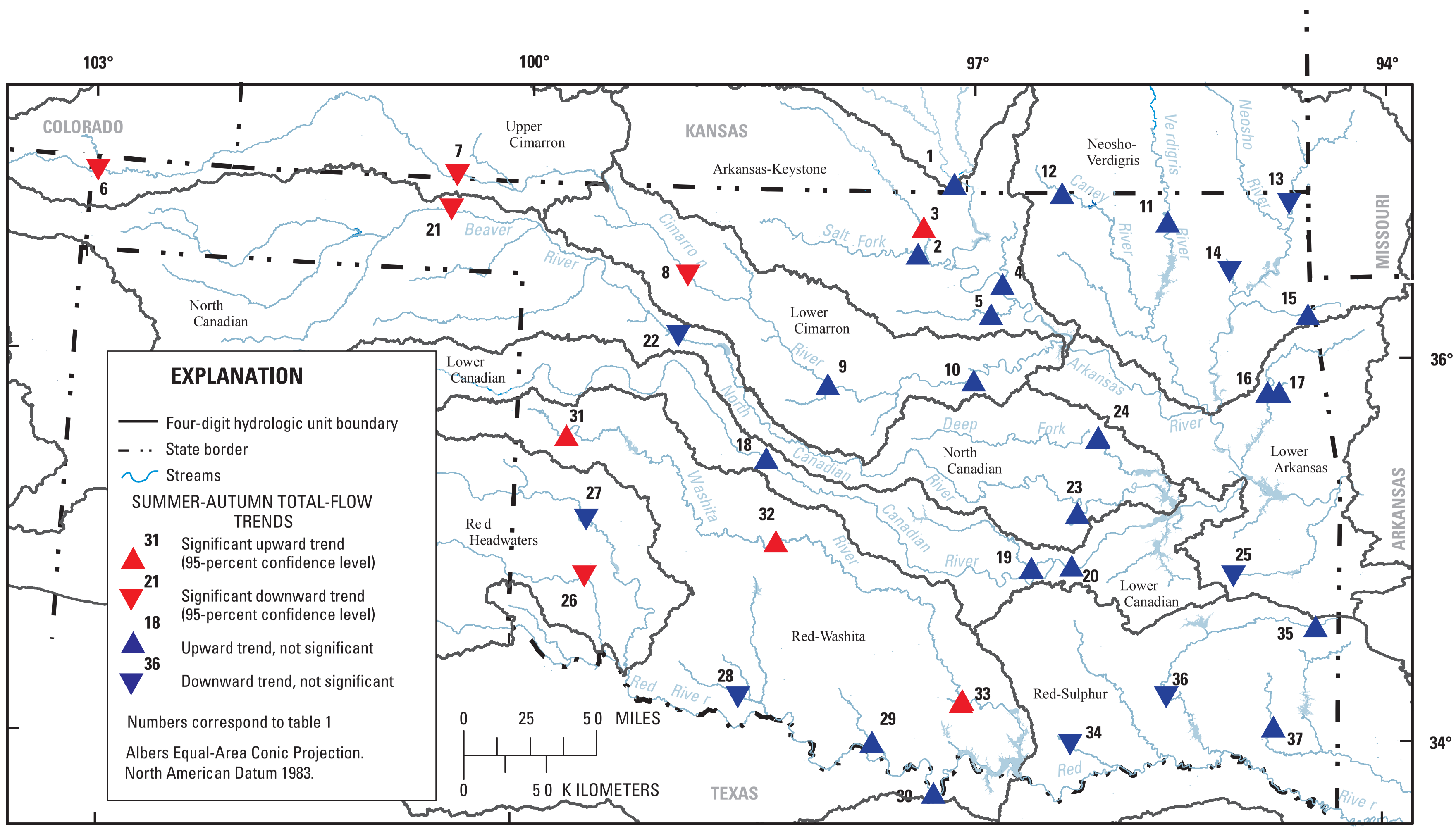

Figure 58. Results of Kendall's tau trend analyses of summer-autumn total-flow volume at selected streamflow-gaging stations in and near Oklahoma.

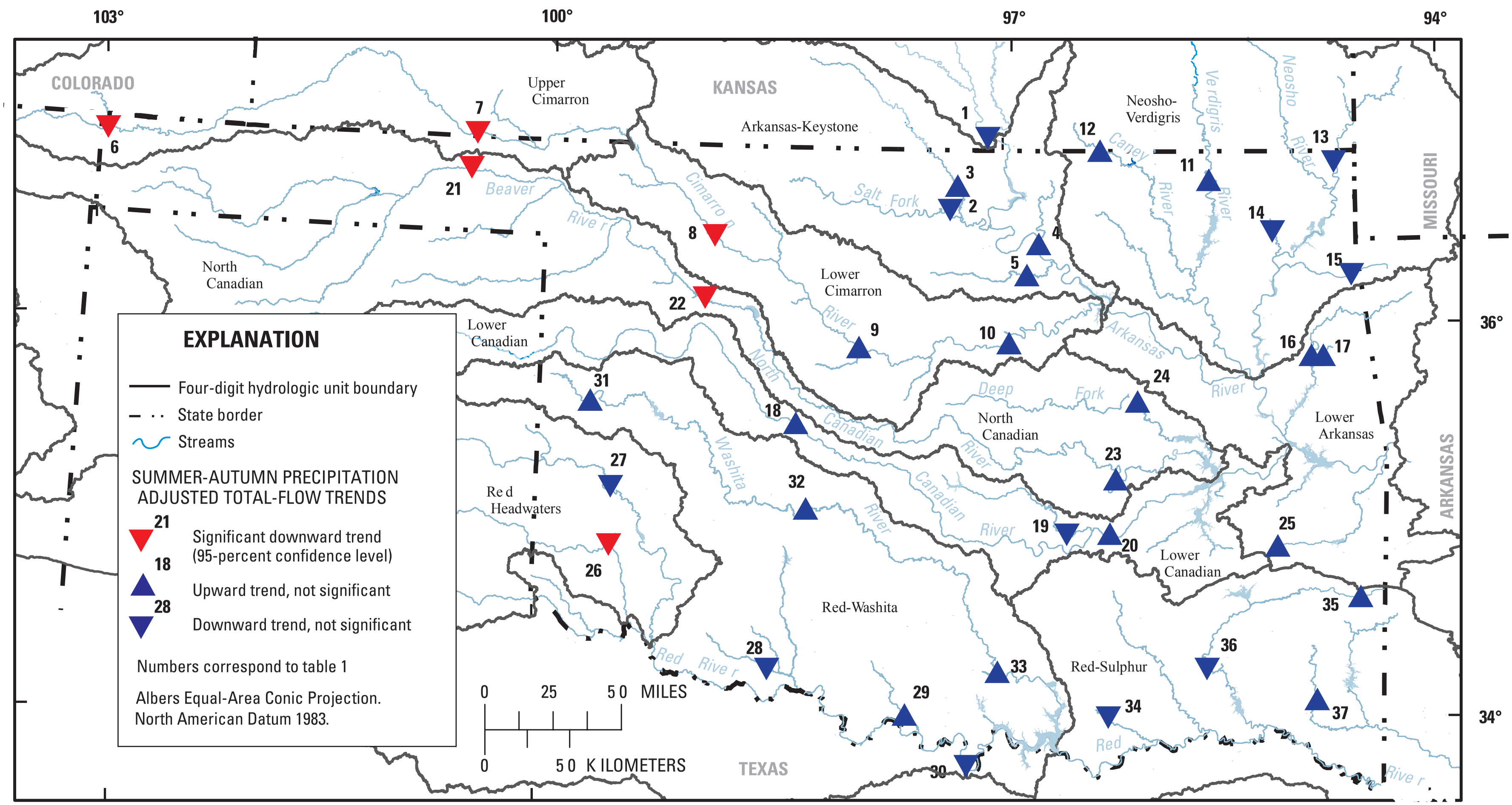

Figure 59. Results of Kendall's tau trend analyses of summer-autumn precipitation-adjusted total-flow volume at selected streamflow-gaging stations in and near Oklahoma.

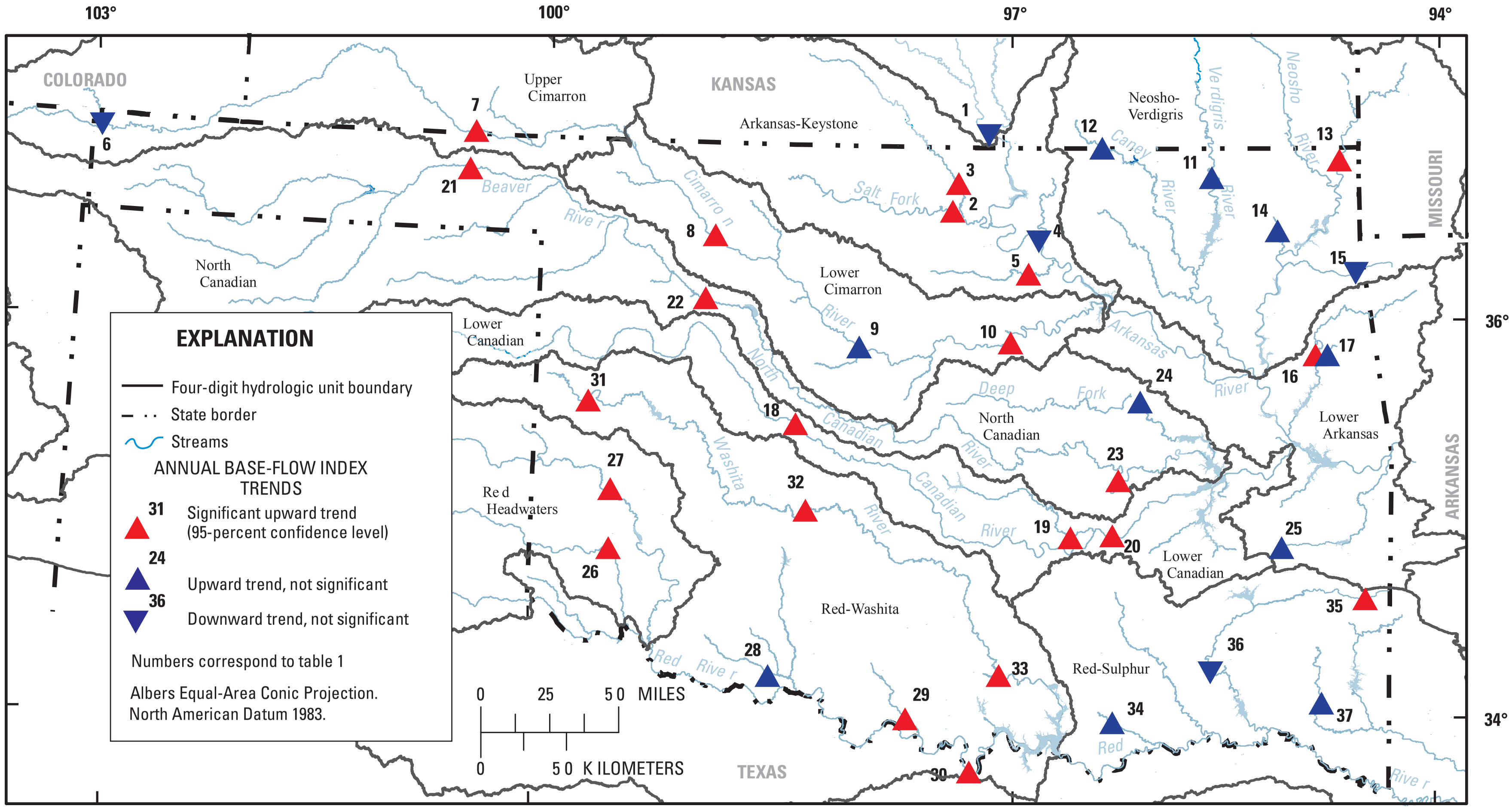

Figure 60. Results of Kendall's tau trend analyses of annual base-flow index at selected streamflow-gaging stations in and near Oklahoma.

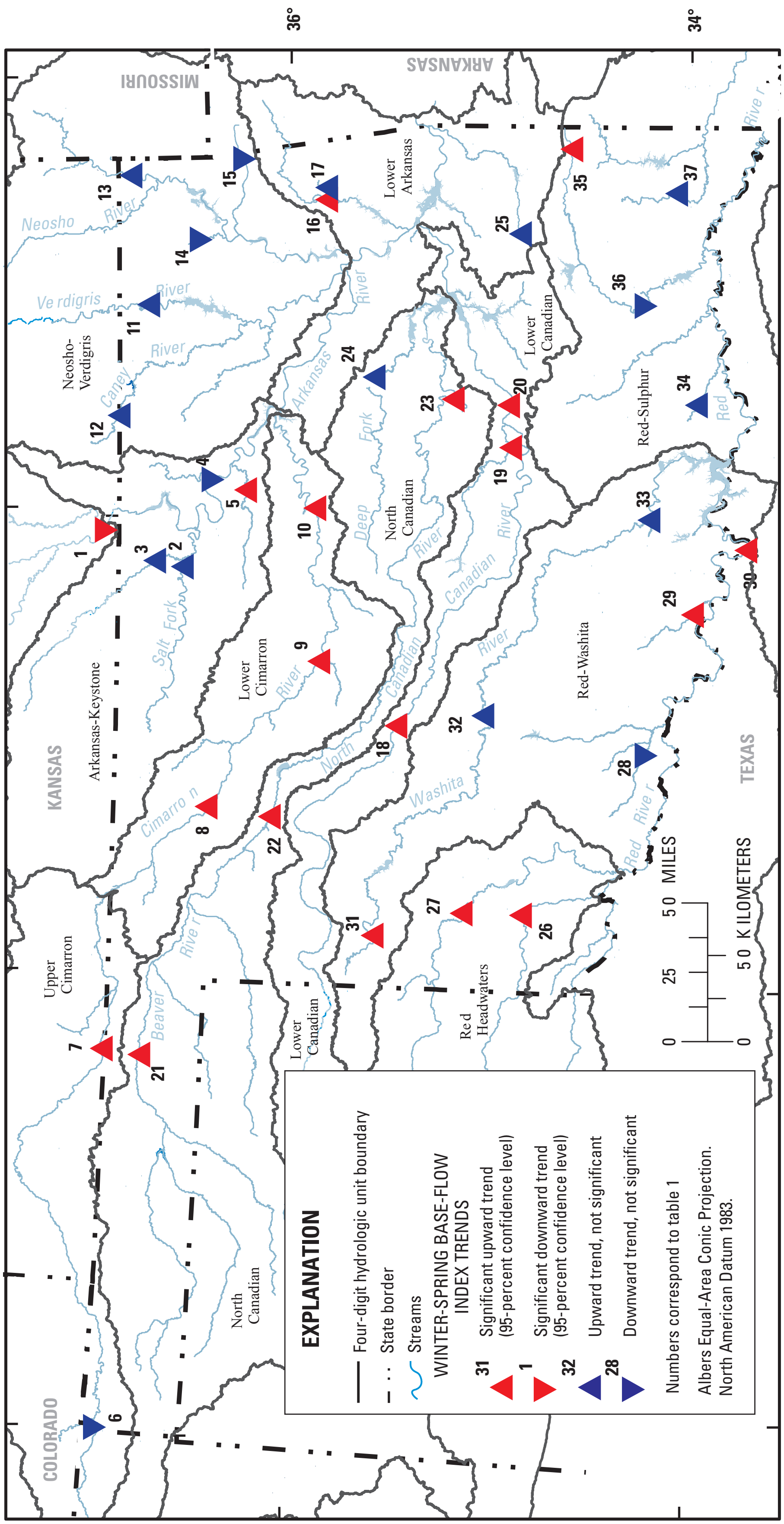

Figure 61. Results of Kendall's tau trend analyses of winter-spring base-flow index at selected streamflow-gaging stations in and near Oklahoma.

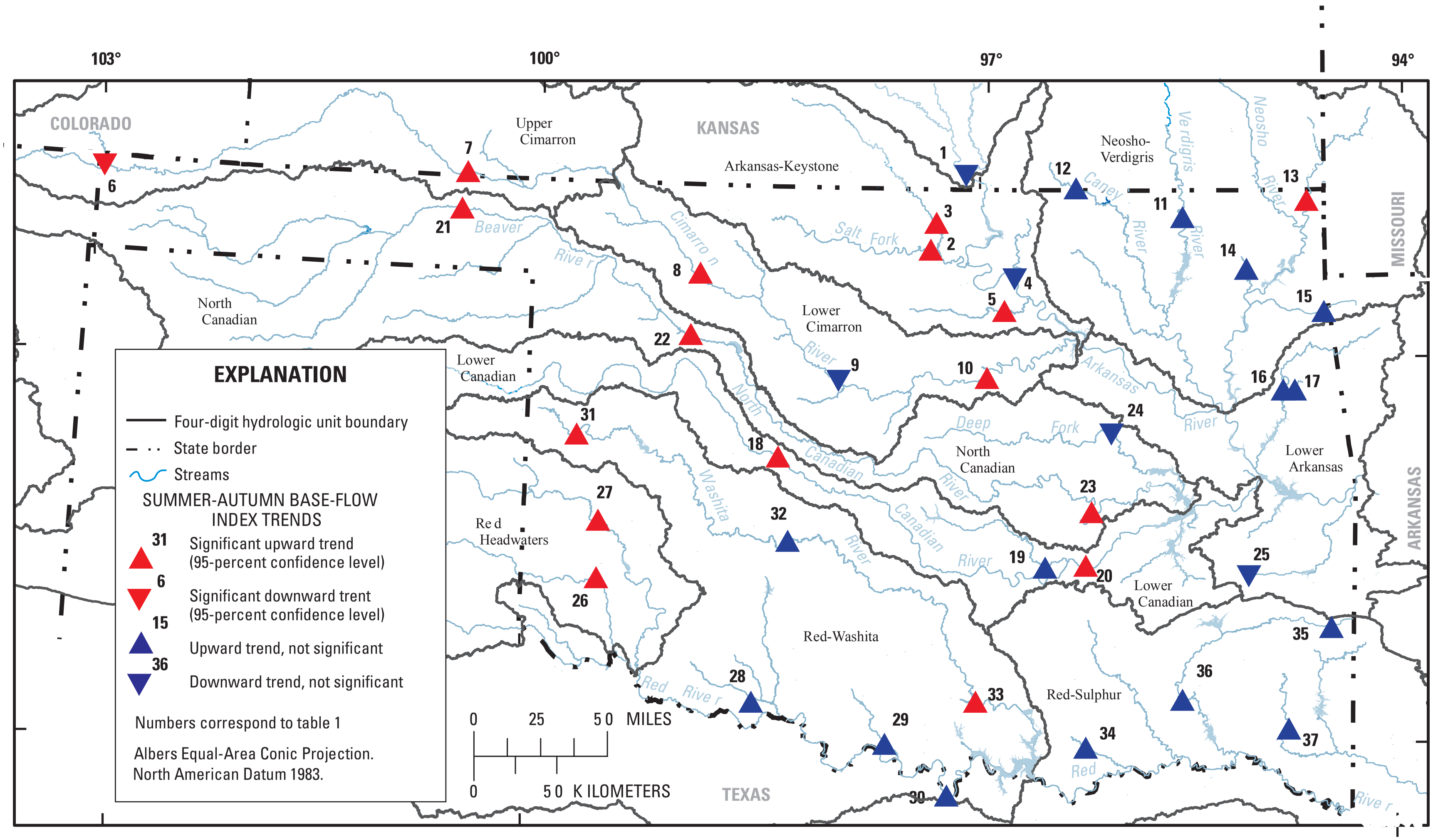

Figure 62. Results of Kendall's tau trend analyses of summer-autumn base-flow index at selected streamflow-gaging stations in and near Oklahoma.

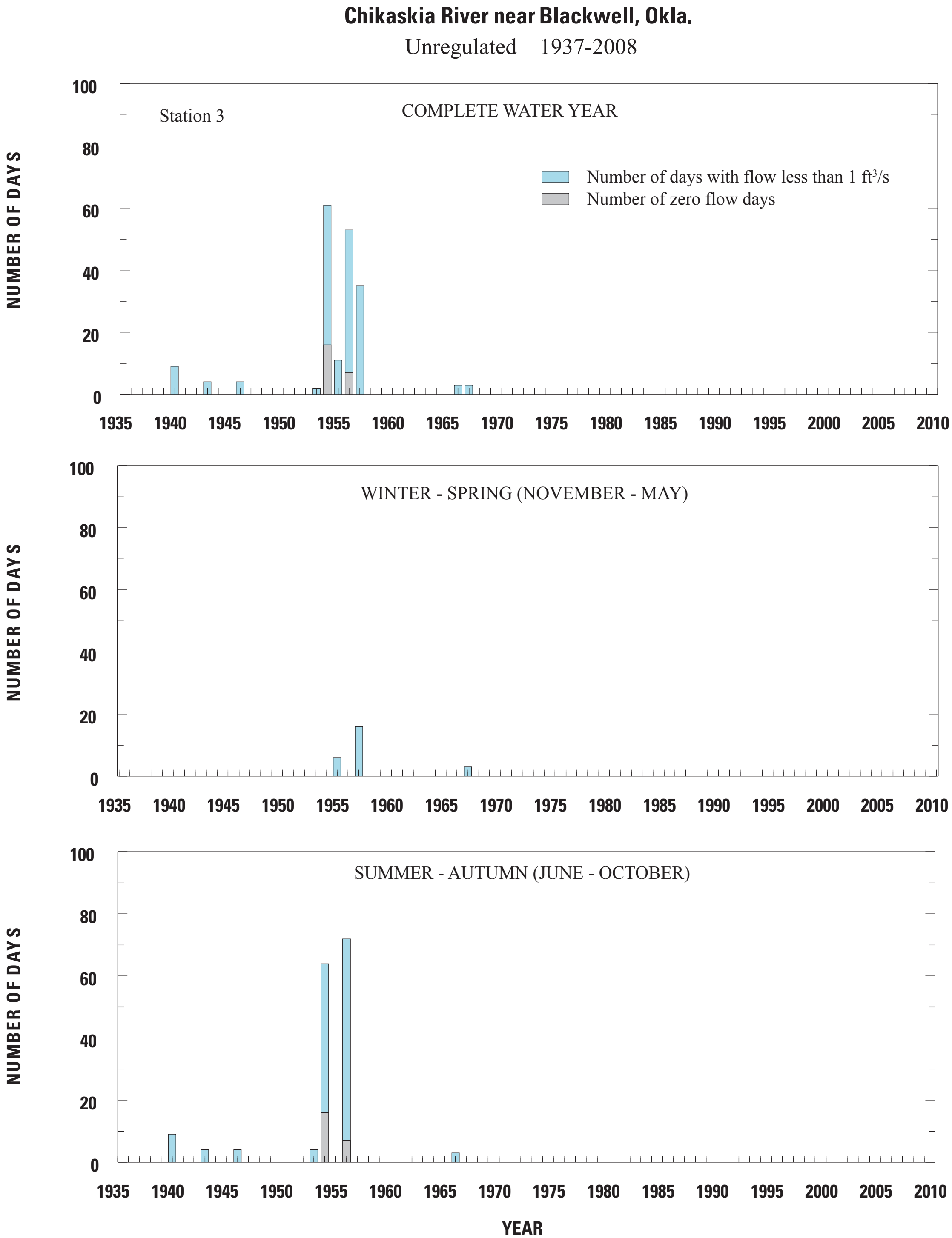

Figure 65. Number of extreme low-flow days for Chickaskia River near Blackwell, Oklahoma, (U.S. Geological Survey station identifier 07152000, station 3 from table 1), water years 1937–2008. (ft^3/s, cubic foot per second).

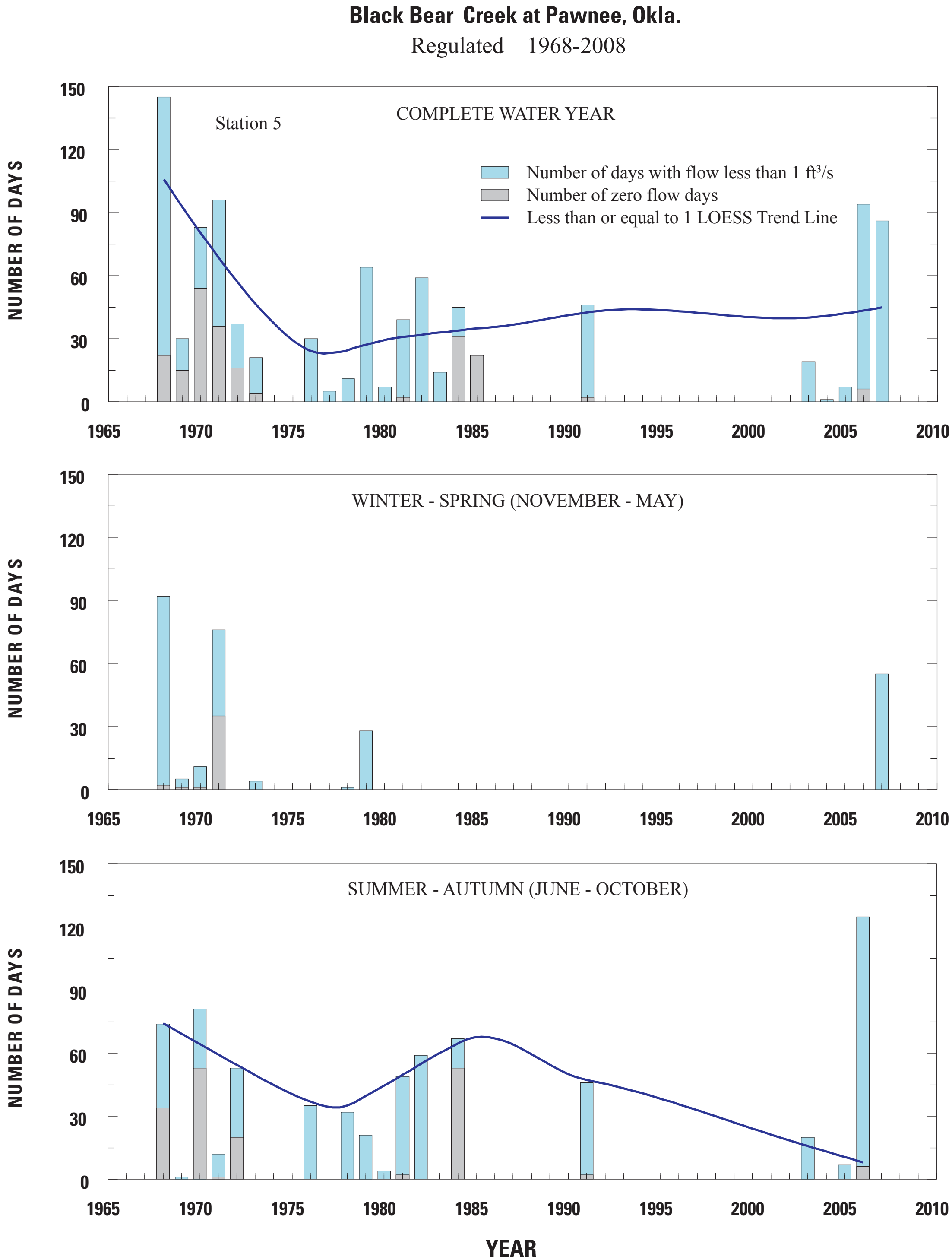

Figure 66. Number of extreme low-flow days for Black Bear Creek at Pawnee, Oklahoma, (U.S. Geological Survey station identifier 07153000, station 5 from table 1), water years 1968–2008. (ft^3/s, cubic foot per second).

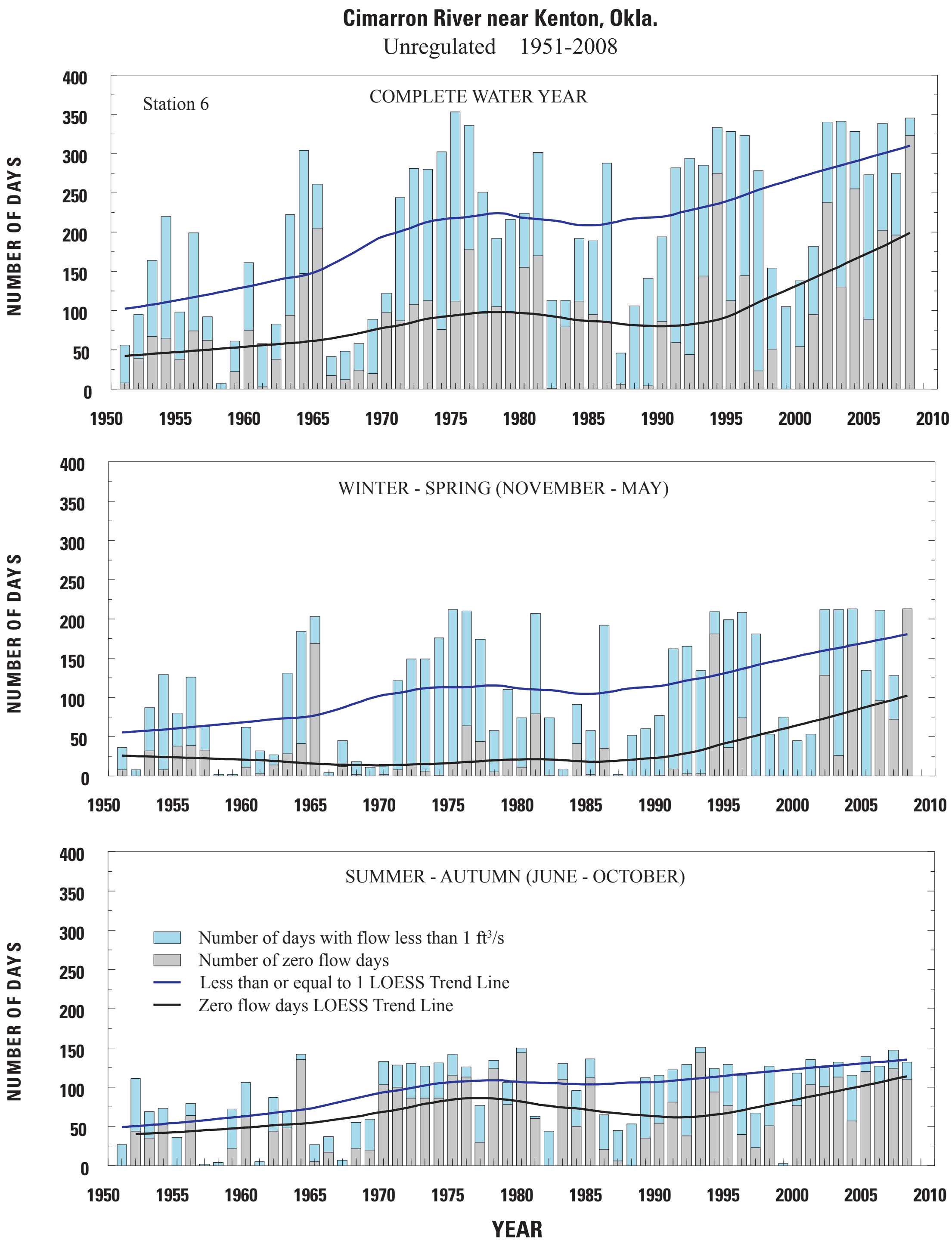

Figure 67. Number of extreme low-flow days for Cimarron River near Kenton, Oklahoma, (U.S. Geological Survey station identifier 07154500, station 6 from table 1), water years 1951–2008. (ft^3/s, cubic foot per second).

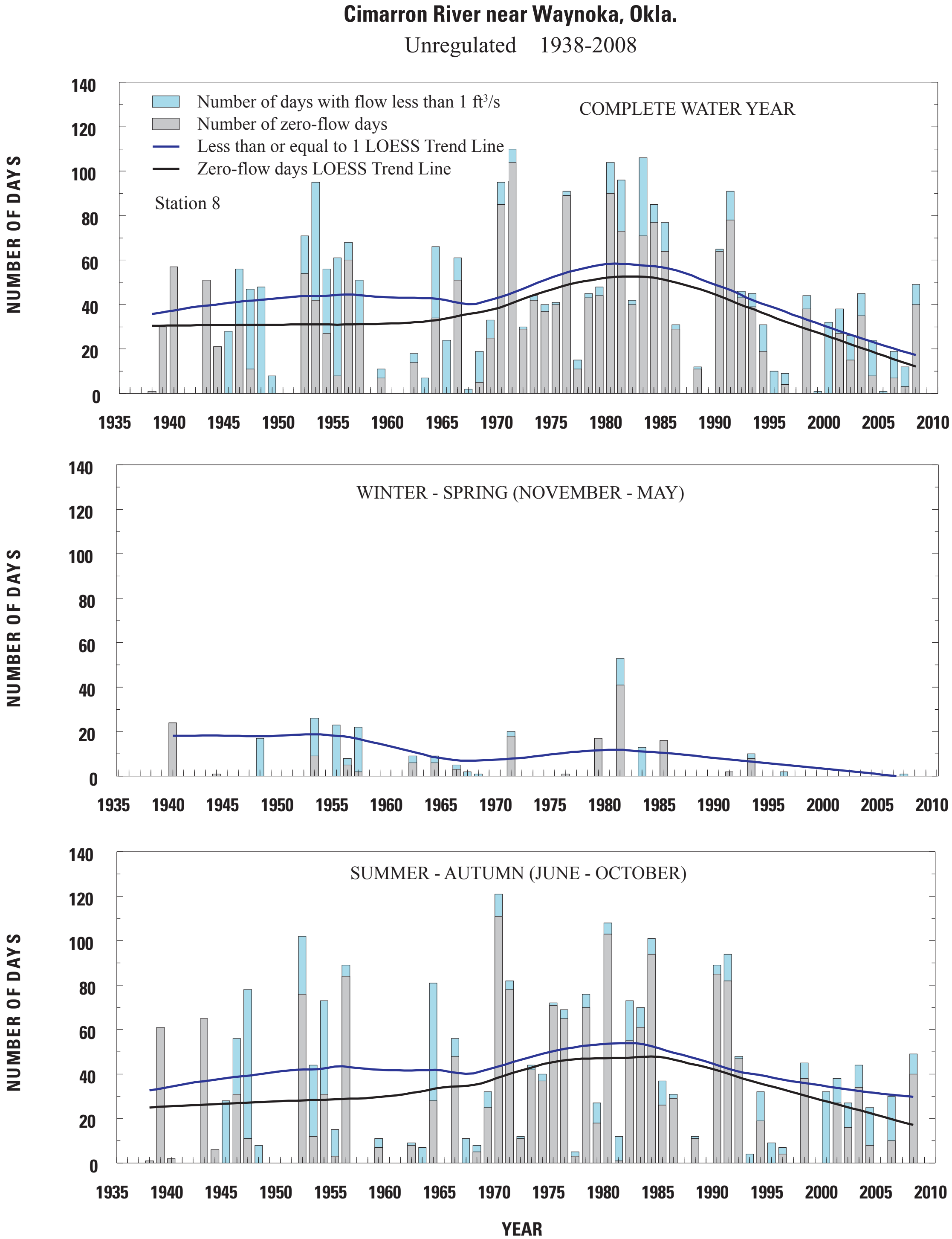

Figure 68. Number of extreme low-flow days for Cimarron River near Waynoka, Oklahoma, (U.S. Geological Survey station identifier 07158000, station 8 from table 1), water years 1938–2008. (ft^3/s, cubic foot per second).

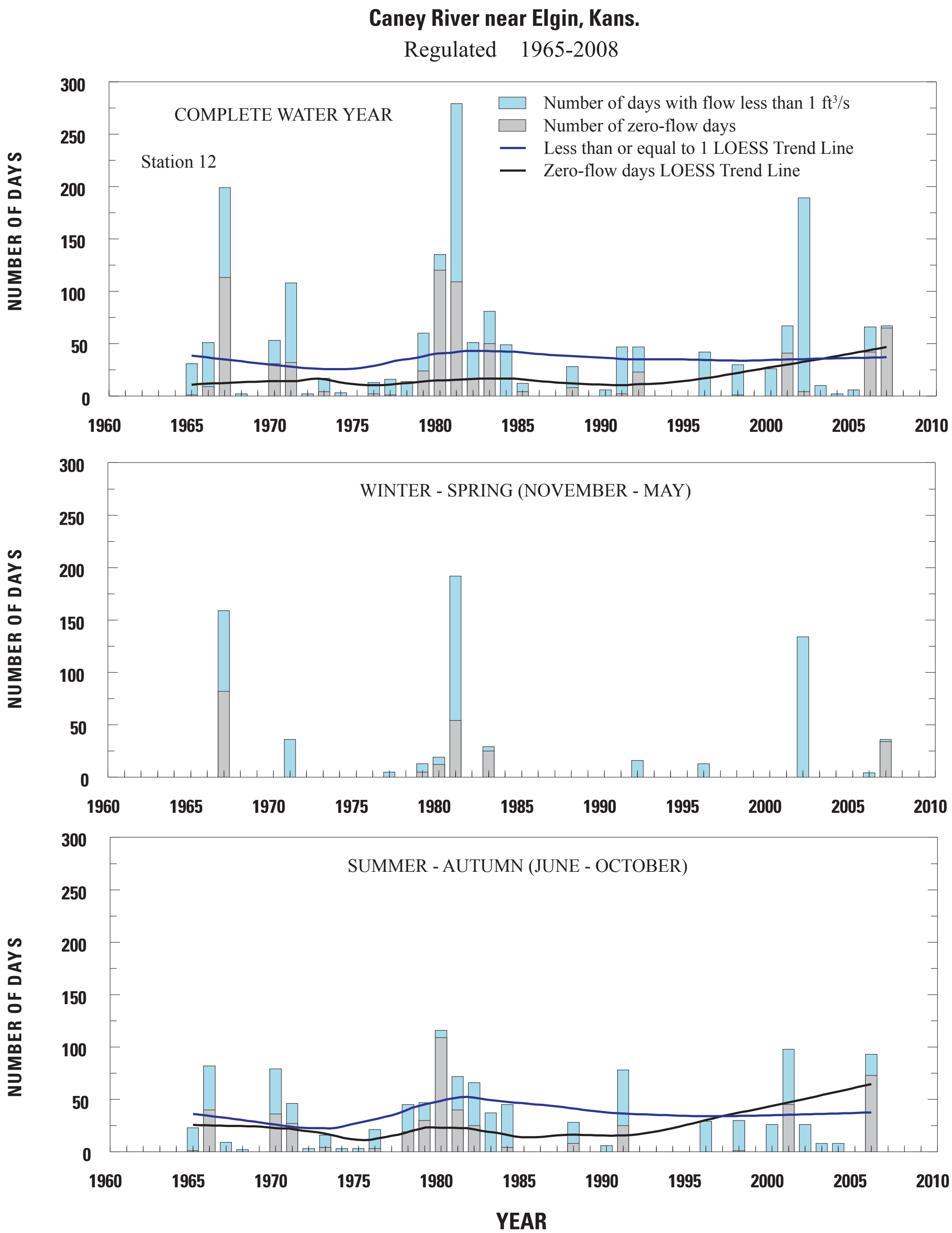

Figure 69. Number of extreme flow-flow days for Caney River near Elgin, Kansas, (U.S. Geological Survey station identifier 07172000, station 12 from table 1), water years 1965–2008. (ft³/s, cubic foot per second).

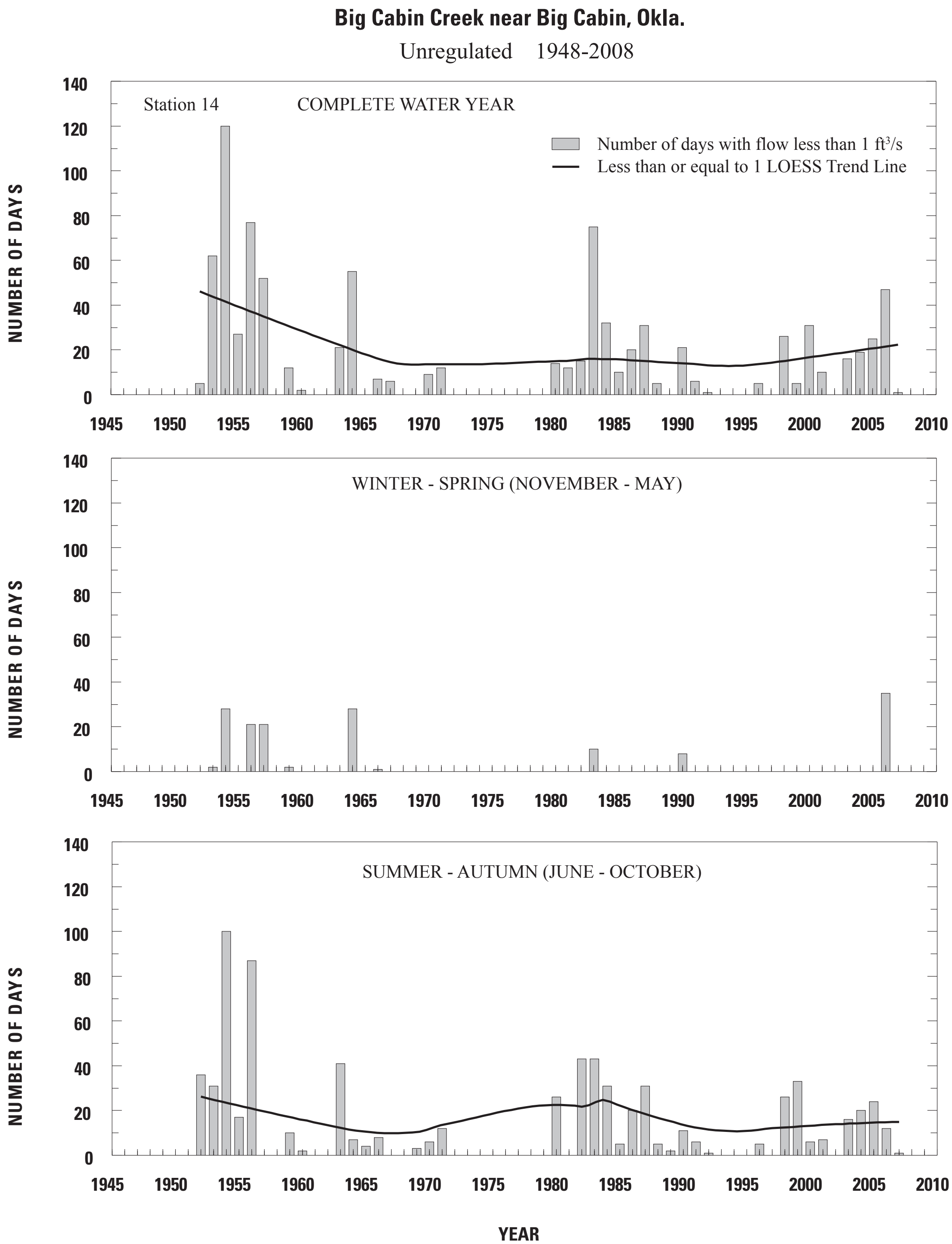

Figure 70. Number of extreme low-flow days for Big Cabin Creek near Big Cabin, Oklahoma, (U.S. Geological Survey station identifier 07191000, station 14 from table 1), water years 1948–2008. (ft^3/s, cubic foot per second).

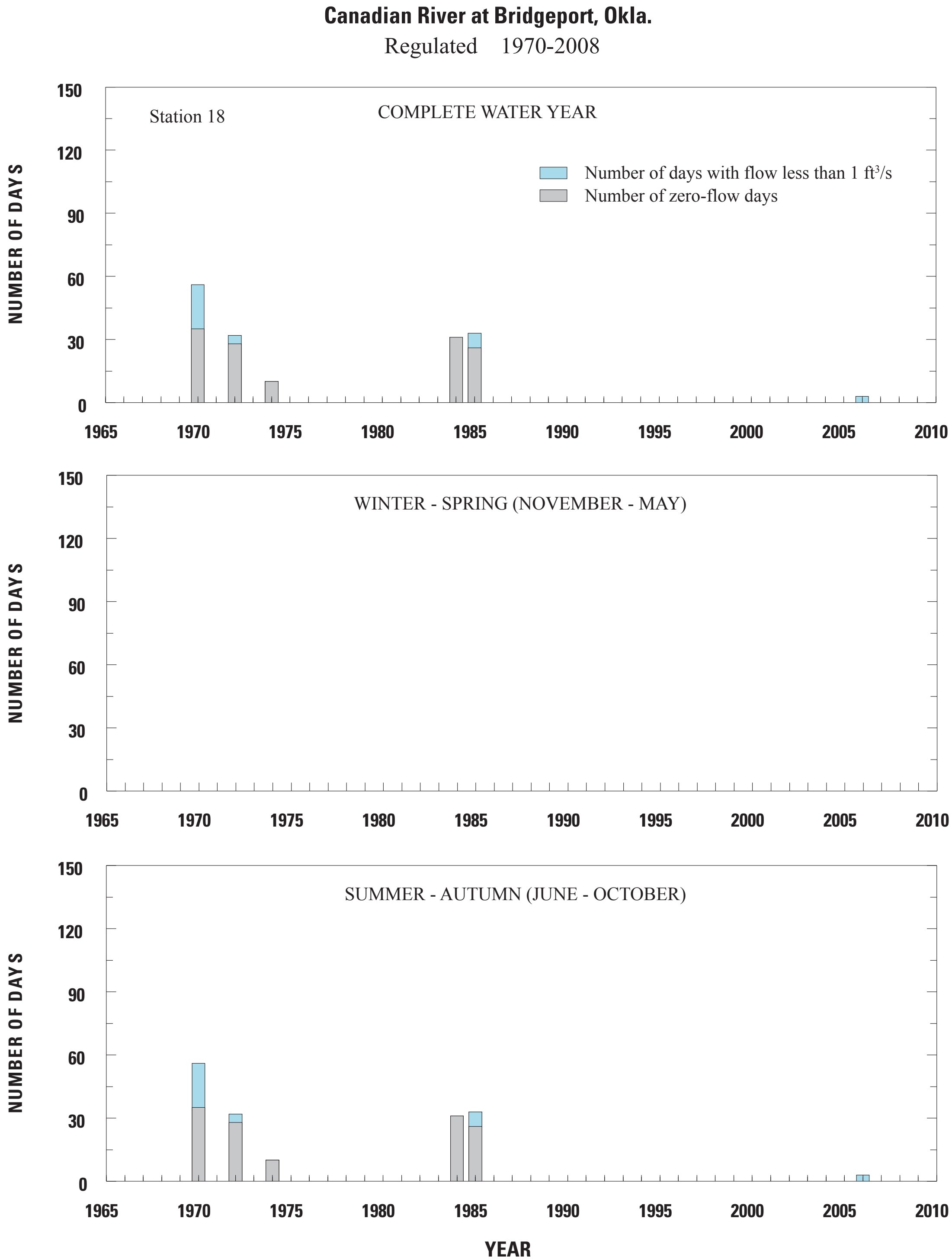

Figure 71. Number of extreme low-flow days for Canadian River at Bridgeport, Oklahoma, (U.S. Geological Survey station identifier 07228500, station 18 from table 1), water years 1970–2008. (ft^3/s, cubic foot per second).

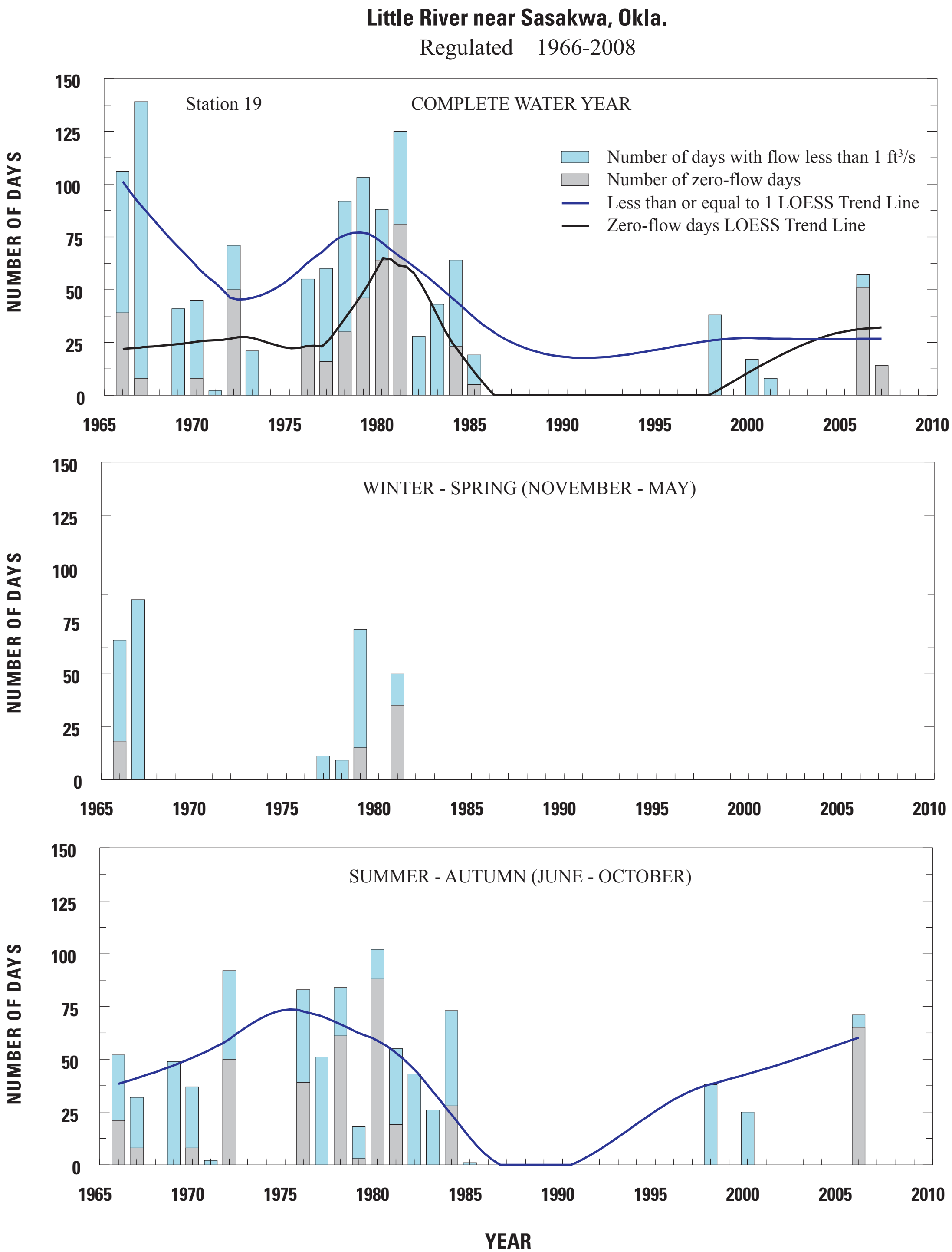

Figure 72. Number of extreme low-flow days for Little River near Sasakwa, Oklahoma, (U.S. Geological Survey station identifier 07231000, station 19 from table 1), water years 1966–2008. (ft^3/s, cubic foot per second).

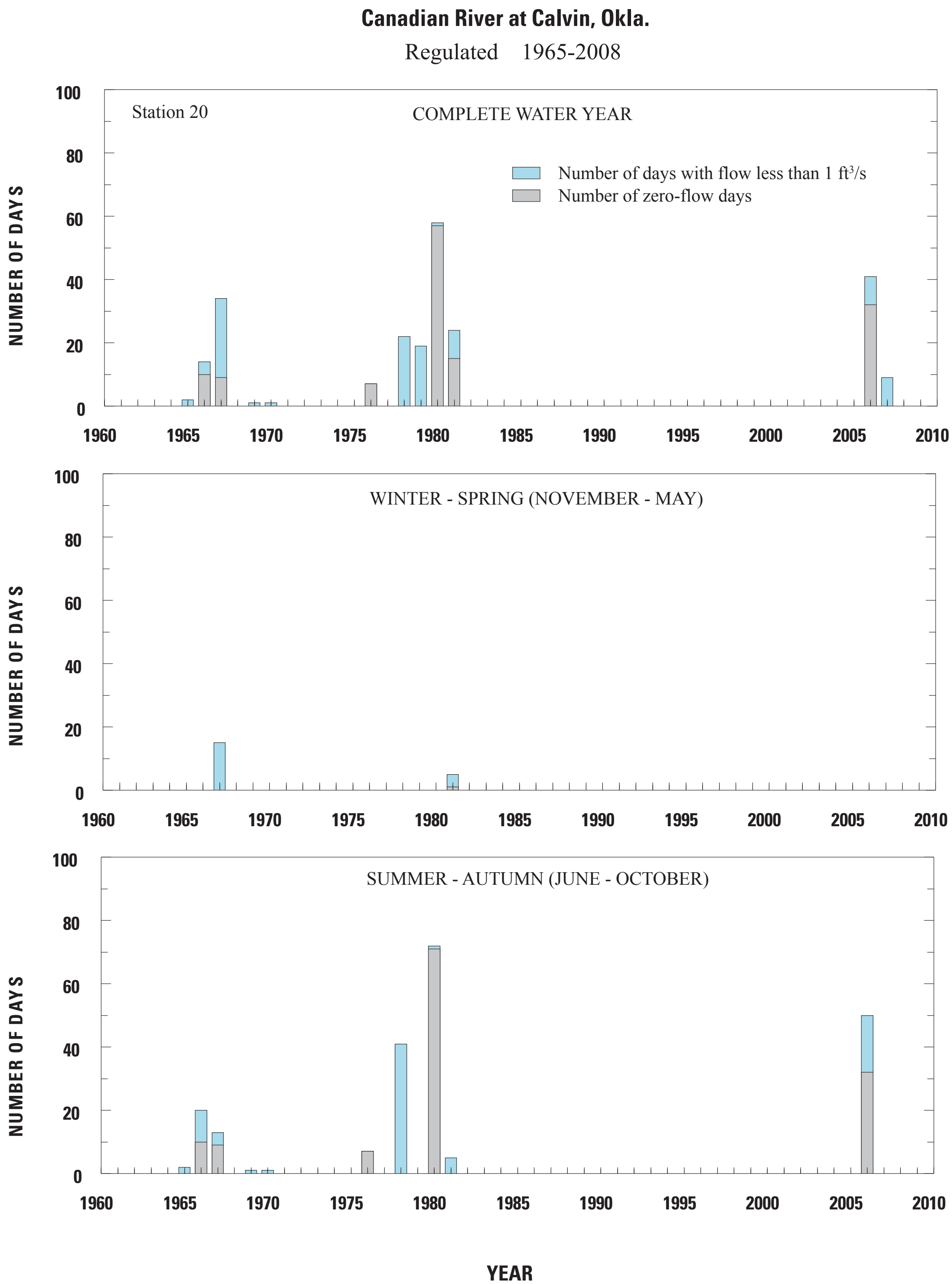

Figure 73. Number of extreme low-flow days for Canadian River at Calvin, Oklahoma, (U.S. Geological Survey station identifier 07231500, station 20 from table 1), water years 1965–2008. (ft^3/s, cubic foot per second).

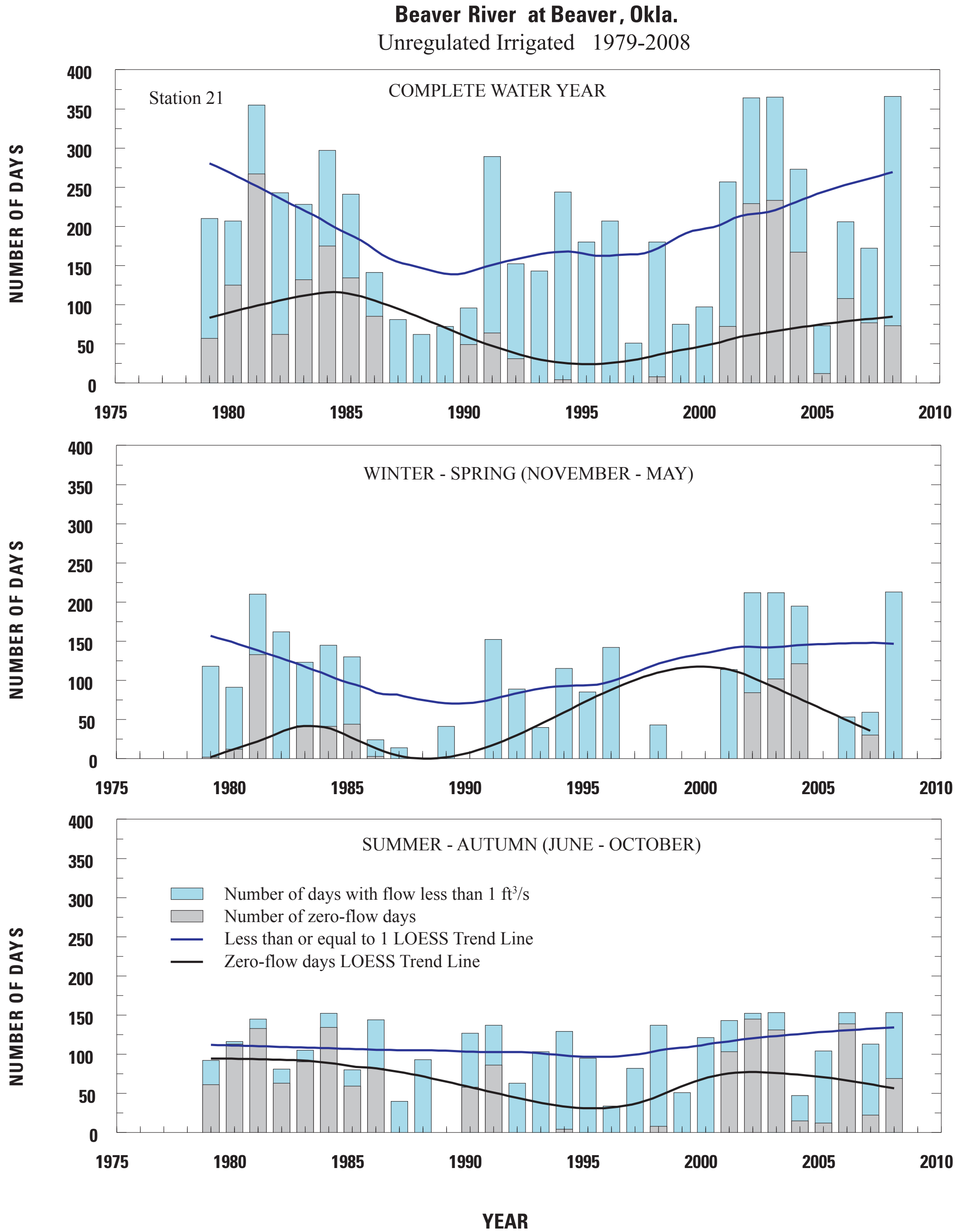

Figure 74. Number of extreme low-flow days for Beaver River at Beaver, Oklahoma, (U.S. Geological Survey station identifier 07234000, station 21 from table 1), water years 1979–2008. (ft^3/s, cubic foot per second).

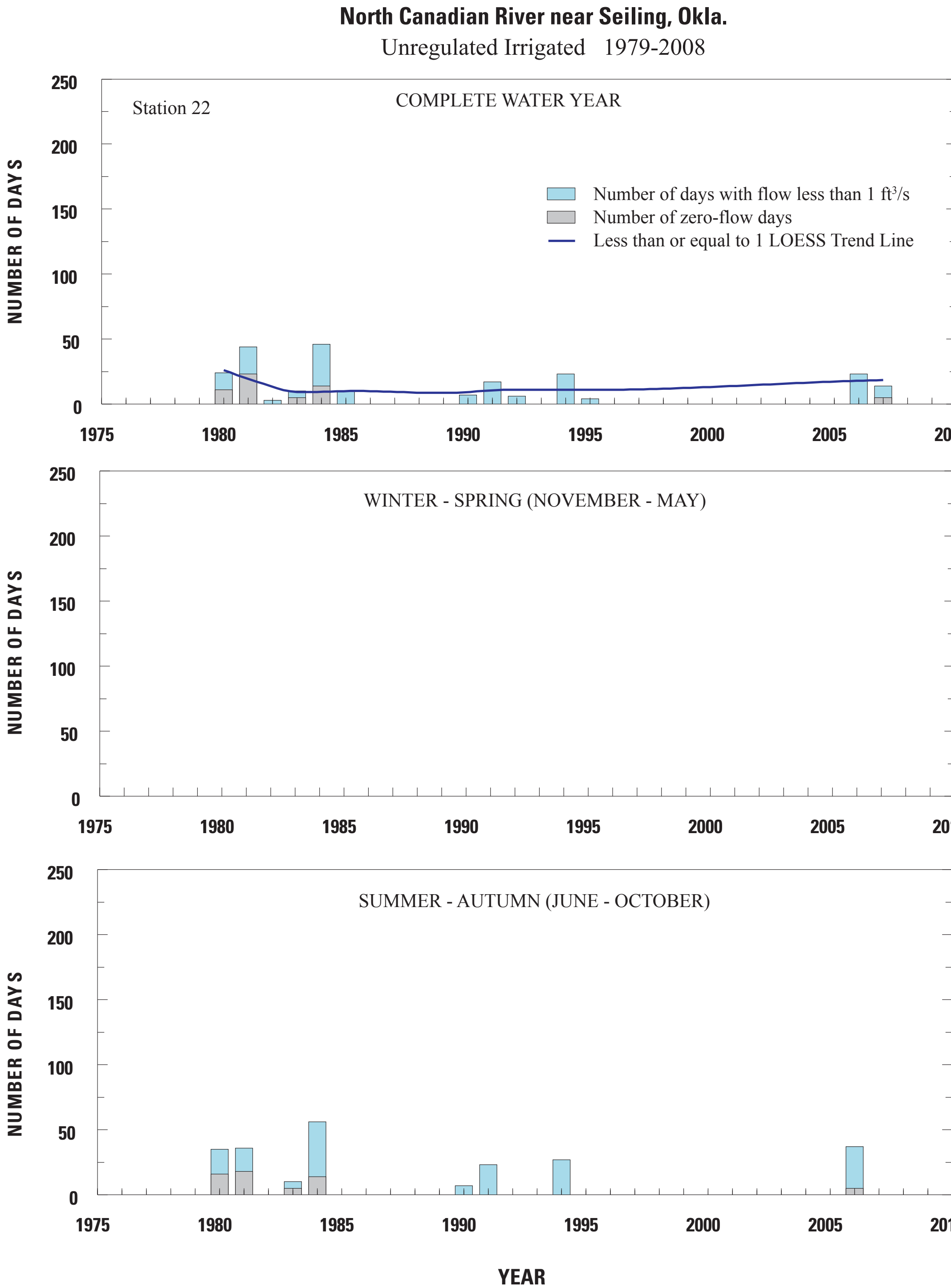

Figure 75. Number of extreme low-flow days for North Canadian River near Seiling, Oklahoma, (U.S. Geological Survey station identifier 07238000, station 22 from table 1), water years 1979–2008. (ft^3/s, cubic foot per second).

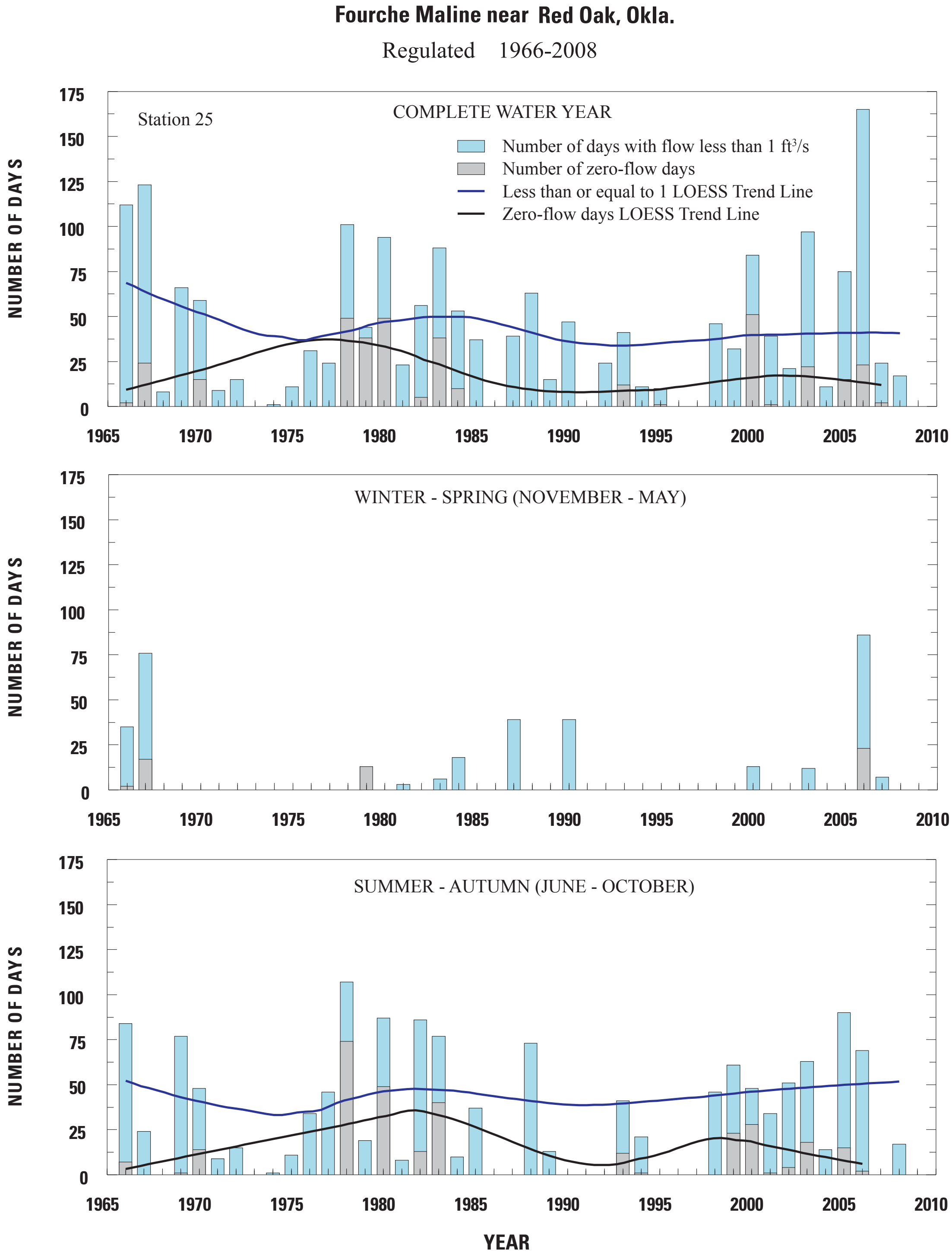

Figure 76. Number of extreme low-flow days for Fourche Maline near Red Oak, Oklahoma, (U.S. Geological Survey station identifier 07247500, station 25 from table 1), water years 1966–2008. (ft^3/s, cubic foot per second).

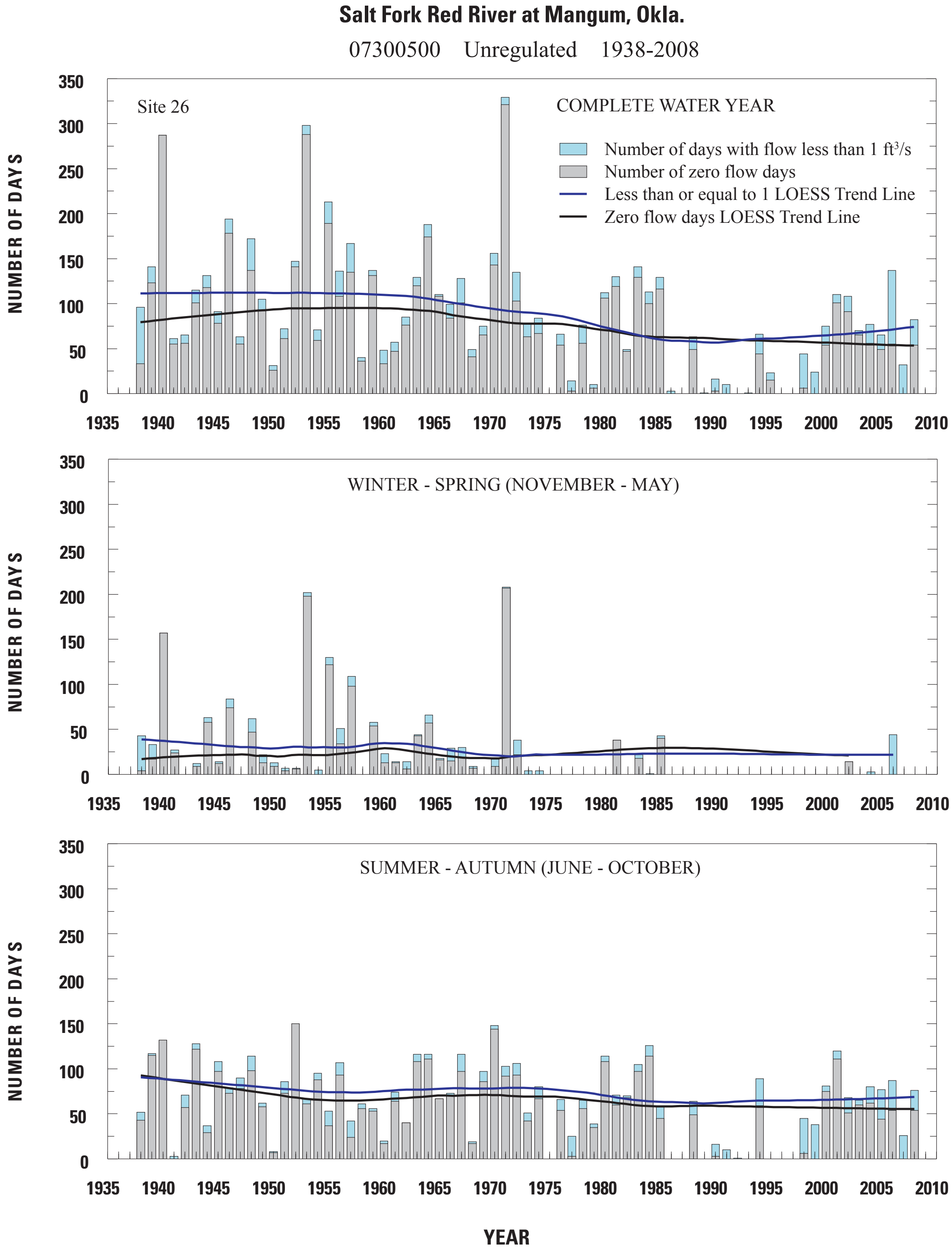

Figure 77. Number of extreme low-flow days for Salt Fork Red River at Mangum , Oklahoma, (U.S. Geological Survey station identifier 07300500, station 26 from table 1), water years 1938–2008. (ft^3/s, cubic foot per second).

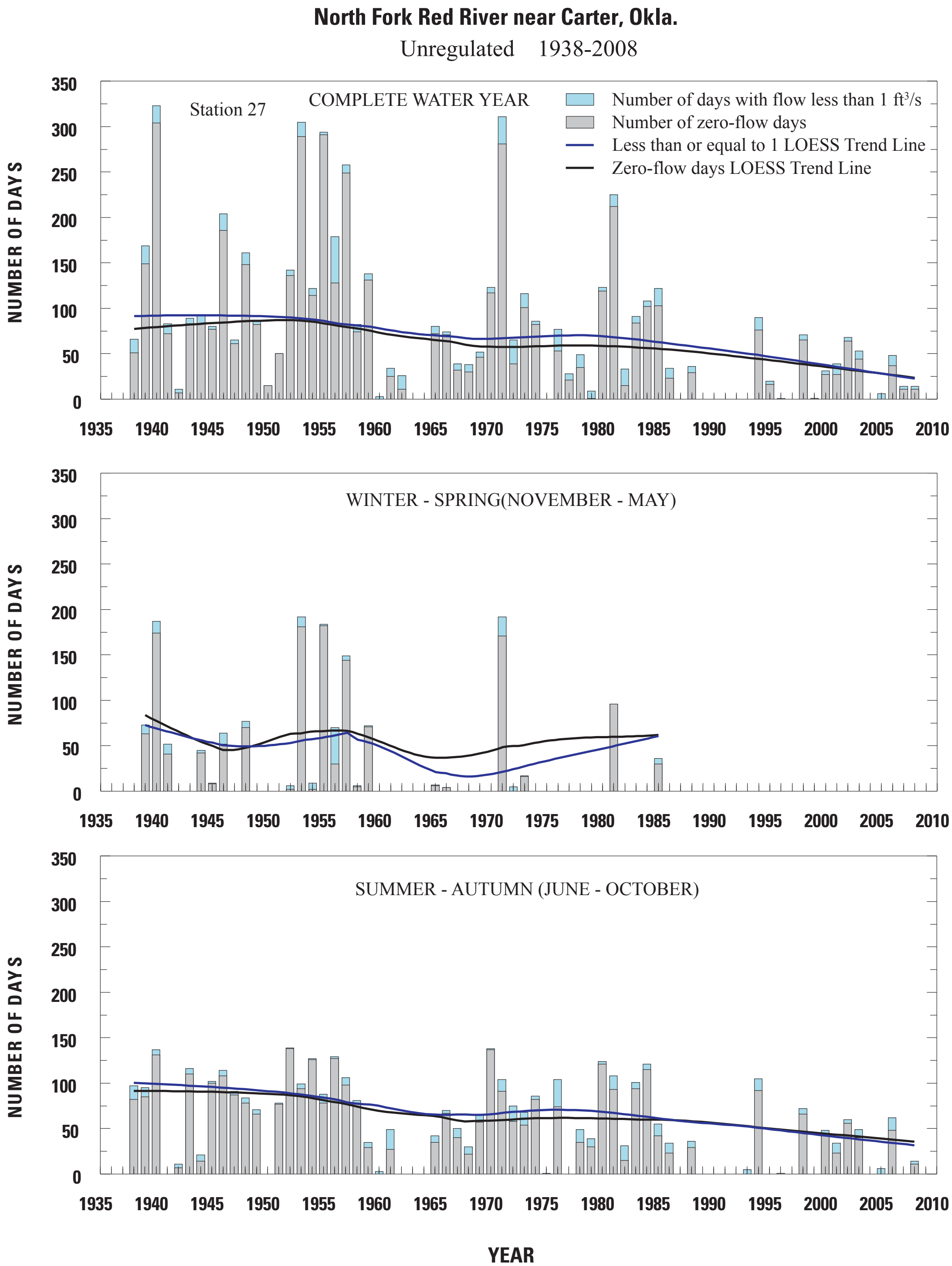

Figure 78. Number of extreme low-flow days for North Fork Red River near Carter , Oklahoma, (U.S. Geological Survey station identifier 07301500, station 27 from table 1), water years 1938–2008. (ft^3/s, cubic foot per second).

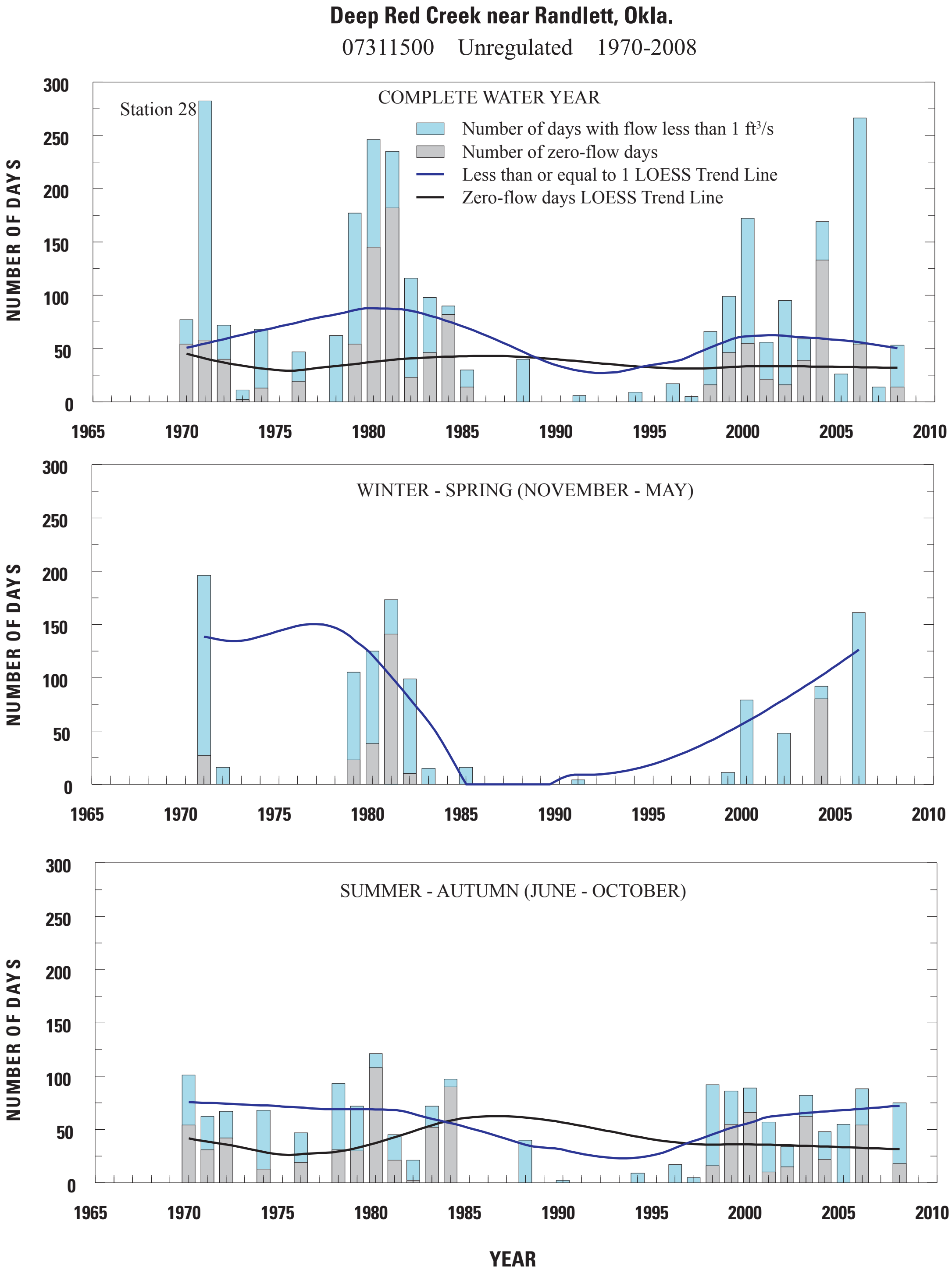

Figure 79. Number of extreme low-flow days for Deep Red Creek near Randlett , Oklahoma, (U.S. Geological Survey station identifier 07311500, station 28 from table 1), water years 1970–2008. (ft^3/s, cubic foot per second).

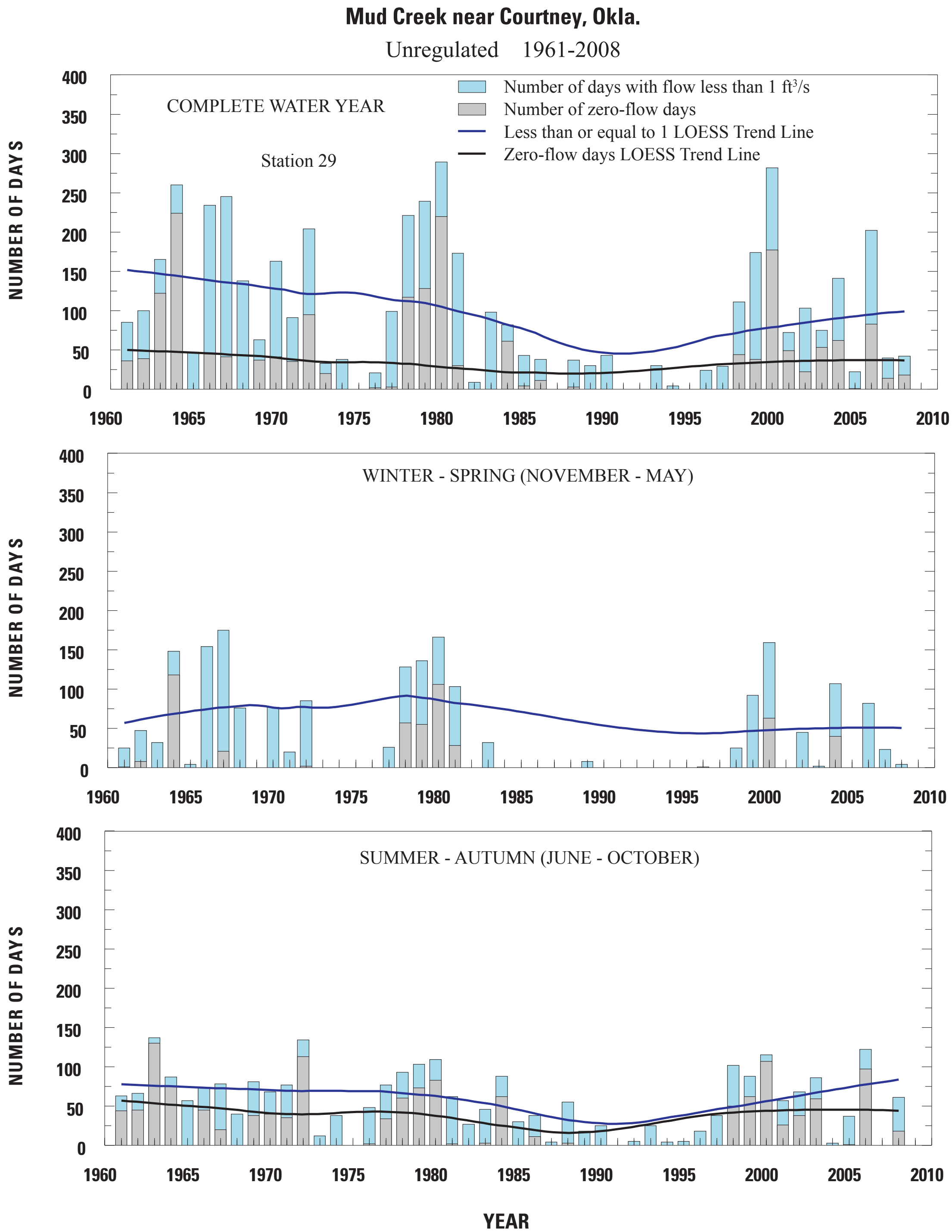

Figure 80. Number of extreme low-flow days for Mud Creek near Courtney , Oklahoma, (U.S. Geological Survey station identifier 07315700, station 29 from table 1), water years 1961–2008. (ft^3/s, cubic foot per second).

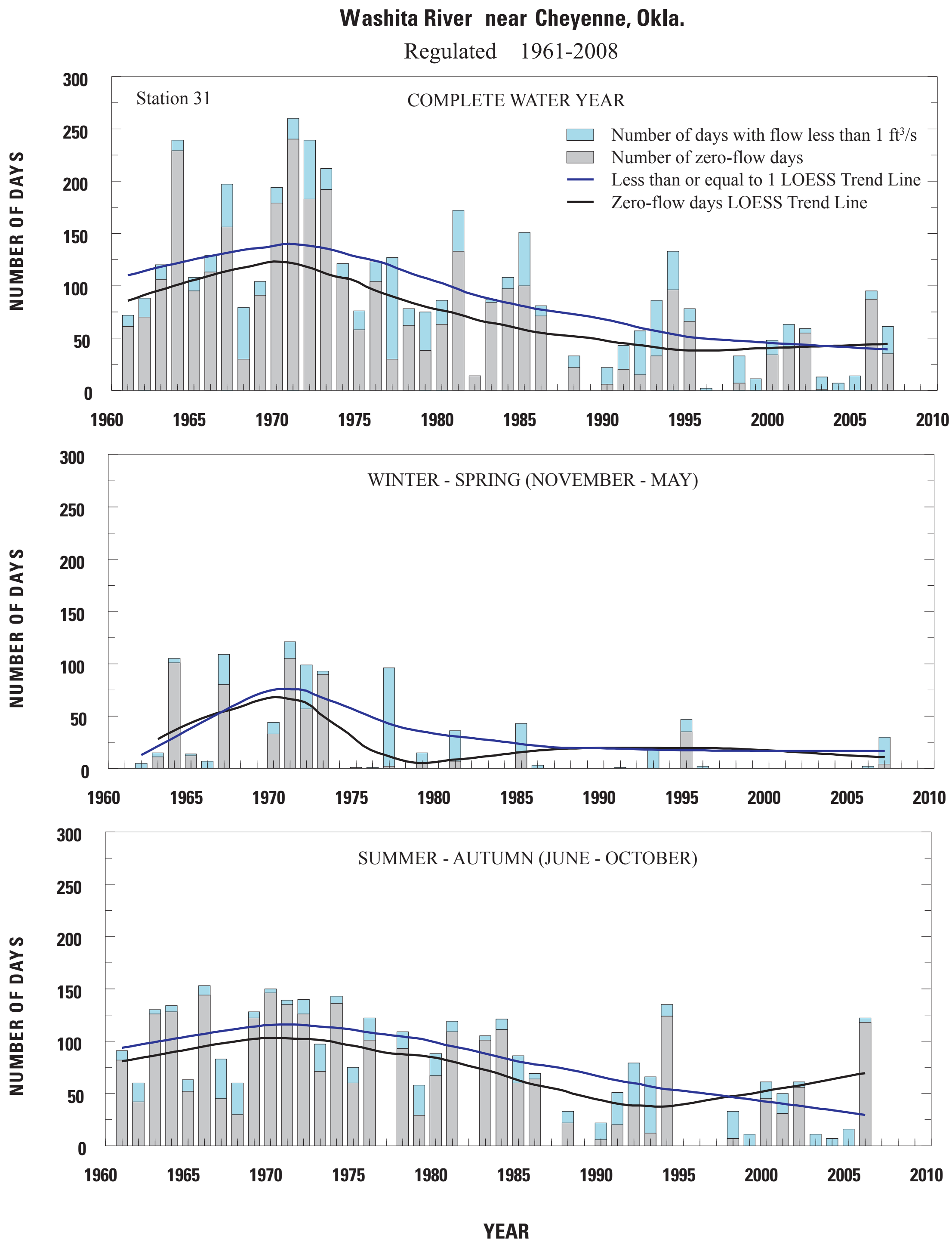

Figure 81. Number of extreme low-flow days for Washita River near Cheyenne , Oklahoma, (U.S. Geological Survey station identifier 07316500, station 31 from table 1), water years 1961–2008. (ft^3/s, cubic foot per second).

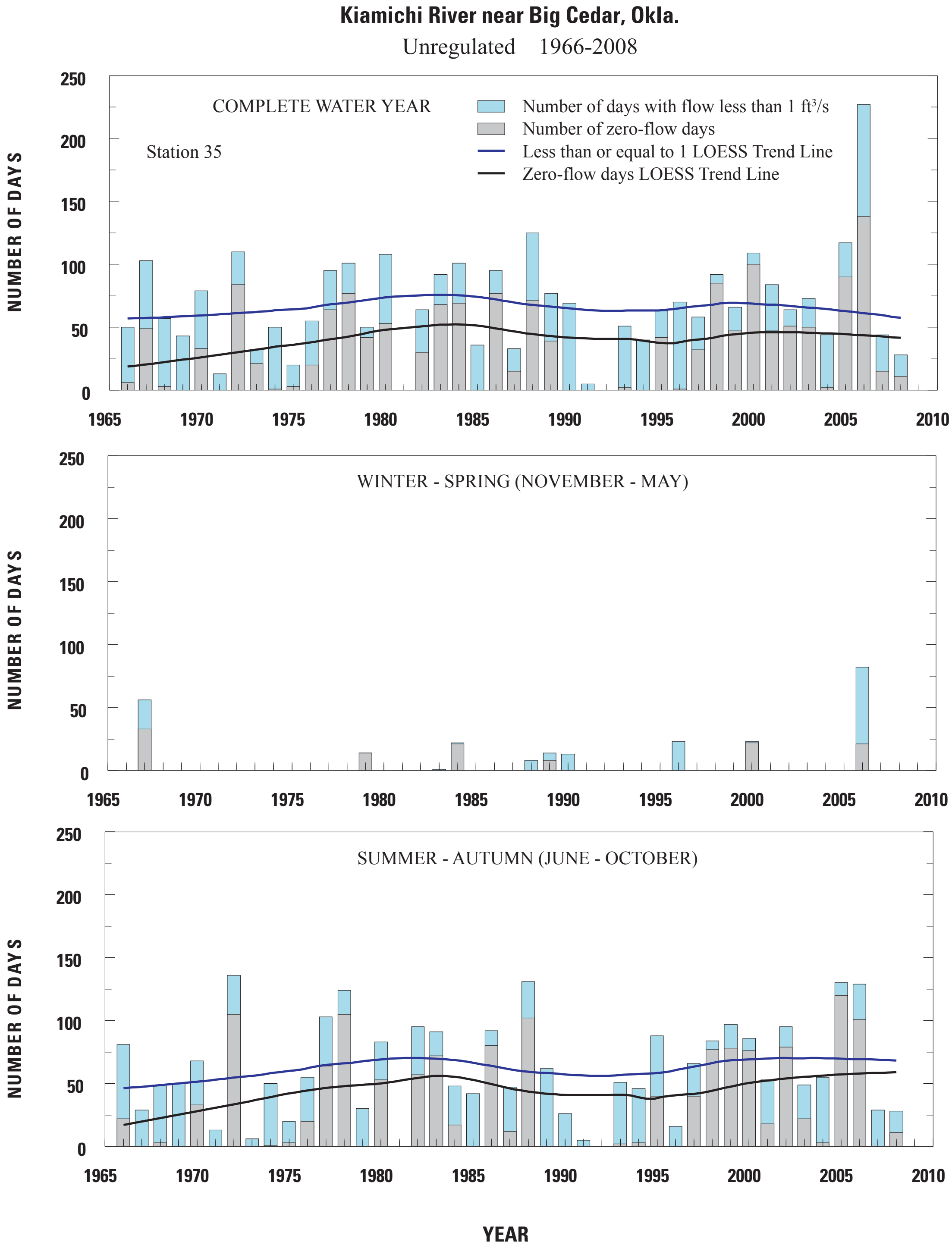

Figure 82. Number of extreme low-flow days for Kiamichi River near Big Cedar , Oklahoma, (U.S. Geological Survey station identifier 07335700, station 35 from table 1), water years 1966–2008. (ft^3/s, cubic foot per second).

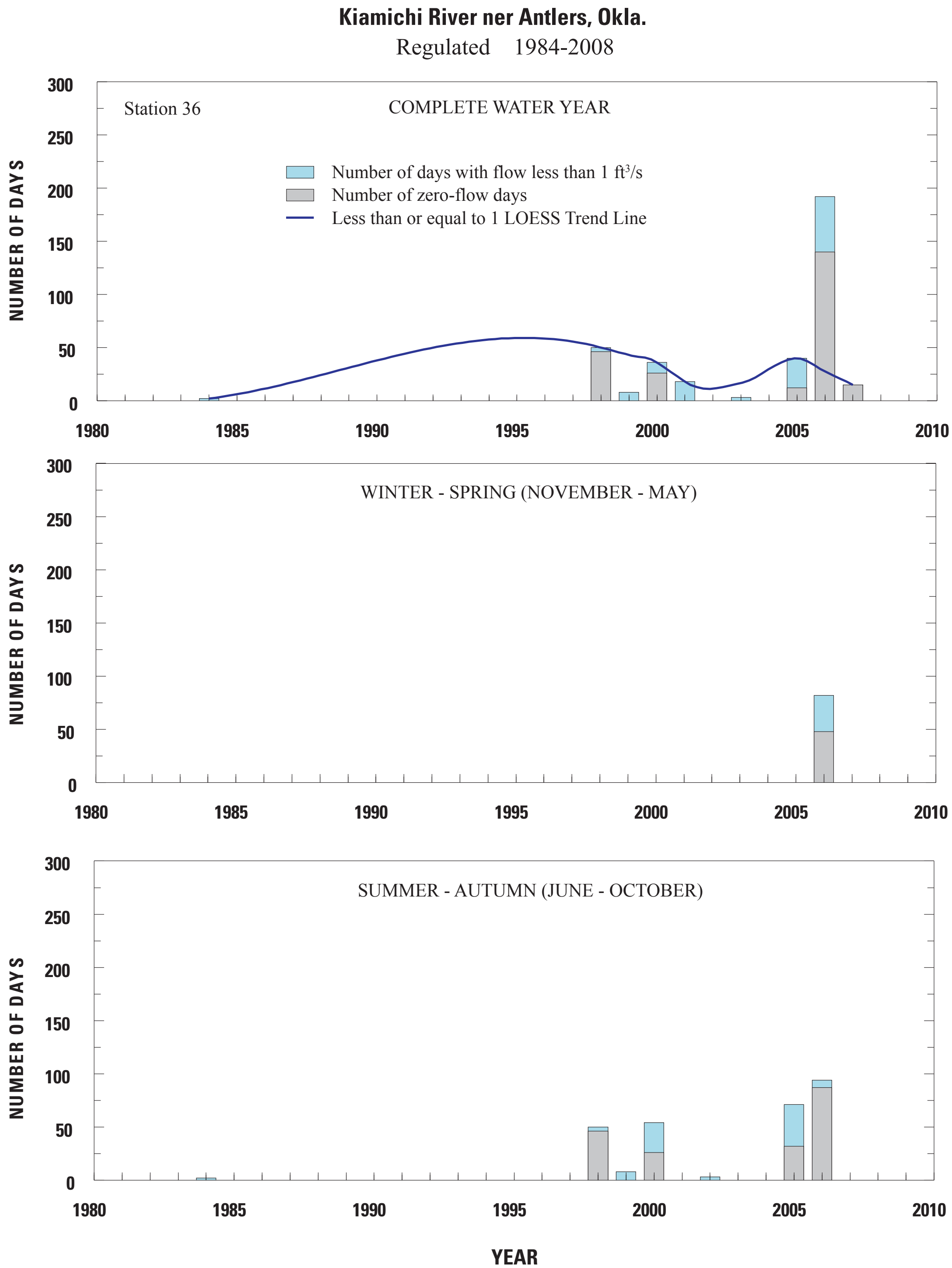

Figure 83. Number of extreme low-flow days for Kiamichi River near Antlers , Oklahoma, (U.S. Geological Survey station identifier 07336200, station 36 from table 1), water years 1984–2008. (ft^3/s, cubic foot per second).

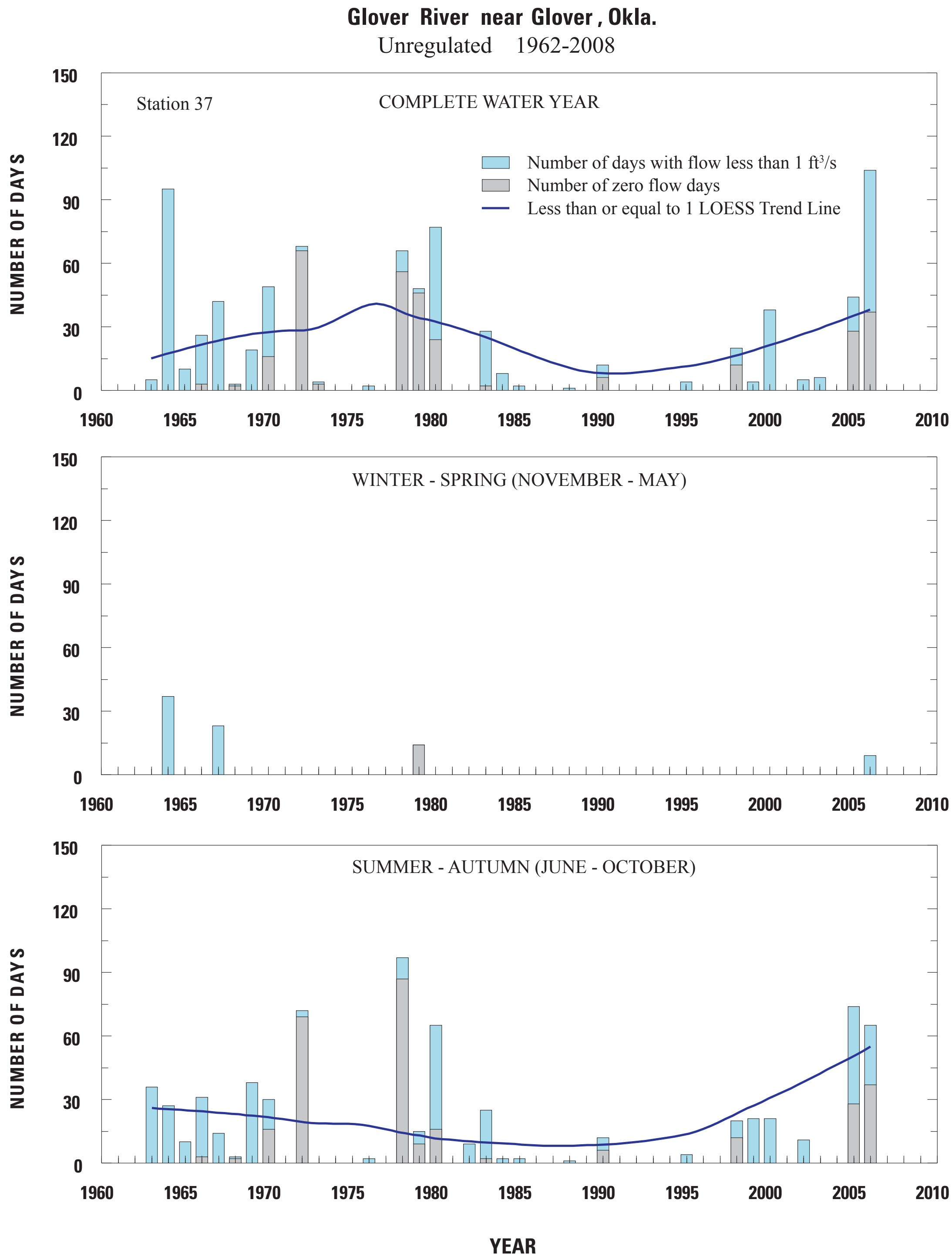

Figure 84. Number of extreme low-flow days for Glover River near Glover, Oklahoma, (U.S. Geological Survey station identifier 07337900, station 37 from table 1), water years 1962–2008. (ft^3/s, cubic foot per second).

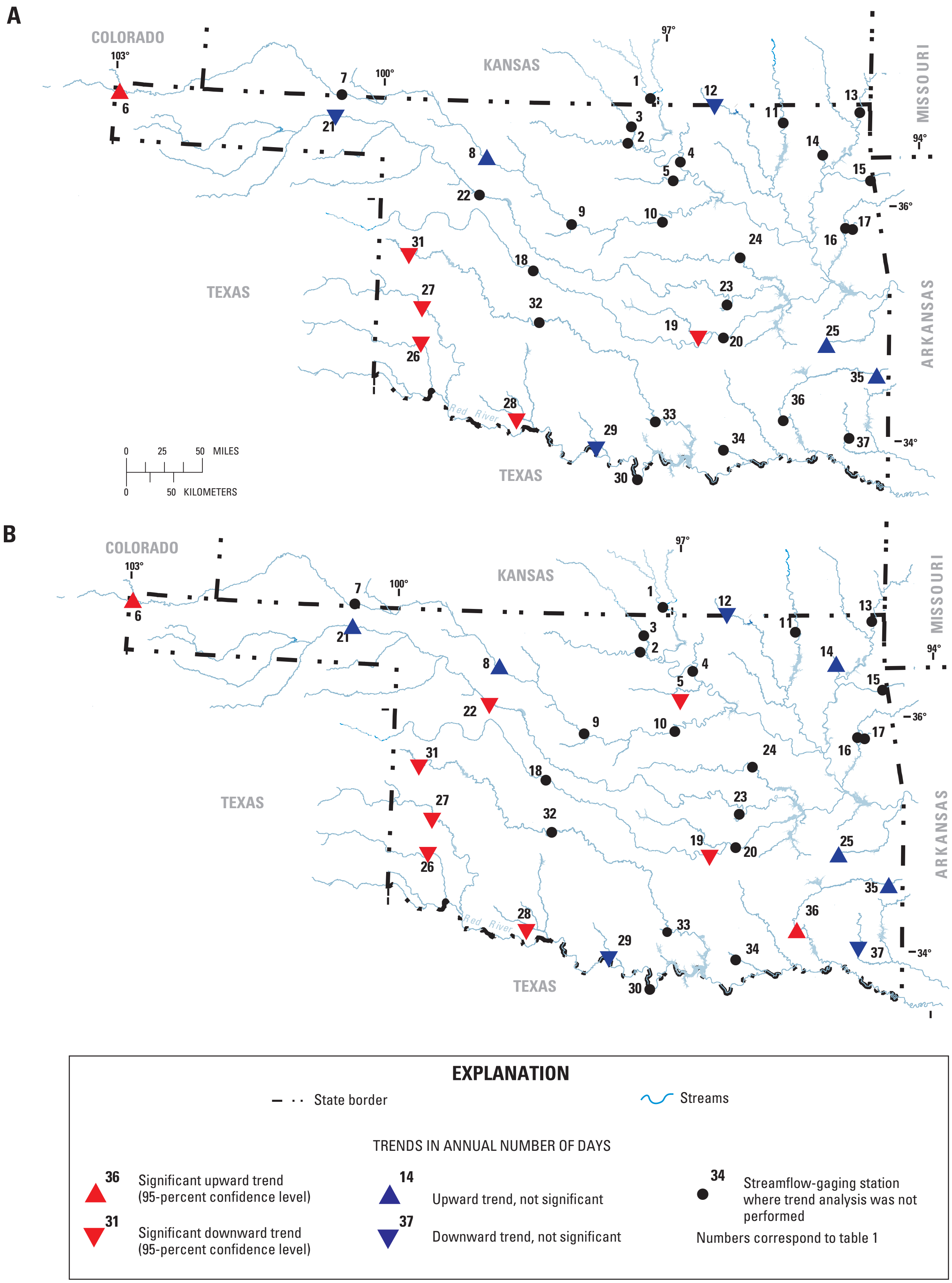

Figure 85. Results of Kendall's tau trend analyses of the annual number of days when streamflow is (A) equal to zero cubic feet per second and (B) less than 1 cubic foot per second for selected streamflow-gaging stations in and near Oklahoma.

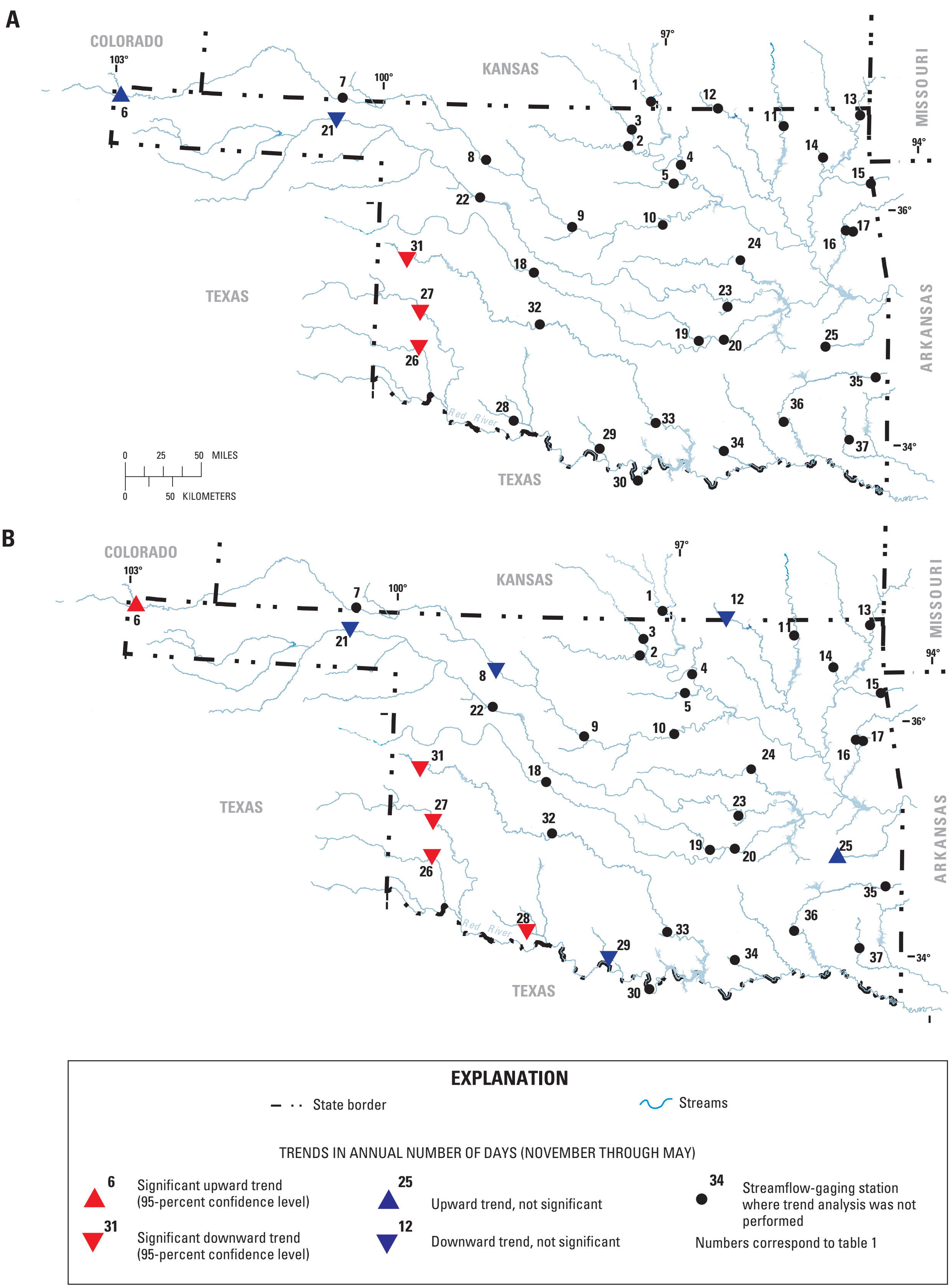

Figure 86. Results of Kendall's tau trend analyses of the number of days per year during the period of November through May (winter-spring) when streamflow is (A) equal to zero cubic feet per second and (B) less than 1 cubic foot per second for selected streamflow-gaging stations in and near Oklahoma.

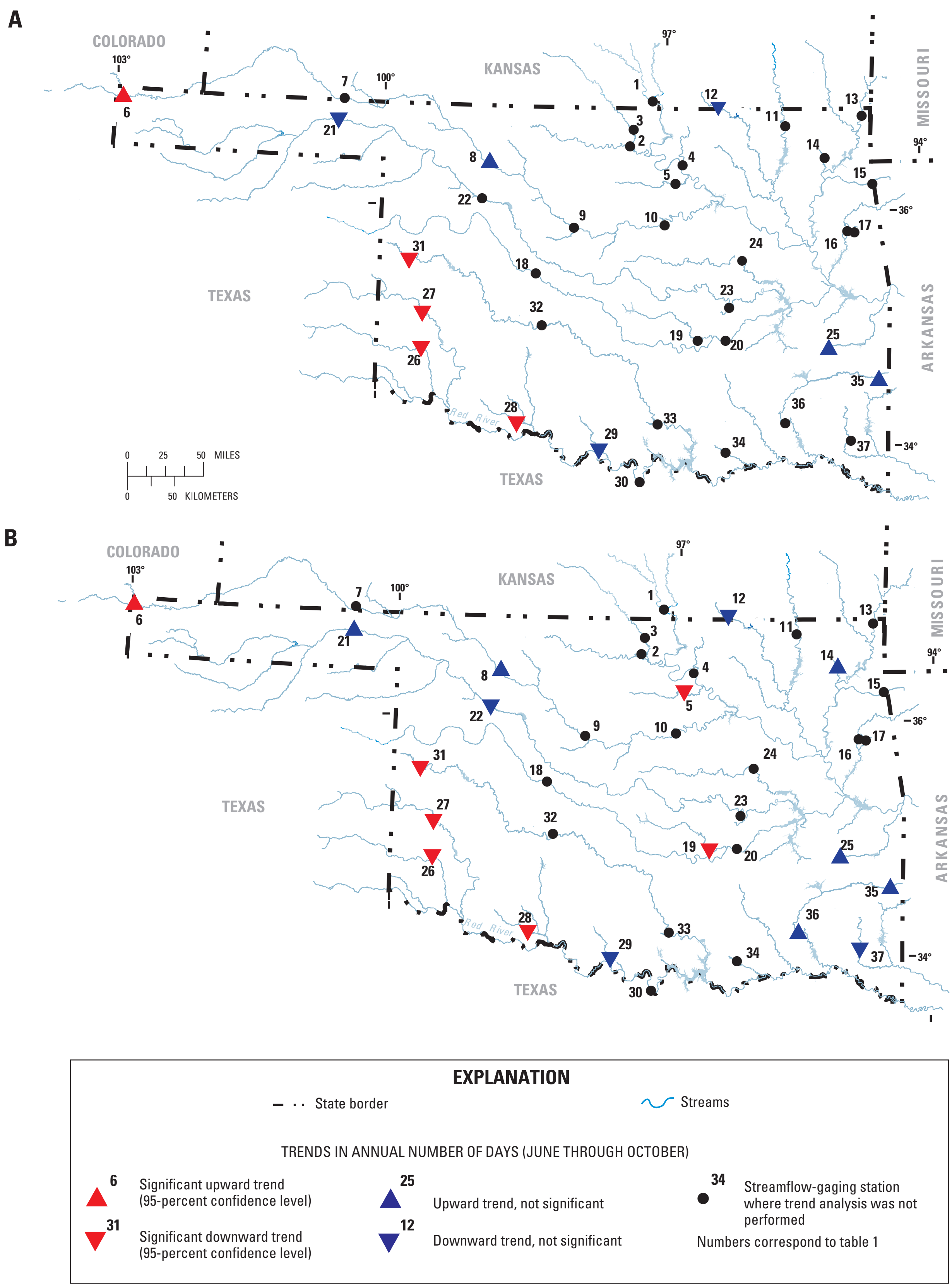

Figure 87. Results of Kendall's tau trend analyses of the number of days per year during the period of June through October (summer-autumn) when streamflow is (A) equal to zero cubic feet per second and (B) less than 1 cubic foot per second for selected streamflow-gaging stations in and near Oklahoma.

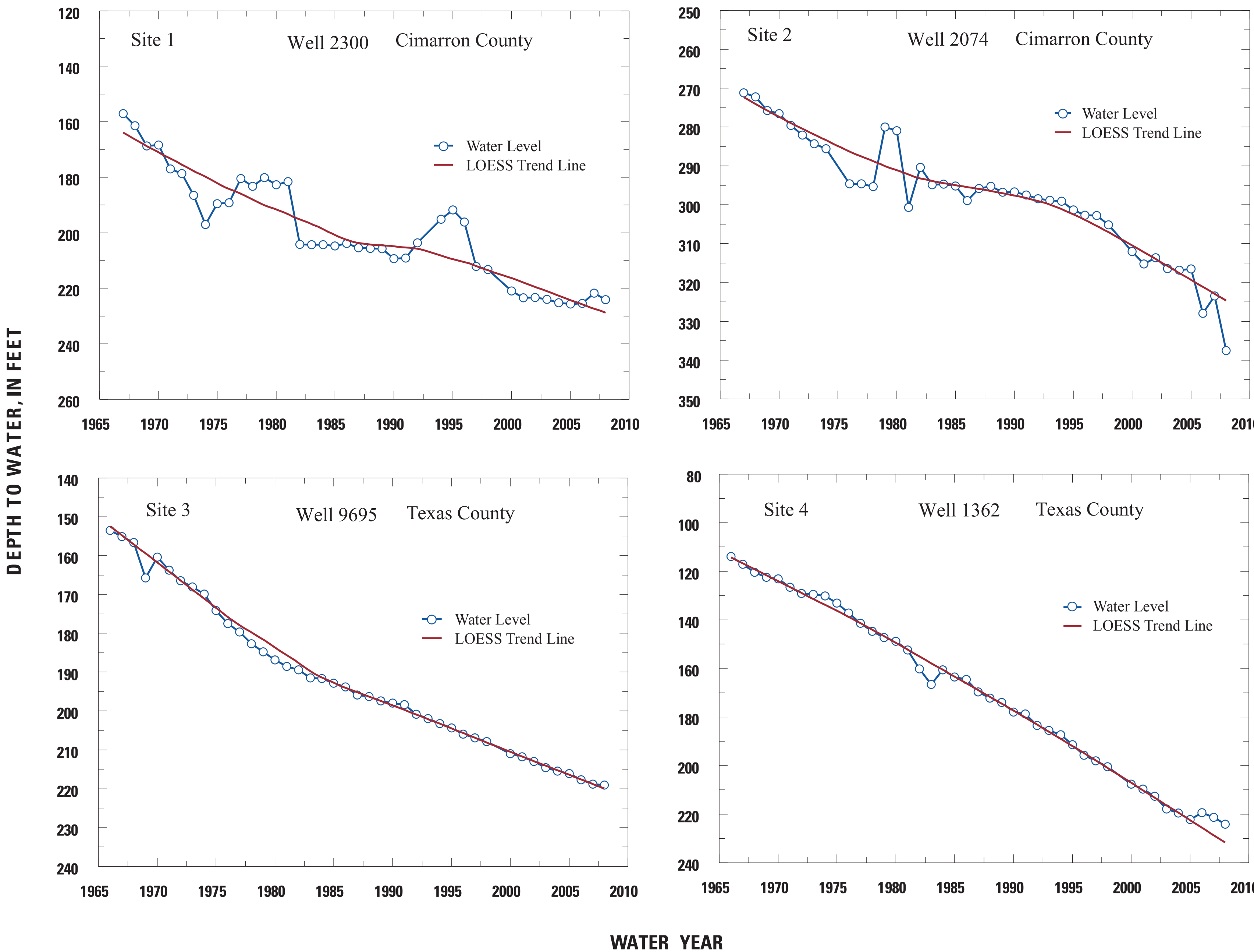

Figure 88. Groundwater levels and LOESS trend lines by using available periods of record for wells 1–4.

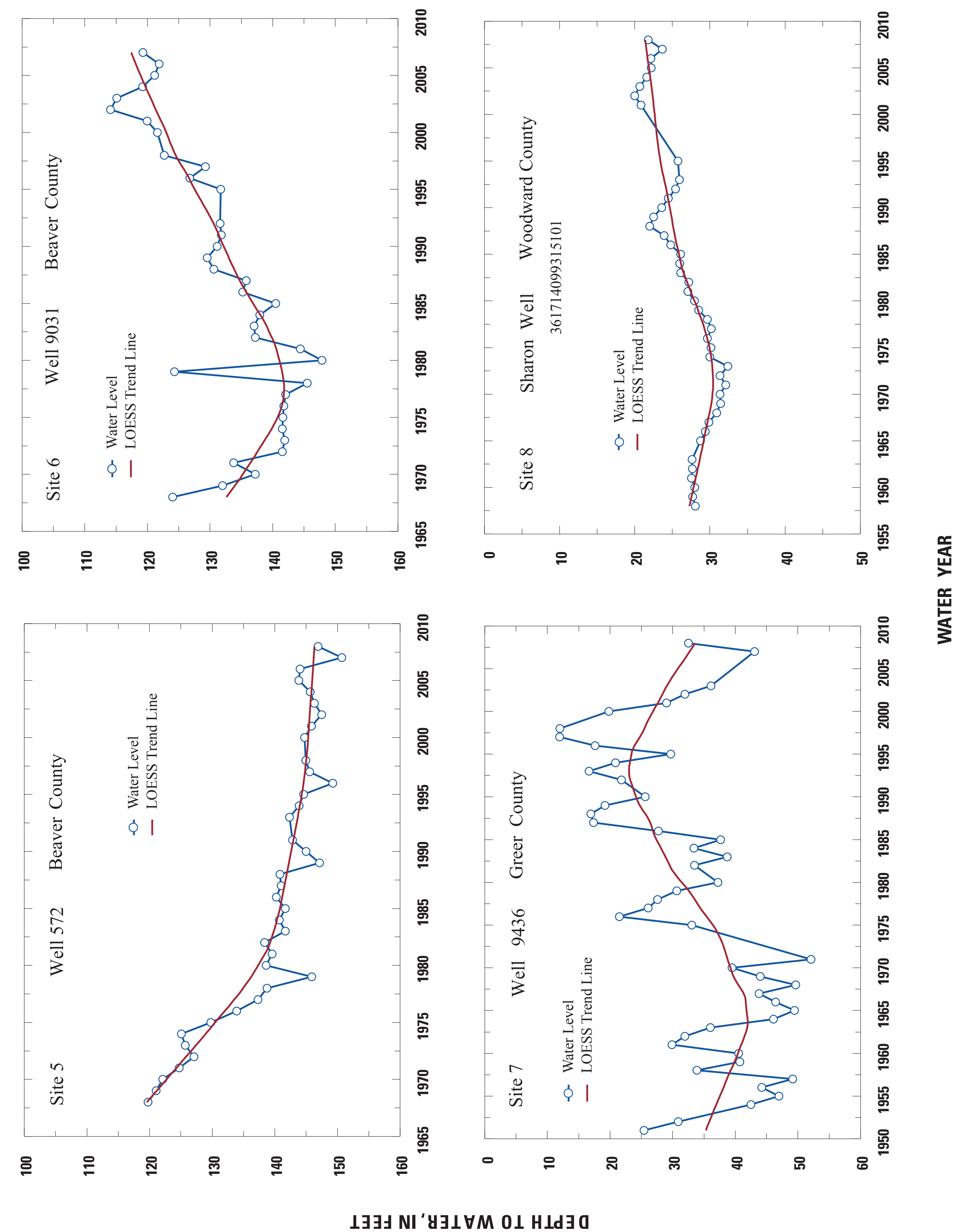

Figure 89. Groundwater levels and LOESS trend lines by using available periods of record for wells 5–8.

Figure 90. Groundwater levels and LOESS trend lines by using available periods of record for wells 9–12.

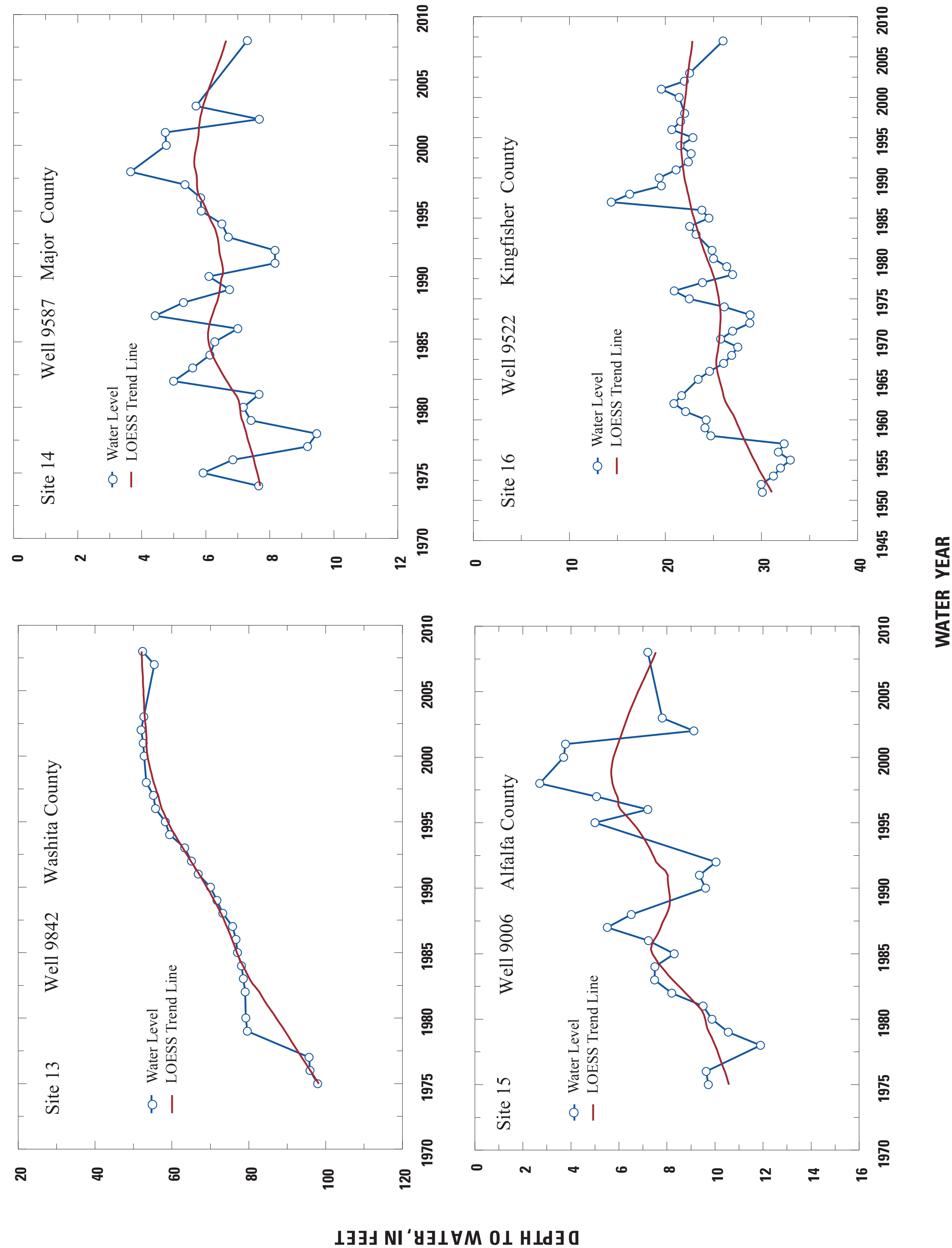

Figure 91. Groundwater levels and LOESS trend lines by using available periods of record for wells 13–16.

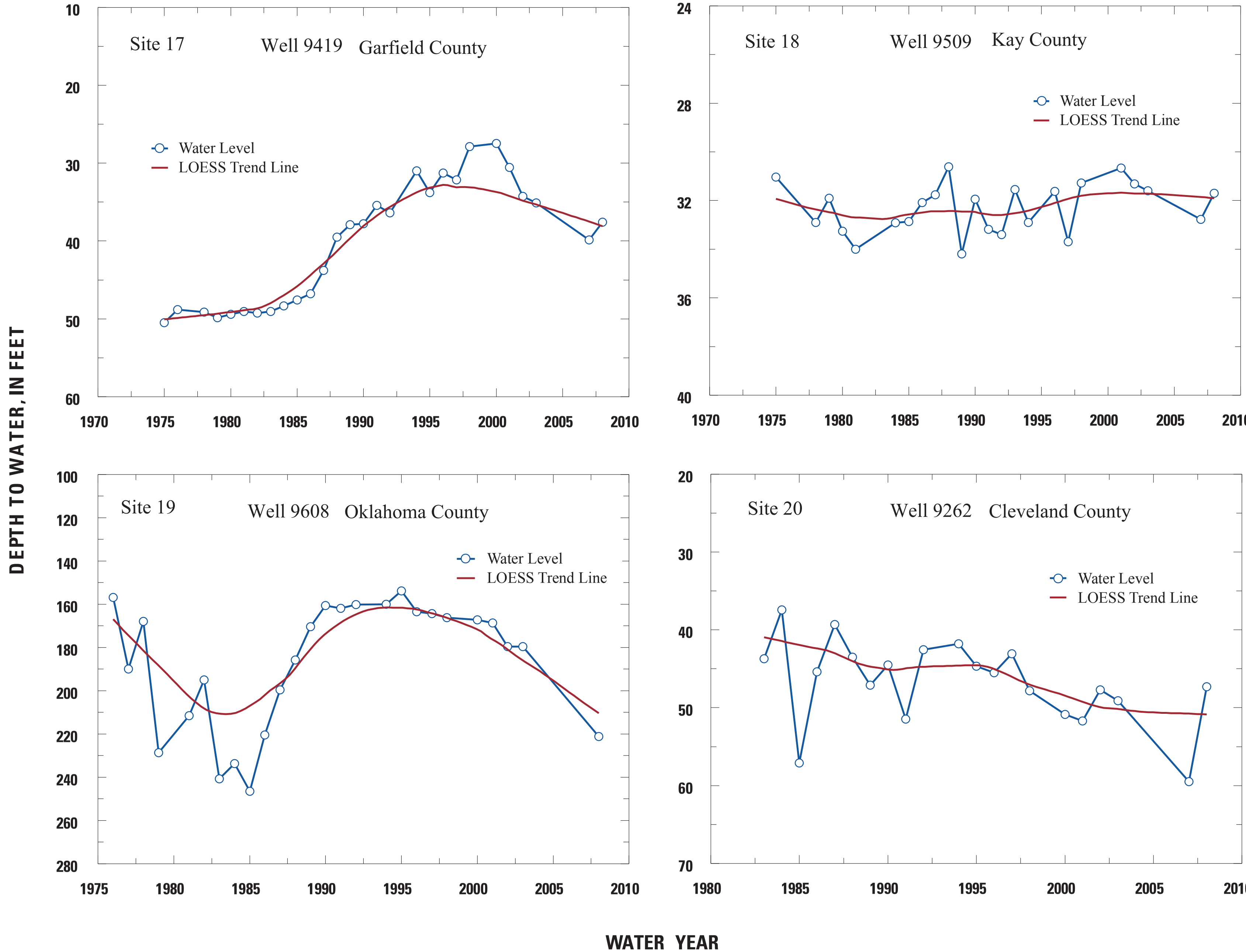

Figure 92. Groundwater levels and LOESS trend lines by using available periods of record for wells 17–20.

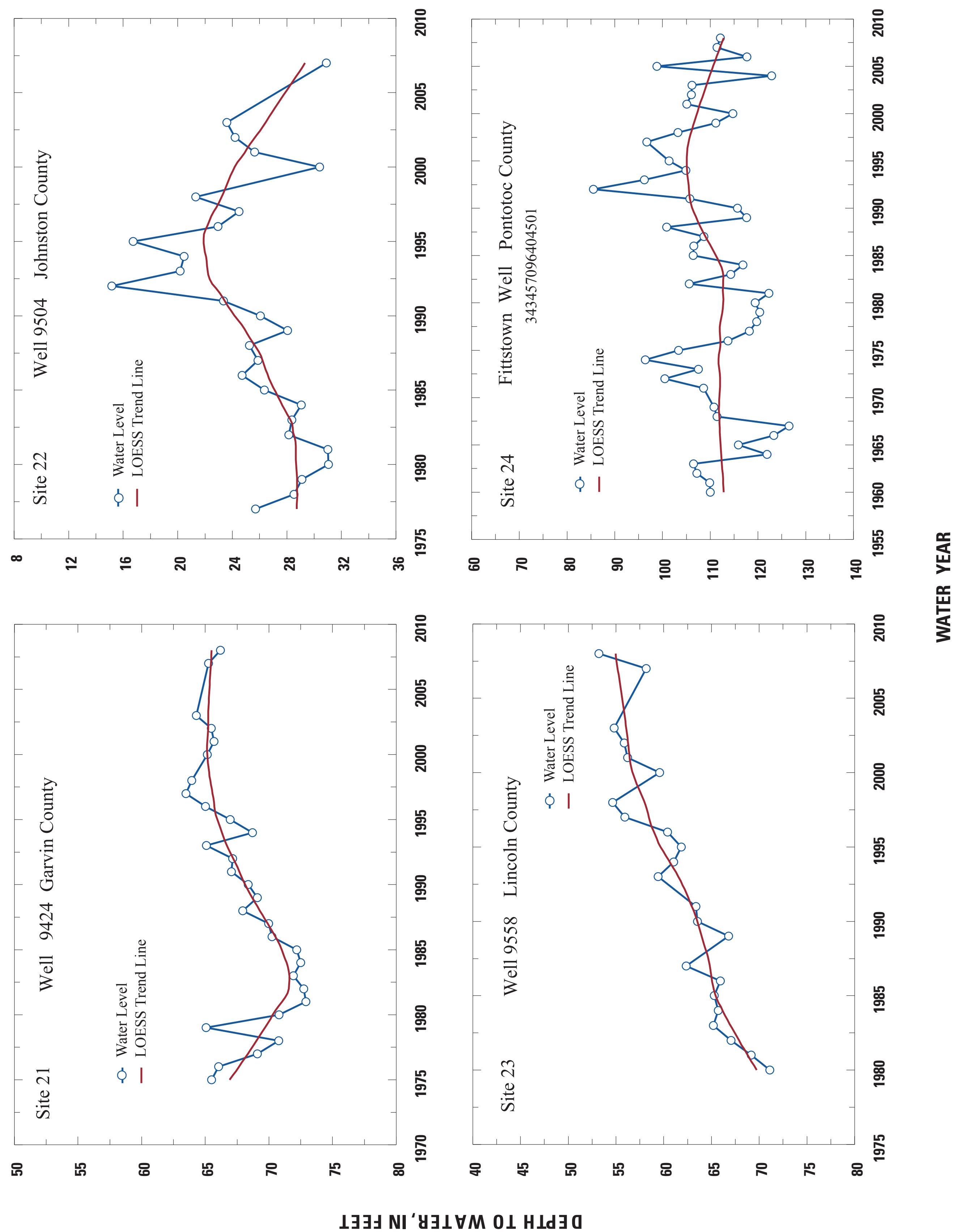

Figure 93. Groundwater levels and LOESS trend lines by using available periods of record for wells 21–24.

Figure 94. Groundwater levels and LOESS trend lines by using available periods of record for wells 25–28.

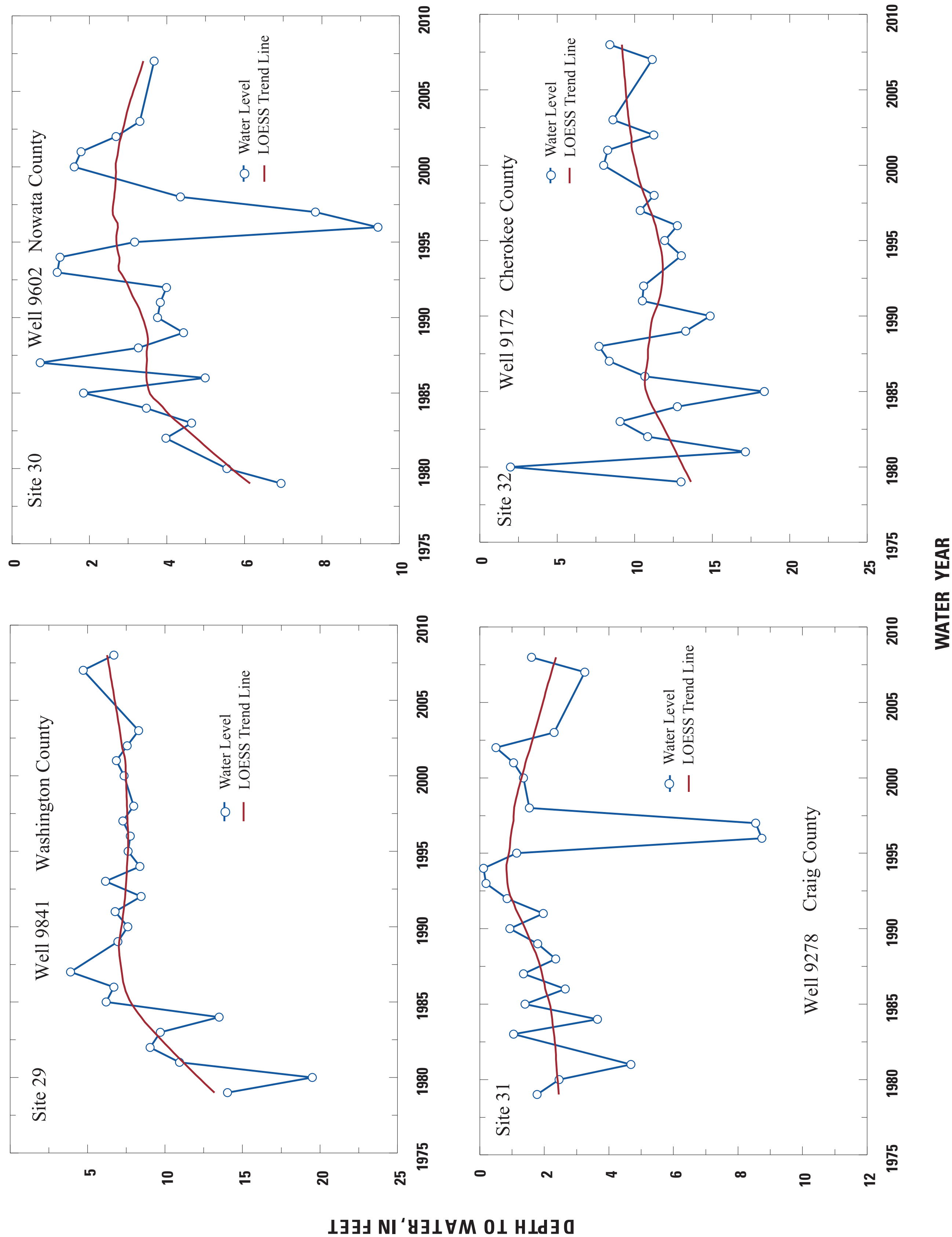

Figure 95. Groundwater levels and LOESS trend lines by using available periods of record for wells 29–32.

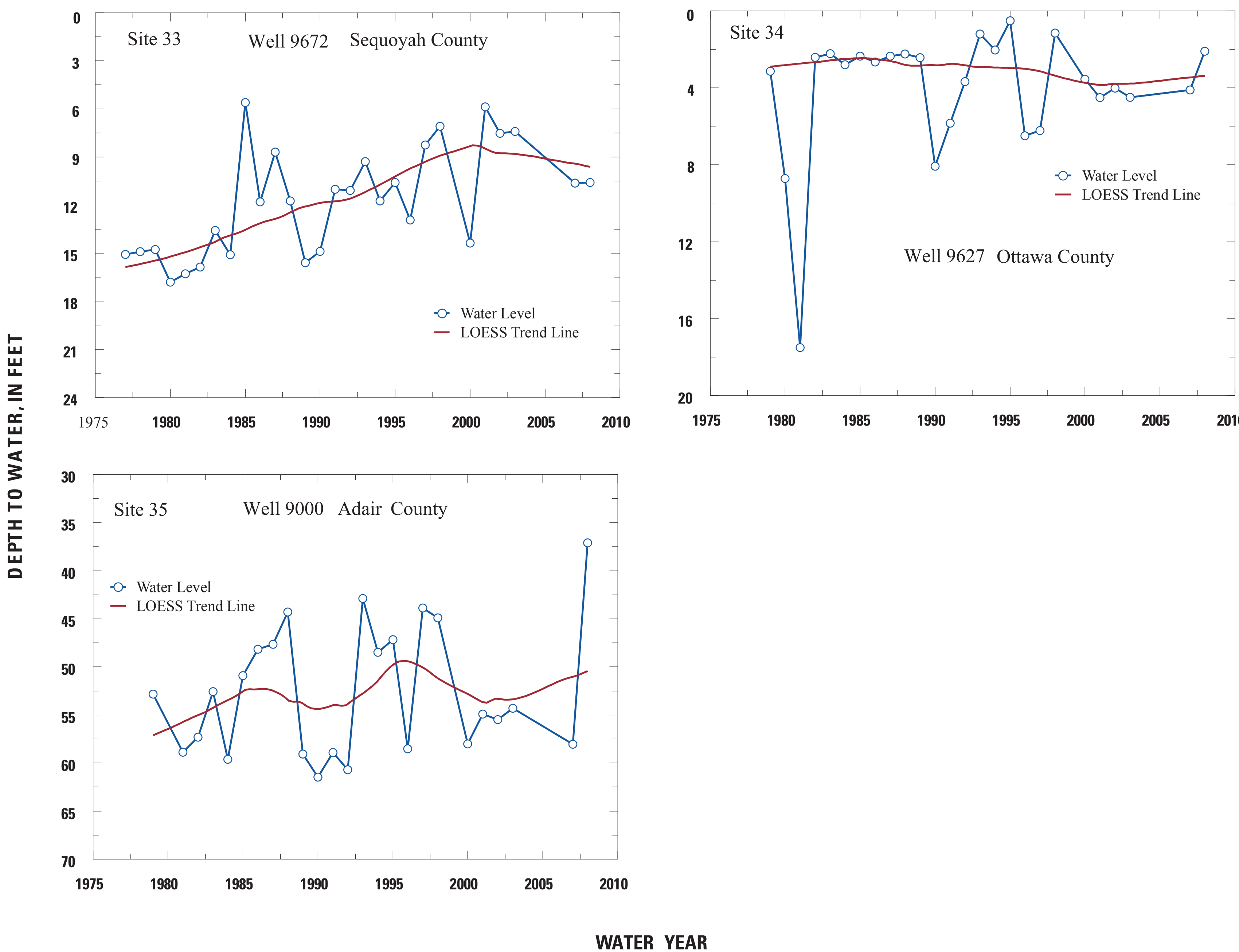

Figure 96. Groundwater levels and LOESS trend lines by using available periods of record for wells 33–35.