EFFECTS OF LOW-FLOW DIVERSIONS FROM THE SOUTH WICHITA RIVER ON DOWNSTREAM SALINITY OF THE SOUTH WICHITA RIVER, LAKE KEMP, AND THE WICHITA RIVER, NORTH TEXAS, OCTOBER 1982–SEPTEMBER 1992

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 95–4288

Prepared in cooperation with the
RED RIVER AUTHORITY OF TEXAS,
CITY OF WICHITA FALLS, AND
WICHITA COUNTY WATER IMPROVEMENT
DISTRICT NO. 2

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By Stanley Baldys III, Peter W. Bush, and Charles C. Kidwell

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Effects of Low-Flow Diversions from the South Wichita River on Downstream Salinity of the South Wichita River, Lake Kemp, and the Wichita River, North Texas, October 1982–September 1992

By Stanley Baldys III, Peter W. Bush, *and* Charles C. Kidwell

Abstract

In parts of the upper reaches of the Red River Basin in Texas, streamflow is characterized by levels of salinity that limit its usefulness for most purposes. Large dissolved solids and dissolved chloride concentrations are caused primarily by flow from natural salt springs in tributaries to the Red River. To reduce downstream salinity in the Wichita River, a dam in the South Wichita River downstream of an area of salt springs (designated salinity source area VIII) diverts low flows (which are the most saline) to a manmade brine lake for evaporation.

Statistical tests on salinity data for the South Wichita River, Lake Kemp, and the Wichita River for the period October 1982–September 1992 were done to determine the effects on downstream salinity of low-flow diversions from the South Wichita River that began in May 1987.

Salinity in the South Wichita River downstream of the low-flow diversion structure was (statistically) significantly less during the 65-month period of record after diversion than during the 55-month period of record before diversion. Wilcoxon rank-sum tests yielded strong evidence that discharge-weighted dissolved solids and discharge-weighted dissolved chloride concentrations, as well as discharge-weighted specific conductance, were significantly less after diversion.

Whether salinity in Lake Kemp had a significant downward trend during the period of record August 1989–August 1992 could not be determined conclusively from observed salinity data. Mann-Kendall trend tests yielded weak evidence that volume-weighted dissolved solids and dissolved chloride concentrations in Lake Kemp tended to decrease with time. However, serial correlation in the time series of salinity data could have adversely affected the test results.

The significant effects of low-flow diversions on salinity in the South Wichita River are not discernible in the Wichita River downstream from Lake Kemp. Although salinity was significantly less downstream from Lake Kemp after diversion, the decrease probably is mostly a result of dilution of Lake Kemp by large inflows of (assumed) low-salinity water that occurred in the spring of 1989 rather than an effect of diversion.

INTRODUCTION

In parts of the upper reaches of the Red River Basin in Texas, including Lake Texoma downstream of the confluence of the Wichita and Red Rivers, use of streamflow for irrigation and for industrial and municipal supply is limited by large dissolved solids and dissolved chloride concentrations in tributaries to the Red River. The large dissolved solids and dissolved chloride concentrations are caused primarily by flow from natural salt springs. Crops irrigated with water from these tributaries generally have reduced average crop yields and decreased values. The corrosive action of the water also damages agricultural equipment. According to Keller and others (1988), industrial and municipal water-treatment facilities, piping systems, and water heaters and other household appliances are damaged by the large chloride concentrations in the water. Millions of acre-feet of ground water in the alluvium along the

Red River also are affected by the chloride concentrations in the streamflow.

In 1957, the U.S. Congress directed the U.S. Public Health Service to initiate studies to identify major sources of salt pollution in the Red River Basin. Ten major source areas of large dissolved solids and dissolved chloride concentrations were identified for the Red River Basin chloride control project—three in the Wichita River Basin (fig. 1) and the rest farther north on other tributaries to the Red River. In addition, the U.S. Army Corps of Engineers was directed to study methods of reducing dissolved solids and dissolved chloride loads[1] in tributaries to the Red River and to recommend alternative control plans.

One of the source areas of salt pollution, area VIII (as designated by the U.S. Army Corps of Engineers, Tulsa District), is in the South Wichita River Basin above Lake Kemp near Guthrie, Tex. (fig. 1). The Water Resources Development Act of 1974 (Keller and others, 1988) provided funding for the construction of water-control structures in area VIII. A water-control structure in area VIII diverts low flows, which are the most saline, from the South Wichita River to the Bateman pump station, which pumps the water through a pipeline to Truscott Brine Lake, where the water evaporates. Construction of Bateman pump station and Truscott Brine Lake began in 1976, and the diversion of low flows began in May 1987.

To better understand the effects of intervention to reduce downstream salinity[2] that originates in area VIII, the U.S. Geological Survey collected and analyzed salinity data in the Wichita River Basin below area VIII. The study was made in cooperation with the Red River Authority of Texas, City of Wichita Falls, and Wichita County Water Improvement District No. 2.

[1]"Load" is the weight per unit time of a constituent material transported by, suspended in, or deposited by water.

[2]Salinity in this report refers to the concentration of dissolved solids in water, or to the related indicators dissolved chloride concentration and specific conductance. The U.S. Geological Survey commonly associates salinity descriptors with ranges of dissolved solids concentration as follows:

Descriptor	Dissolved solids concentration (milligrams per liter)
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	more than 35,000

Purpose and Scope

The purpose of this report is to summarize salinity data from the Wichita River Basin below salinity source area VIII for the period October 1982–September 1992 and to document the results of statistical tests on the data to determine the effects of low-flow diversions that began in May 1987 on salinity downstream of area VIII.

Continuous discharge and specific conductance data were collected at two streamflow-gaging stations on the South Wichita River above Lake Kemp and one station on the Wichita River below Lake Kemp. Monthly dissolved solids and dissolved chloride loads, and discharge-weighted specific conductance, for one of the South Wichita River stations and the Wichita River station (the stations with records before and after diversion) were computed from the data. Summary statistics of the data are presented. Hypothesis tests were done on the loads and conductance data as appropriate to determine whether the after-diversion data were significantly less than the before-diversion data. Two time series of 10 volume-weighted constituent concentrations from Lake Kemp, one dissolved solids and the other dissolved chloride, for the period August 1989–August 1992 were subjected to hypothesis tests to determine whether concentrations tended to decrease with time.

Physical Setting

The study area comprises the part of the Wichita River Basin that includes salinity source area VIII and Lake Kemp (fig. 1). The Wichita River is formed by two major tributaries, the South Wichita River and the North Wichita River, whose confluence is about 14 river miles upstream from Lake Kemp (station Lake Kemp near Mabelle, Tex. (07312000)). Lake Kemp is impounded by an earthfill dam that was completed in 1923. The capacity of the lake at the top of the conservation pool is 268,000 acre-feet (acre-ft).

Keller and others (1988, p. 14) conclude that most of the dissolved chloride entering Lake Kemp discharges from springs and seeps in area VIII along the South Wichita River. Six salt springs issue from cavernous openings in the gypsum cliffs on the north side of the river. Keller and others (1988, p. 23) estimate that the springs flow at a rate of about 2 cubic feet per second (ft^3/s) and produce about 195 tons/day of chloride.

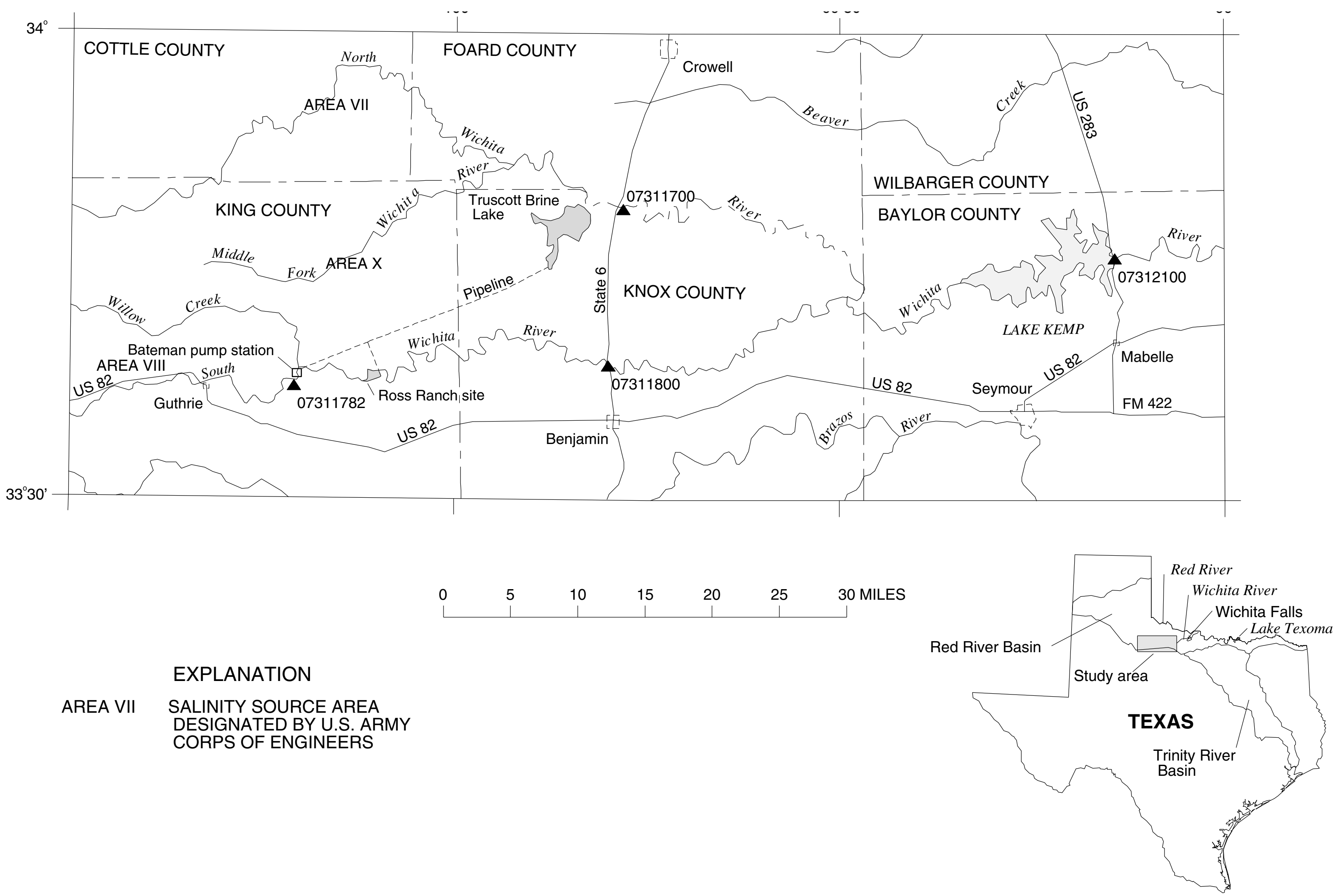

Figure 1. Location of study area.

The water-control structure downstream of area VIII at the Bateman pump station, about 105 river miles upstream from Lake Kemp, is an inflatable dam. The dam is inflated during low flow, impounding water in a pool behind it. The impounded water is pumped through a 23-mile (mi) pipeline to Truscott Brine Lake for evaporation. The dam is deflated during conditions other than low flow, when salinity is less because of dilution from runoff.

The more upstream of the two gaging stations on the South Wichita River above Lake Kemp for which data are analyzed, South Wichita River at low-flow dam near Guthrie, Tex. (07311782), at the Bateman pump station, records continuous discharge and selected properties of the water pumped to Truscott Brine Lake. The drainage area above the gaging station is 223 square miles (mi^2). No annual mean discharge is computed for this station because it records flow diverted from, rather than flow of, the South Wichita River.

The next downstream gaging station on the South Wichita River for which data are analyzed, South Wichita River near Benjamin, Tex. (07311800), about 55 river miles upstream from Lake Kemp, records continuous discharge and selected properties of water in the river. The drainage area above the gaging station is 584 mi^2, and annual mean discharge for the period of record October 1960–September 1994 is 40.9 ft^3/s.

A gaging station on the North Wichita River, North Wichita River near Truscott, Tex. (07311700), records continuous discharge and selected properties of water in that stream. (Data for this station were not analyzed for this report.) The drainage area above the gaging station is 937 mi^2, and annual mean discharge for the period of record October 1960–September 1994 is 65.5 ft^3/s. Thus, records from this station and the station on the South Wichita River near Benjamin indicate that about 60 percent of the long-term annual mean flow in the Wichita River upstream of Lake Kemp is contributed by the North Wichita River.

On the Wichita River, the gaging station for which data are analyzed, Wichita River near Mabelle, Tex. (07312100), records continuous discharge and selected properties of water released at the Lake Kemp dam. The drainage area above the dam and gaging station is 2,086 mi^2, and annual mean discharge for the period of record October 1960–September 1994 is 162 ft^3/s.

Methods of Analysis

To determine whether salinity downstream of the low-flow diversion dam was significantly less during the period of record after diversion than during the period of record before diversion, monthly discharge-weighted dissolved solids, dissolved chloride, and specific conductance for the two stations South Wichita River near Benjamin and South Wichita River near Mabelle for the before- and after-diversion periods of record were statistically compared. The comparisons were made using the Wilcoxon rank-sum test (Helsel and Hirsch, 1992, p. 118).

Monthly discharge-weighted dissolved solids, dissolved chloride, and specific conductance were computed from the equation

$$\bar{C} = \frac{\sum_{i=1}^{\text{No. of days in month}} (C)_i Q_i}{\sum_{i=1}^{\text{No. of days in month}} Q_i}, \qquad (1)$$

where

$\bar{C}$ = discharge-weighted dissolved solids or chloride concentration, or specific conductance, in milligrams per liter or microsiemens per centimeter at 25 degrees Celsius, as appropriate;

$(C)_i$ = instantaneous constituent concentration or property, in units as above; and

Q_i = daily mean discharge, in cubic feet per second.

Discharge-weighted constituent concentrations and specific conductance also were computed for the station South Wichita River near Guthrie (flow to Truscott Brine Lake) after diversion. The data for all three stations are reported in the annual Water Resources Data for Texas reports (U.S. Geological Survey, 1984–93).

The question to be answered by the statistical tests on discharge-weighted concentrations and conductance (one-sided hypothesis tests) is, were either dissolved solids concentrations or dissolved chloride concentrations, or specific conductance, less at the

$\alpha = 0.1$ significance level during the period of record after diversion than before. If the p-value[3] of the test is less than α, then the conclusion is that the concentration or conductance was significantly less during the period after diversion than before; and if the p-value is greater than α, then the conclusion is that the concentration or conductance was not less after diversion.

Setting $\alpha = 0.1$ allows a 1-in-10 chance that test results will lead to the conclusion that one of the constituent concentrations or conductance is significantly less after diversion than before, when the true situation is that the concentration or conductance is not less after diversion. A smaller α could be selected, but reducing α increases the chances of drawing a different wrong conclusion—that the after-diversion data are not less after diversion, when the true situation is that the after-diversion data are significantly less.

Although loads are not a direct indicator of salinity (because differences in discharge will either augment or attenuate a decrease in load due to diversion), monthly dissolved solids and dissolved chloride loads were computed for the two stations South Wichita River near Benjamin and South Wichita River near Mabelle for the before- and after-diversion periods (and also for the station South Wichita River near Guthrie [loads to Truscott Brine Lake] after diversion). Wilcoxon rank-sum tests were done on the loads at the Benjamin station to determine whether loads were significantly less after diversion.

To compute loads, daily discharge and concentrations of dissolved solids and dissolved chloride at the streamflow-gaging stations are needed. Daily discharge data are available from continuous streamflow records. However, only periodic constituent concentration data are available. Because dissolved solids and dissolved chloride concentrations are highly correlated with specific conductance, and continuous specific conductance data are available for the three streamflow-gaging stations, regression equations that relate constituent concentrations to specific conductance can be used to obtain estimates of daily constituent concentrations from specific conductance. Regression equations derived for each station are of the form

$$C_i = \beta_0 + \beta_1 (SC)_i + \beta_2 (SC)_i^2 \,, \qquad (2)$$

where

C_i = instantaneous constituent concentration, in milligrams per liter;

$(SC)_i$ = instantaneous specific conductance, in microsiemens per centimeter at 25 degrees Celsius; and

$\beta_0, \beta_1, \beta_2$ = regression coefficients.

The regression coefficients for equation 1, by station and constituent, are listed below.

Station	Constituent	β_0	β_1	β_2
07311782	dissolved solids	0	0.6239	0.0000014
	dissolved chloride	0	.2636	.0000021
07311800	dissolved solids	0	.6581	.0000016
	dissolved chloride	0	.1878	.0000050
07312100	dissolved solids	0	.5619	.0000098
	dissolved chloride	0	.1727	.0000127

The regression model above was developed in the early 1980's from a statewide data base of specific conductance, dissolved solids, dissolved chloride, and dissolved sulfate concentrations for the purpose of computing constituent loads at selected gaging stations for the annual Water Resources Data for Texas reports (U.S. Geological Survey, 1984–93). Regression coefficients at each station for which the model is used are re-evaluated at 2-year intervals to take advantage of the latest available data (F.C. Wells, U.S. Geological Survey, oral commun., 1995).

Daily loads were computed from the equation

$$L_i = Q_i \times C_i \times K \,, \qquad (3)$$

where

L_i = daily constituent load, in tons per day;

Q_i = daily mean discharge, in cubic feet per second;

C_i = instantaneous constituent concentration, in milligrams per liter, computed from equation 1 (assumption is made that instantaneous concentration is satisfactory estimate of daily mean concentration); and

K = 0.0027, a units conversion factor, in tons per day/cubic foot per second-milligram per liter.

[3]The p-value is the "attained significance level" of a particular test, which is the probability of getting the computed test statistic under the assumption (null hypothesis) that the data being compared are not different. "Not different" in this context means that the data are from the same population distribution.

Monthly dissolved solids and dissolved chloride loads were computed by summing the individual daily loads computed from equations 2 and 3. The data are reported in the annual Water Resources Data for Texas reports (U.S. Geological Survey, 1984–93).

As an indicator of the effect of differences in discharge on loads, monthly discharges (the sum of daily mean discharges for each month) for the Benjamin and Mabelle stations for the periods of record before and after diversion were statistically compared. To determine whether discharge was significantly less at the stations after diversion, Wilcoxon rank-sum tests on monthly discharge were done. If discharge is less, it will augment a decrease in load due to diversion. If the p-value from the test is less than α, then the conclusion is that discharge was significantly less at the $\alpha = 0.1$ level after diversion; and if the p-value is greater than α, then the conclusion is that discharge was not significantly less after diversion.

Water samples for analysis of dissolved solids and dissolved chloride were collected from Lake Kemp in summer, winter, and spring during August 1989–August 1992 to determine whether concentrations tended to decrease with time. On each of 10 sampling dates, samples were collected for analysis at 2 or more selected depths at each of 3 sites on the lake. The point concentrations are reported in the annual Water Resources Data for Texas reports (U.S. Geological Survey, 1990–93). Volume-weighted daily mean dissolved solids and dissolved chloride concentrations for Lake Kemp for each sampling day were computed using the method of Wells and Schertz (1984).

A statistical test, the Mann-Kendall trend test (Helsel and Hirsch, 1992), was used to determine whether the series of 10 volume-weighted daily mean dissolved solids concentrations and the series of 10 volume-weighted daily mean dissolved chloride concentrations tended to decrease with time. Like the Wilcoxon rank-sum test as applied to the load and conductance data, the Mann-Kendall test as applied to the concentration data is a one-sided hypothesis test designed to indicate whether there is a downward trend at the $\alpha = 0.1$ significance level. If the p-value of the test is less than α, then the conclusion is that there is a downward trend in concentration with time; and conversely, if the p-value of the test is greater than α, then the conclusion is that there is no downward trend.

EFFECTS OF LOW-FLOW DIVERSIONS ON SALINITY

South Wichita River (Upstream from Lake Kemp)

Diversion of low flows from the South Wichita River near Guthrie to Truscott Brine Lake began in May 1987. The median monthly discharge-weighted dissolved solids concentration of the diverted flow during the 65 months of record May 1987–September 1992 is 20,200 milligrams per liter (mg/L) (table 1); and the monthly minimum and maximum concentrations are 2,340 mg/L in May 1987 and 26,000 mg/L in November 1989 (excluding January 1990, when the pump at Bateman pump station was not operating) (fig. 2). The median monthly discharge-weighted dissolved chloride concentration is 9,900 mg/L; and the monthly minimum and maximum concentrations are 1,100 mg/L in May 1987 and 13,000 mg/L November 1989 (excluding January 1990) (fig. 3). The median and mean monthly discharge-weighted specific conductances are about 30,000 microsiemens per centimeter at 25 degrees Celsius (µS/cm). This conductance is about 60 percent of the approximate conductance of seawater (Hem, 1985, p. 69).

During the 65 months of record, about 565,000 tons of dissolved solids was transported in flow to Truscott Brine Lake (table 1). The monthly dissolved solids load in the diverted flow ranged from 47 tons in December 1988 to 13,900 tons in March 1988 (excluding January 1990) (fig. 4). About one-half of the dissolved solids load (about 277,000 tons) was dissolved chloride. The monthly dissolved chloride load ranged from 23 tons in December 1988 to 6,890 tons in March 1988 (excluding January 1990) (fig. 5).

At the next downstream gage (South Wichita River near Benjamin), which records flow toward Lake Kemp, data from which to compute discharge-weighted constituent concentrations, specific conductance, and loads are available for the 55 months October 1982–April 1987 before diversion of low flows and for the 65 months May 1987–September 1992 after diversion. The median monthly discharge-weighted dissolved solids concentration before diversion is 11,500 mg/L (table 1); and the median monthly discharge-weighted dissolved solids concentration after diversion is 5,760 mg/L. The medians of monthly discharge-weighted dissolved chloride concentrations before and after diversion are 5,200 mg/L and 2,300

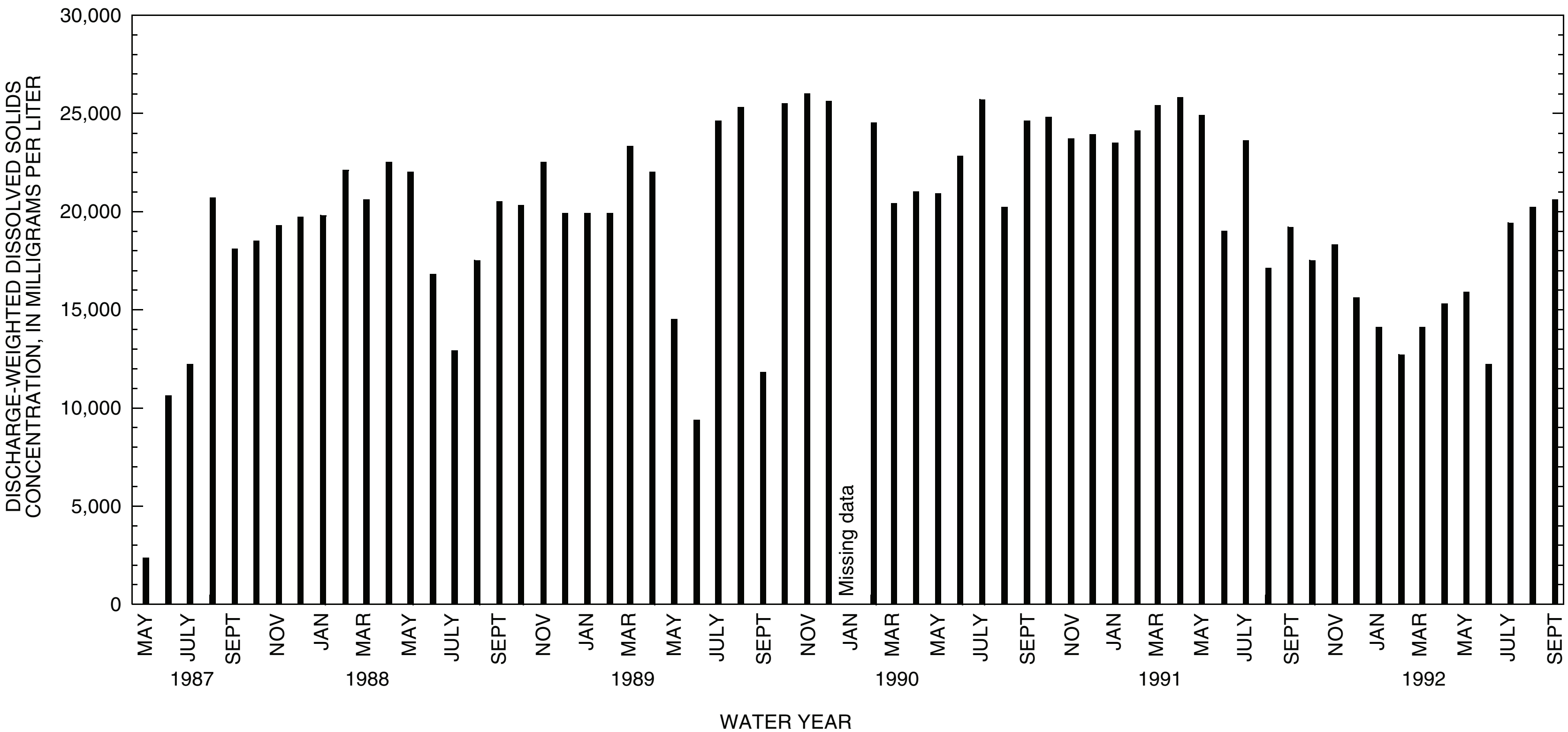

Figure 2. Discharge-weighted dissolved solids concentrations for streamflow-gaging station 07311782 South Wichita River at low-flow dam near Guthrie, Texas.

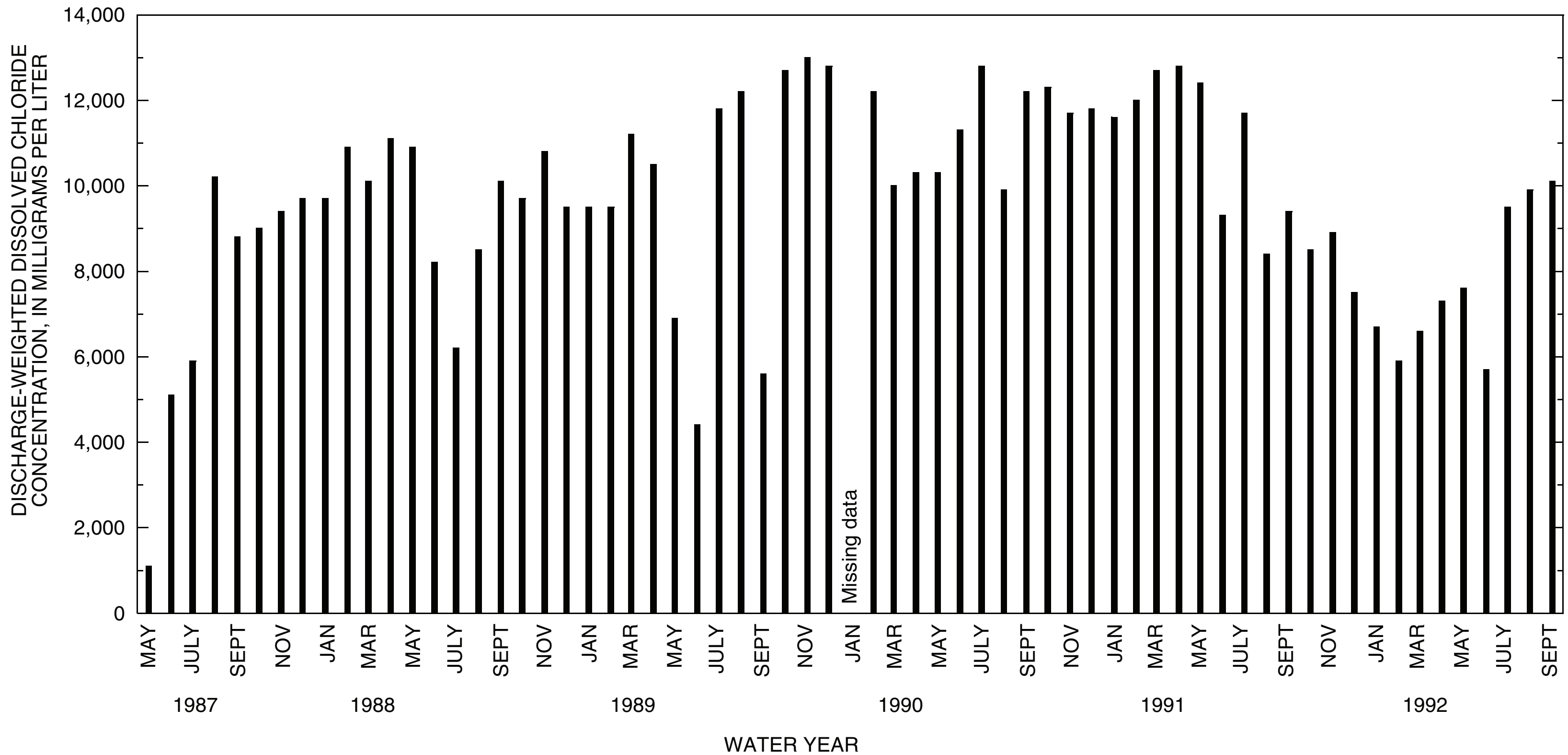

Figure 3. Discharge-weighted dissolved chloride concentrations for streamflow-gaging station 07311782 South Wichita River at low-flow dam near Guthrie, Texas.

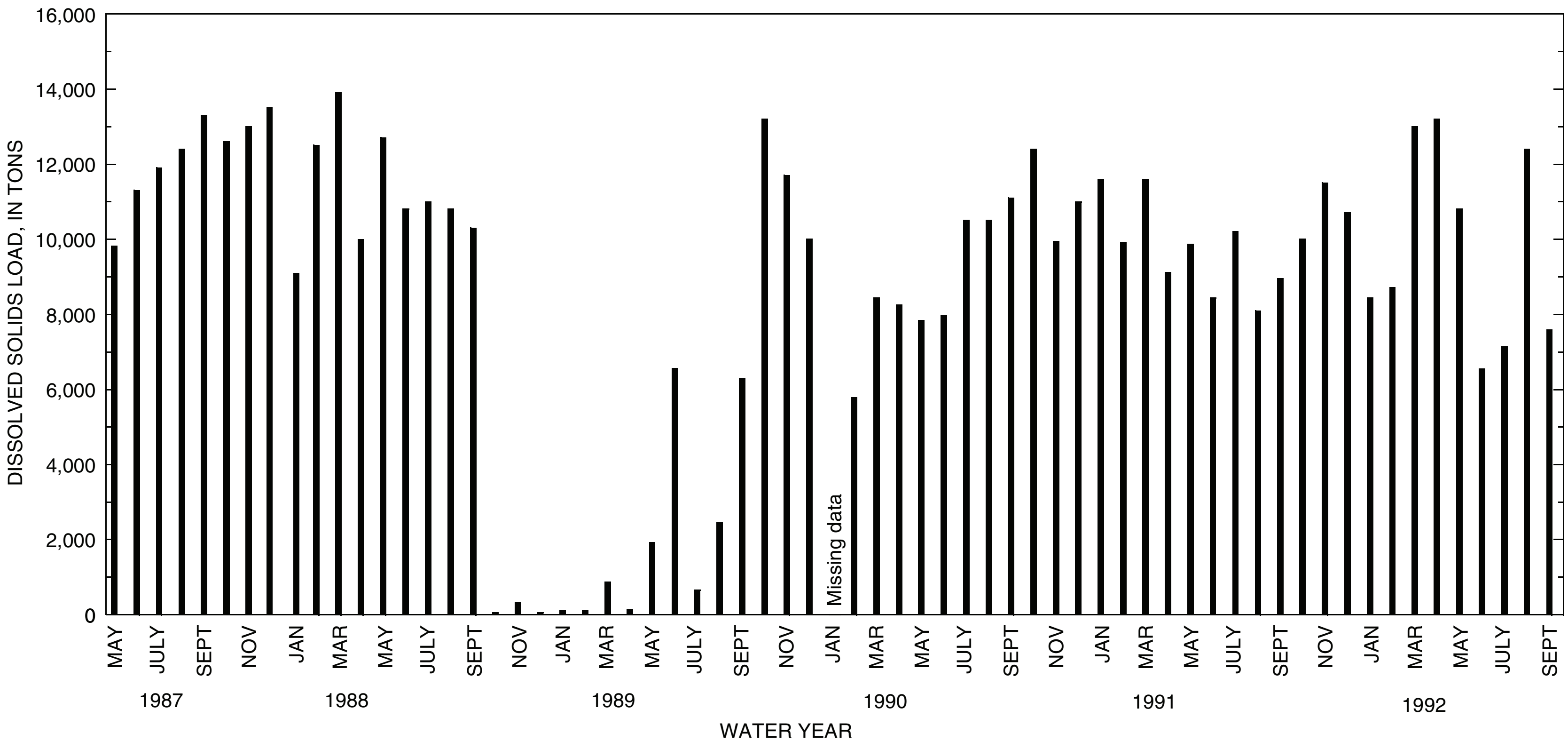

Figure 4. Dissolved solids loads for streamflow-gaging station 07311782 South Wichita River at low-flow dam near Guthrie, Texas.

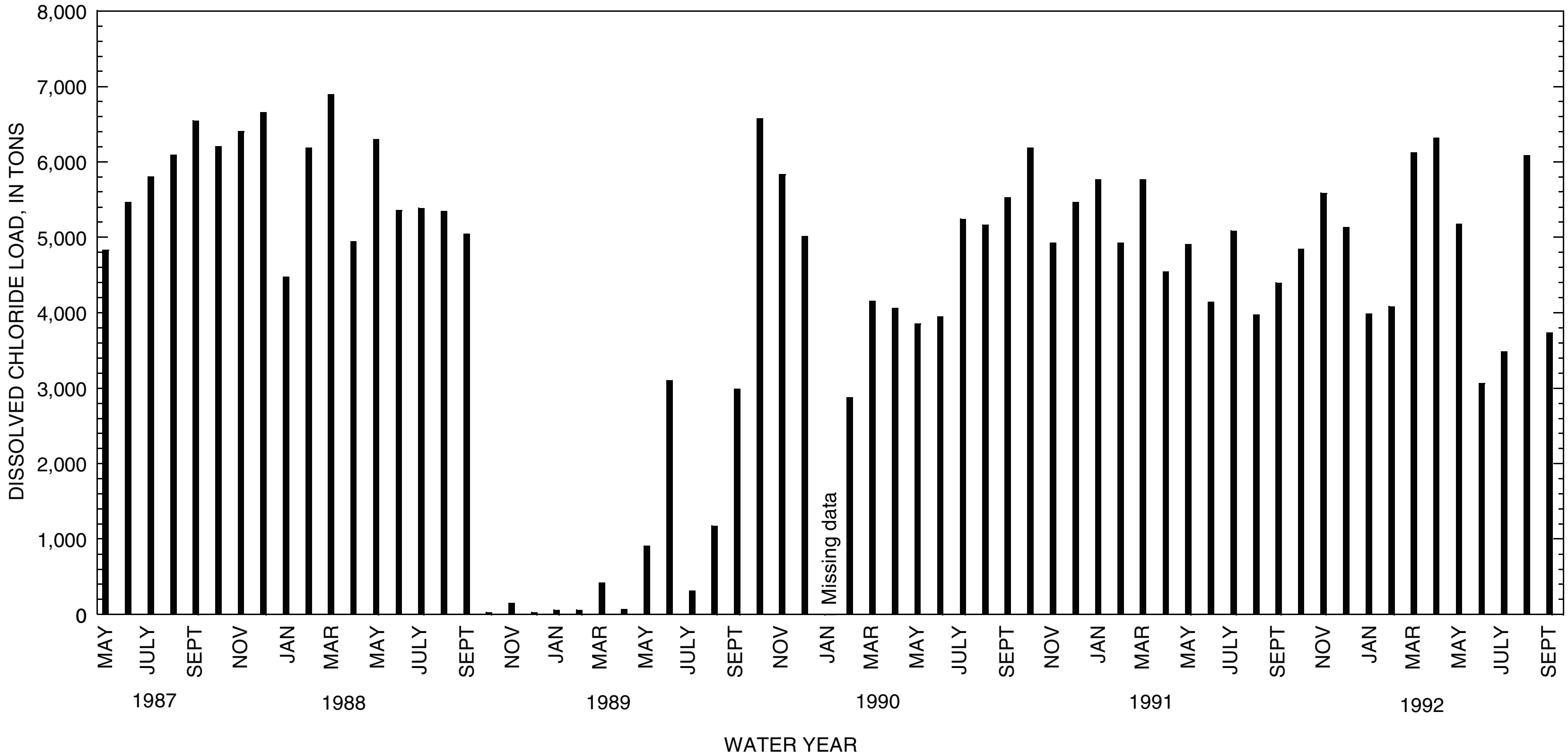

Figure 5. Dissolved chloride loads for streamflow-gaging station 07311782 South Wichita River at low-flow dam near Guthrie, Texas.

Table 1. Summary statistics of monthly discharge, salinity, and loads at three streamflow-gaging stations, South Wichita and Wichita Rivers, north Texas, October 1982–September 1992

[ft^3/s-day, cubic feet per second-day; --, no record; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

Constituent load or property and statistic	07311782 South Wichita River near Guthrie[1]		07311800 South Wichita River near Benjamin		07312100 Wichita River near Mabelle	
	55 months 10/82–04/87	65 months 05/87–09/92	55 months 10/82–04/87	65 months 05/87–09/92	55 months 10/82–04/87	65 months 05/87–09/92
Discharge (ft^3/s-days)						
sum	--	10,600	82,100	106,000	292,000	506,000
median	--	171	481	433	2,350	4,310
mean	--	163	1,490	1,630	5,310	7,780
Discharge-weighted dissolved solids concentration (mg/L)						
median	--	20,200	11,500	5,760	3,620	2,820
mean	--	19,300	11,300	6,680	3,530	2,910
Discharge-weighted dissolved chloride concentration (mg/L)						
median	--	9,900	5,200	2,300	1,500	1,100
mean	--	9,600	5,300	2,770	1,440	1,150
Discharge-weighted specific conductance (µS/cm)						
median	--	31,100	16,600	8,650	5,830	4,630
mean	--	30,200	16,600	9,800	5,710	4,780
Dissolved solids load (tons)						
sum	--	565,000	1,100,000	813,000	2,670,000	3,660,000
median	--	9,990	15,300	6,130	24,800	32,100
mean	--	8,690	19,900	12,500	48,600	56,300
Dissolved chloride load (tons)						
sum	--	277,000	493,000	302,000	1,080,000	1,420,000
median	--	4,920	7,240	2,350	10,100	12,500
mean	--	4,260	8,970	4,640	19,700	21,800

[1]Gaging station records discharge and selected properties of water diverted to Truscott Brine Lake.

mg/L, respectively. The medians of monthly discharge-weighted specific conductance before and after diversion are 16,600 µS/cm and 8,650 µS/cm, respectively.

The monthly discharge-weighted dissolved concentrations of both constituents generally were less after diversion than before (figs. 6, 7). The Wilcoxon rank-sum tests to determine whether the differences were statistically significant yielded strong evidence that both discharge-weighted dissolved constituent concentrations were significantly less after diversion. The p-value of each test is less than 0.0001, very much less than the significance level of $\alpha = 0.1$, the threshold for rejecting the assumption that salinity was not less after diversion. The test result on discharge-weighted specific conductance is similar. The p-value from that test also is less than 0.0001, a definite indication that salinity was less after diversion than before.

The median monthly dissolved solids load before diversion is 15,300 tons (table 1); and the median monthly dissolved solids load after diversion is 6,130

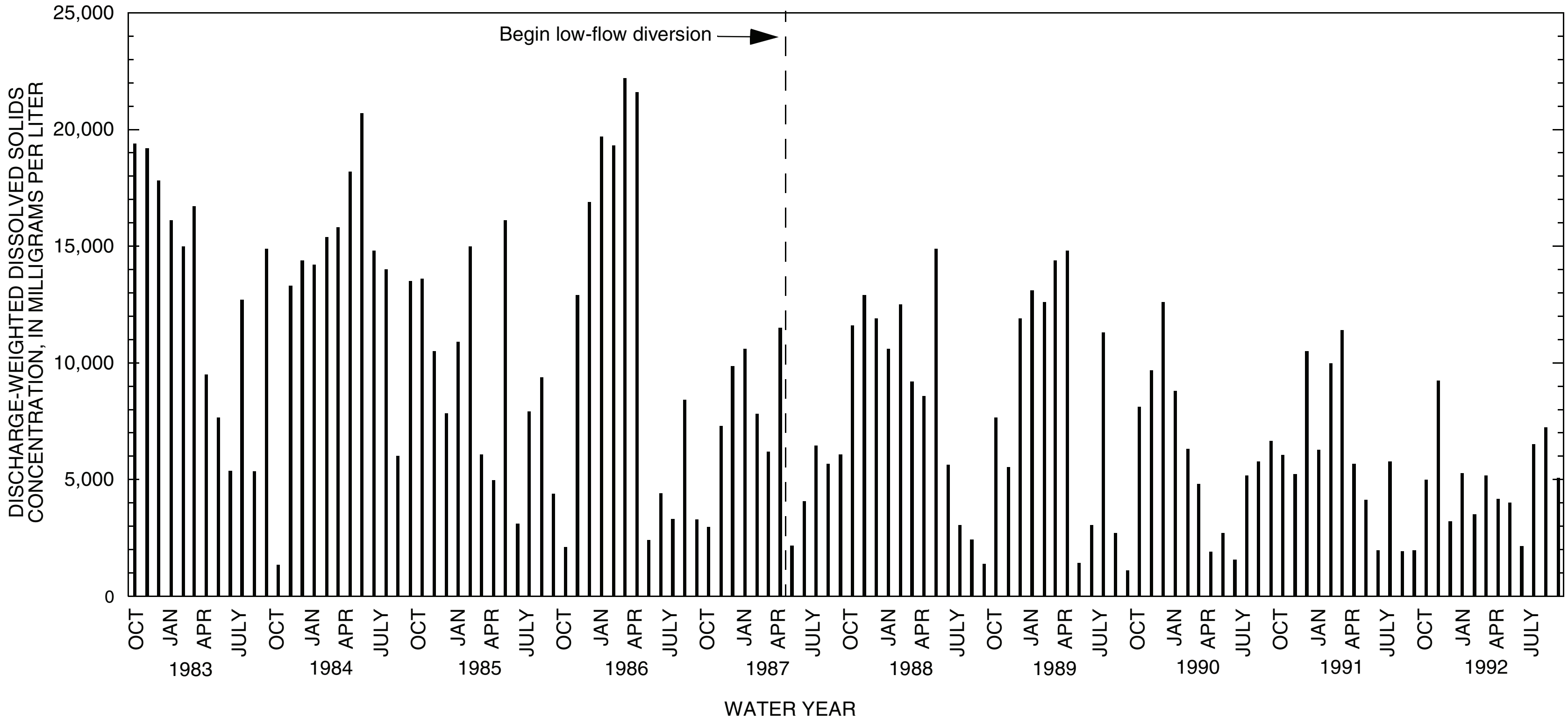

Figure 6. Discharge-weighted dissolved solids concentrations for streamflow-gaging station 07311800 South Wichita River near Benjamin, Texas.

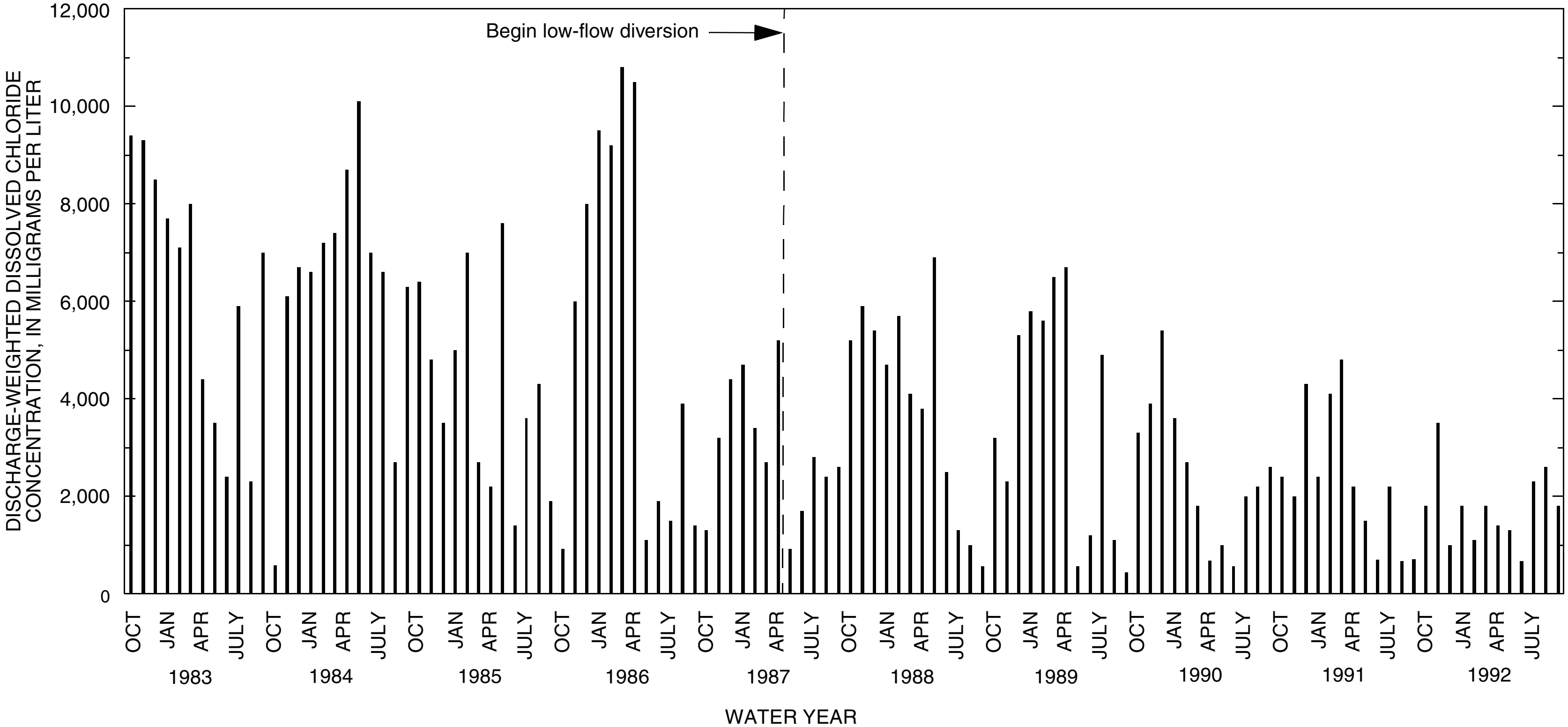

Figure 7. Discharge-weighted dissolved chloride concentrations for streamflow-gaging station 07311800 South Wichita River near Benjamin, Texas.

tons. The medians of monthly dissolved chloride before and after diversion are 7,240 tons and 2,350 tons, respectively. Monthly dissolved solids and dissolved chloride loads varied substantially during the periods of record before and after diversion. The range of variability for both constituent loads was larger before diversion than after (figs. 8, 9). The largest monthly load of each constituent (107,000 tons dissolved solids; 45,200 tons dissolved chloride) occurred in October 1986.

The Wilcoxon rank-sum test to determine whether dissolved solids loads at the gage near Benjamin were significantly less after diversion of low flows than before yielded strong evidence that dissolved solids loads were significantly less after diversion. The p-value of the test is 0.0004. The rank-sum test on dissolved chloride loads before and after diversion yielded even stronger evidence of significantly reduced loads after diversion. The p-value from that test is less than 0.0001.

The median monthly discharge at the Benjamin gage is larger before diversion than after. The median monthly discharge is 481 cubic feet per second-days (ft^3/s-days) before diversion and 433 ft^3/s-days after diversion. A rank-sum test on discharge during the before- and after-diversion periods indicates that discharge was not significantly less after diversion (p-value 0.2304); thus the decrease in load is not appreciably augmented by a decrease in discharge.

Lake Kemp

The water samples collected from Lake Kemp in the summer, winter, and spring during August 1989–August 1992 yielded a series of 10 volume-weighted daily mean dissolved solids concentrations and 10 volume-weighted daily mean dissolved chloride concentrations (fig. 10; table 2). Neither constituent time series shows a noticeable pattern of seasonal variation or an appreciable decrease with time. The averages of the summer, winter, and spring dissolved solids concentrations (2,480, 2,640, and 2,600 mg/L, respectively) differ from one another by no more than about 6 percent. The averages of the summer, winter, and spring dissolved chloride concentrations (1,500, 1,510, and 1,520 mg/L, respectively) are about equal to one another.

The Mann-Kendall tests to determine whether the dissolved solids and dissolved chloride concentrations had significant downward trends during the period of record were inconclusive. The p-value of the test on dissolved solids concentrations is 0.108, and the p-value of the test on dissolved chloride is 0.093. Strict adherence to the trend/no-trend decision criteria associated with a significance level $\alpha = 0.1$ would indicate a conclusion that there is no trend in the dissolved solids concentrations, and that there is a significant downward trend in the dissolved chloride concentrations. However, the fact that the p-values are very close to the significance level makes those conclusions tenuous. There is some evidence for a downward trend in both constituent time series; but the evidence is weak.

A caveat regarding interpretation of the Mann-Kendall trend-test results involves serial correlation (the dependence or correlation of an observation with the preceding observation) in the time series of dissolved solids and dissolved chloride data. The frequency of sampling (3- to 6-month intervals for 3 years) relative to the water-residence time of the lake (estimated to be 2 to 2.3 years) indicates that serial correlation could exist in the data. There must be no serial correlation for the p-value from the test to be correct (Helsel and Hirsch, 1992, p. 327). Graphical indicators of and statistical tests for serial correlation yielded mixed results; thus serial correlation cannot be ruled out and the p-values from the trend tests might not be correct.

Longer time series of dissolved solids and dissolved chloride data could benefit the trend analyses: If the time series were longer, samples or subsets of the data with larger between-sample time intervals could be tested for trends to lessen the probability of serial correlation. For example, time series comprising only winter samples, or only summer samples, would increase the interval to 1 year; such a time series also would eliminate any seasonal patterns in the data, although as mentioned, the Lake Kemp time series data do not exhibit noticeable seasonal patterns. Also, regardless of serial correlation, the power of the trend test to yield definitive results can be increased for a given significance level by increasing the amount of data (E.J. Gilroy, U.S. Geological Survey, oral commun., 1995).

As previously described, the South Wichita River merges with the North Wichita River to form the Wichita River upstream of Lake Kemp (fig. 1); and discharge records indicate that about 60 percent of the long-term annual mean flow of the Wichita River upstream of Lake Kemp is contributed by the North Wichita River. Water-property records indicate that

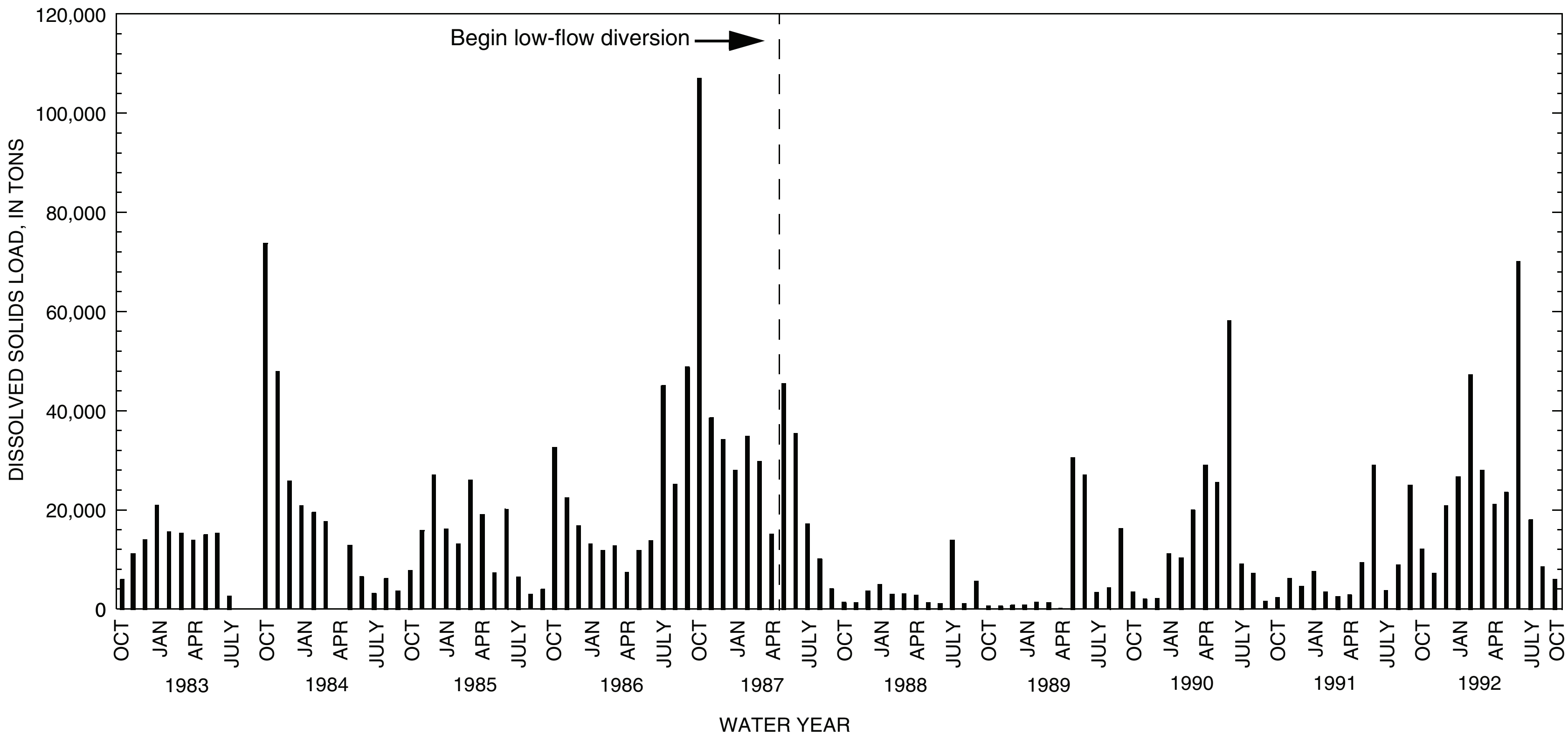

Figure 8. Dissolved solids loads for streamflow-gaging station 07311800 South Wichita River near Benjamin, Texas.

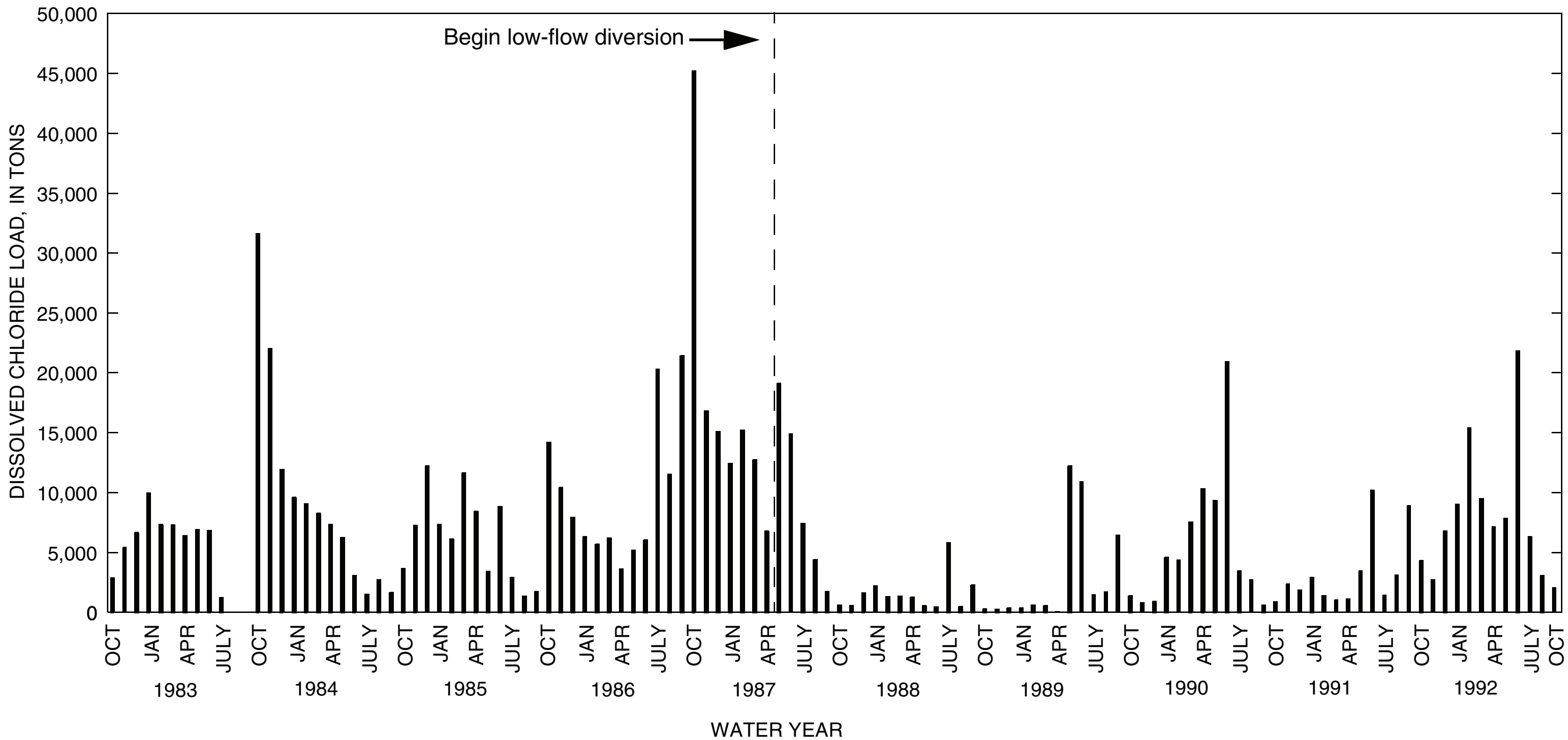

Figure 9. Dissolved chloride loads for streamflow-gaging station 07311800 South Wichita River near Benjamin, Texas.

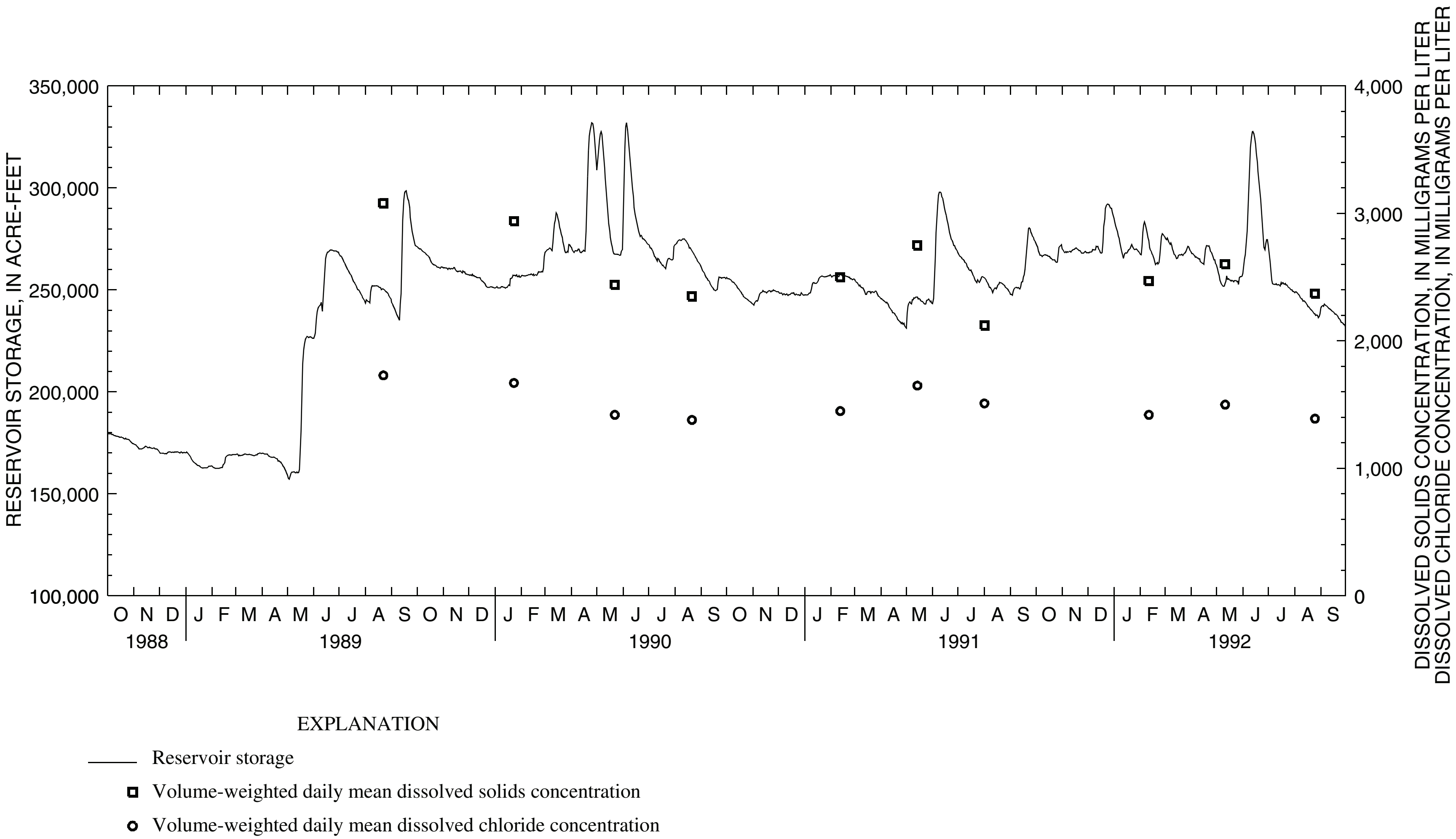

Figure 10. Hydrograph showing reservoir storage and volume-weighted daily mean dissolved solids and dissolved chloride concentrations, Lake Kemp, north Texas.

Table 2. Volume-weighted daily mean dissolved solids and dissolved chloride concentrations in Lake Kemp, north Texas, August 1989–August 1992

Date of sampling	Volume-weighted daily mean dissolved solids concentration (milligrams per liter)	Volume-weighted daily mean dissolved chloride concentration (milligrams per liter)
Aug. 22, 1989	3,080	1,730
Jan. 23, 1990	2,940	1,670
May 22	2,440	1,420
Aug. 21	2,350	1,380
Feb. 12, 1991	2,500	1,450
May 14	2,750	1,650
Aug. 1	2,120	1,510
Feb. 11, 1992	2,470	1,420
May 19	2,600	1,500
Aug. 25	2,370	1,390

specific conductance of the North Wichita River is similar in magnitude to that of the South Wichita River before diversion. Therefore, the significant effects of reduced salinity in the South Wichita River are attenuated by flow from the North Wichita River before the water reaches Lake Kemp.

Wichita River (Downstream from Lake Kemp)

At the gaging station Wichita River near Mabelle, which records flow from Lake Kemp, data from which to compute discharge-weighted constituent concentrations, specific conductance, and loads are available for the 55 months October 1982–April 1987 before diversion of low flows and for the 65 months May 1987–September 1992 after diversion. The median monthly discharge-weighted dissolved solids concentration before diversion is 3,620 mg/L (table 1); and the median monthly discharge-weighted dissolved solids concentration after diversion is 2,820 mg/L. The medians of monthly discharge-weighted dissolved chloride concentrations before and after diversion are 1,500 mg/L and 1,100 mg/L, respectively. The medians of monthly discharge-weighted specific conductance before and after diversion are 5,830 μS/cm and 4,630 μS/cm, respectively.

The monthly discharge-weighted dissolved concentrations of both constituents generally were less after diversion than before (figs. 11, 12); and specifically, less after the spring of 1989 when Lake Kemp received about a 50-percent increase in storage (fig. 10). The Wilcoxon rank-sum tests to determine whether the differences were statistically significant yielded strong evidence that both discharge-weighted dissolved constituent concentrations were significantly less after diversion. The p-value of each test is less than 0.0001. The test result on discharge-weighted specific conductance is similar. The p-value from that test also is less than 0.0001.

Unlike at the South Wichita River near Benjamin station, the median monthly dissolved constituent loads for the periods compared are smaller before diversion than after: The median monthly dissolved solids load before diversion is 28,400 tons (table 1); and the median monthly dissolved solids load after diversion is 32,100 tons. The medians of monthly dissolved chloride load before and after diversion are 10,100 tons and 12,500 tons, respectively. The range of variability for both constituent loads was larger after diversion than before (figs. 13, 14). The largest monthly load of each constituent (391,000 tons dissolved solids; 154,000 tons dissolved chloride) occurred in June 1987. Because both constituent loads were larger during the period after diversion than before, no statistical test was done to determine if loads were significantly less after diversion than before.

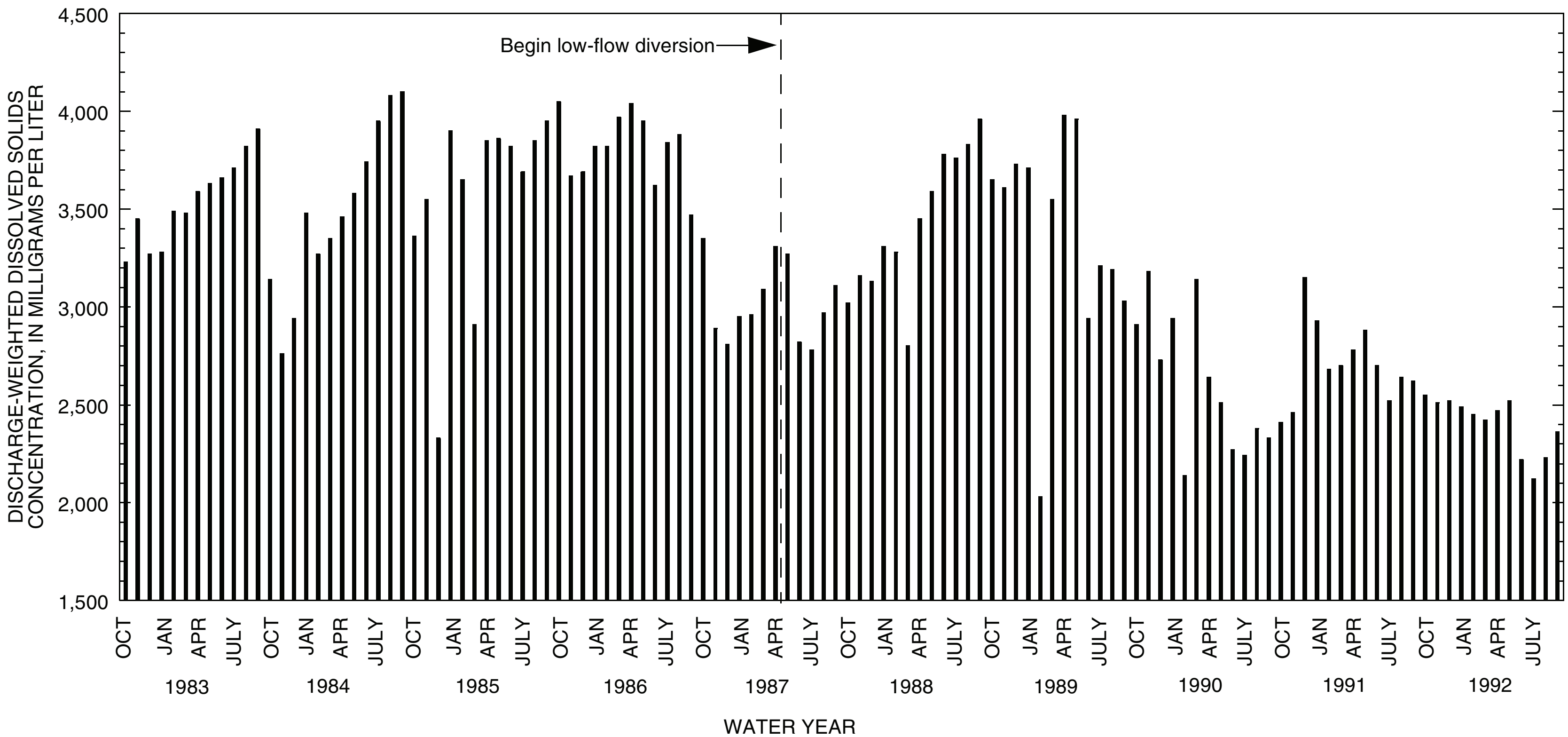

Figure 11. Discharge-weighted dissolved solids concentrations for streamflow-gaging station 07312100 Wichita River near Mabelle, Texas.

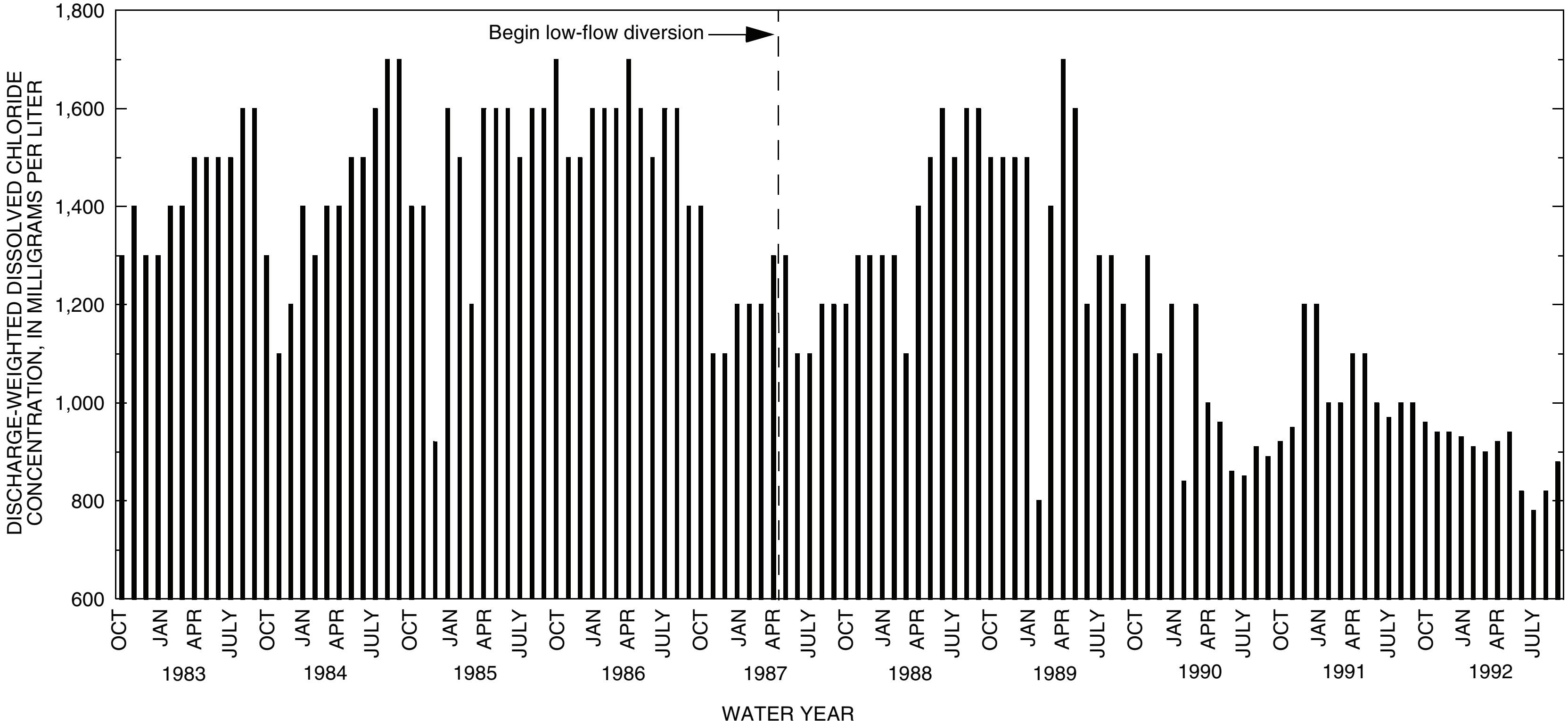

Figure 12. Discharge-weighted dissolved chloride concentrations for streamflow-gaging station 07312100 Wichita River near Mabelle, Texas.

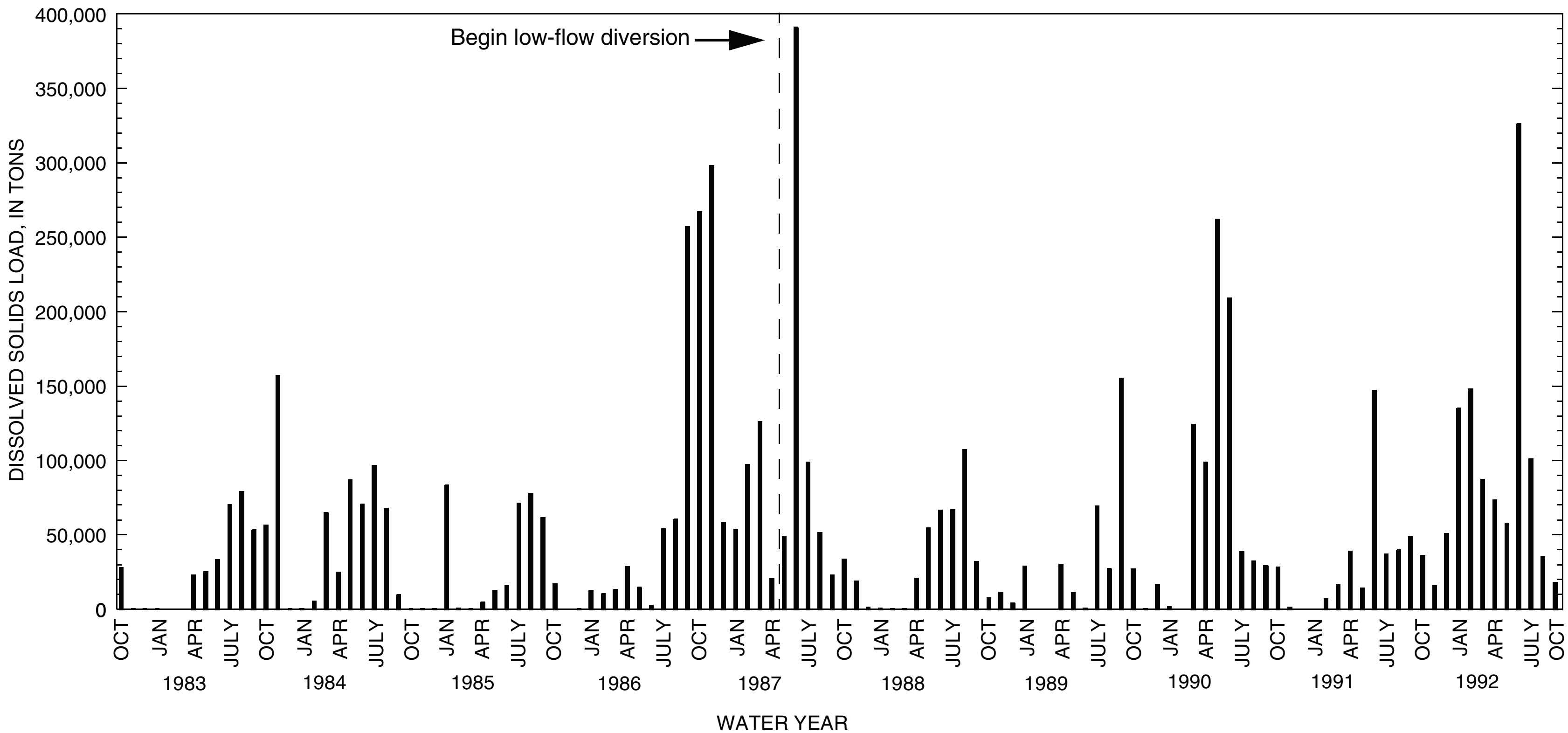

Figure 13. Dissolved solids loads for streamflow-gaging station 07312100 Wichita River near Mabelle, Texas.

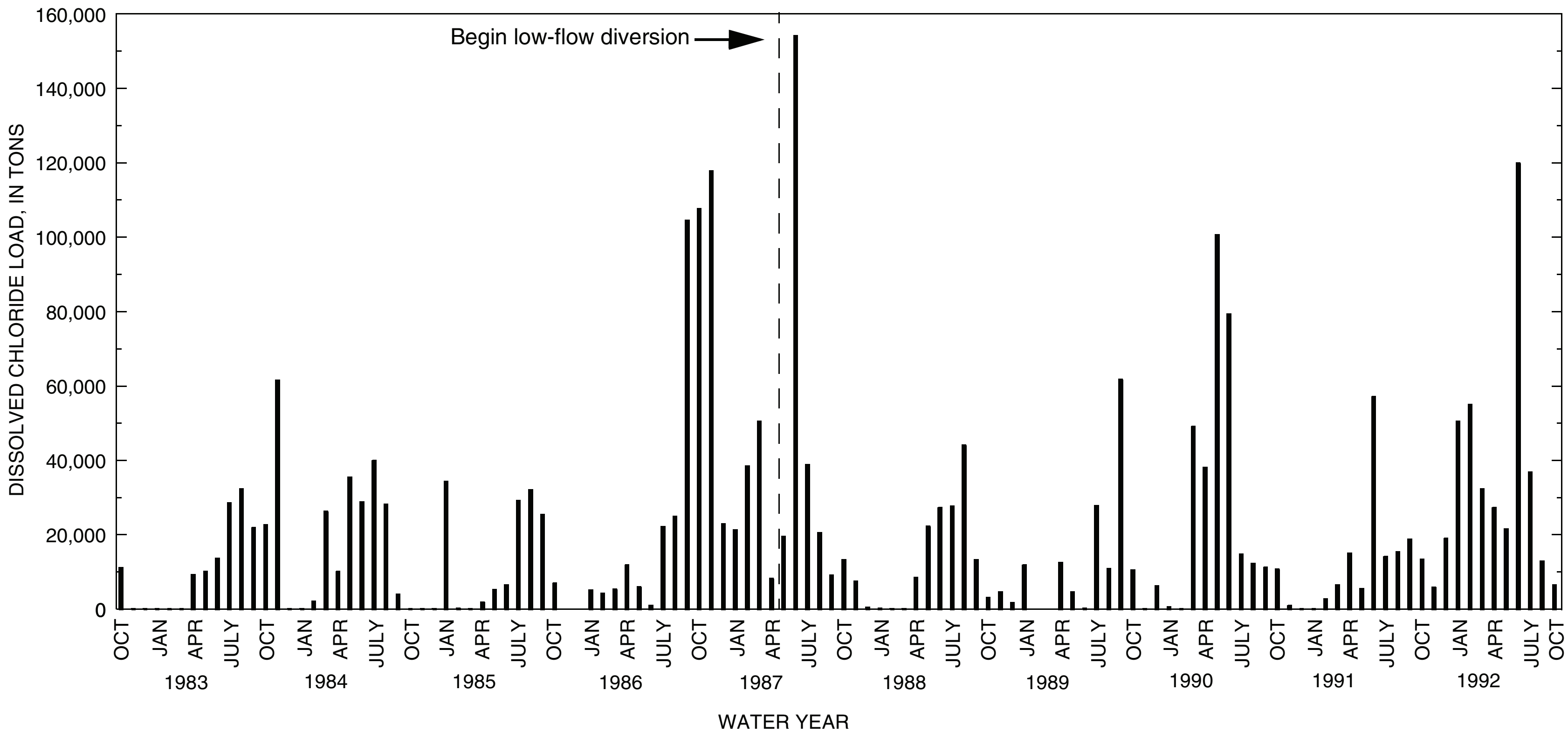

Figure 14. Dissolved chloride loads for streamflow-gaging station 07312100 Wichita River near Mabelle, Texas.

As with loads, the median monthly discharge at the Mabelle station is larger after diversion than before: The median monthly discharge is 2,350 ft^3/s-days before diversion and 4,310 ft^3/s-days after diversion. To indicate whether discharge was significantly larger after diversion, a rank-sum test on monthly discharge was done. The test showed weak evidence at the $\alpha = 0.1$ significance level (p-value = 0.0940) that discharge was significantly larger after diversion than before; thus an increase in discharge could have augmented an increase in load.

The Mabelle data and statistical tests show that, for the periods compared, salinity is significantly less after diversion but loads are larger and discharge is significantly larger. These results, plus the fact that the beginning of the marked decrease in salinity is coincident with about a 50-percent increase in Lake Kemp storage (figs. 10–12), indicate that significantly lower salinity after diversion probably is mostly a result of dilution of Lake Kemp by large inflows of (assumed) low-salinity water that occurred in the spring of 1989 rather than an effect of diversion. The effects of low-flow diversion in the South Wichita River, while significant relative to the salinity of water in that stream, are not discernible in the Wichita River below Lake Kemp.

CONCLUSIONS

At least three conclusions regarding the effects of diverting highly saline low flows from the South Wichita River on downstream salinity of the South Wichita River, Lake Kemp, and the Wichita River follow from the results presented in this report:

1. Salinity in the South Wichita River downstream of the low-flow diversion structure was (statistically) significantly less during the 65-month period of record after diversion than during the 55-month period of record before diversion.

   Wilcoxon rank-sum tests yielded strong evidence (attained significance levels less than 0.0001) that discharge-weighted dissolved solids and discharge-weighted dissolved chloride concentrations, as well as discharge-weighted specific conductance, were significantly less after diversion began in May 1987.

2. Whether salinity in Lake Kemp had a significant downward trend during the period of record August 1989–August 1992 could not be determined conclusively from observed salinity data.

   Mann-Kendall trend tests yielded weak evidence (attained significance levels of about 0.1) that volume-weighted dissolved solids and dissolved chloride concentrations in Lake Kemp tended to decrease with time. However, serial correlation (the dependence or correlation of an observation with the preceding observation) in the time series of salinity data, which cannot be ruled out, could cause the attained significance levels to be incorrect.

   Longer time series of salinity data could allow trend tests with less probability of serial correlation and more power to yield definitive results.

   Flow from the North Wichita River, which merges with flow from the South Wichita River before the combined flows reach Lake Kemp, could have a damping effect on any downward trend.

3. The significant effects of low-flow diversions on salinity in the South Wichita River are not discernible in the Wichita River downstream from Lake Kemp.

   Although salinity was significantly less downstream from Lake Kemp after diversion, the decrease probably is mostly a result of dilution of Lake Kemp by large inflows of (assumed) low-salinity water that occurred in the spring of 1989 rather than an effect of diversion.

REFERENCES CITED

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: New York, Elsevier, 522 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Keller, J., Rawson, J., Grubb, H., Kramer, J., and Sullivan, G., 1988, Report on the evaluation of the effectiveness of operation of area VIII Red River Chloride Control Project: Red River Chloride Control Project Report, 35 p.

U.S. Geological Survey, 1984–93, Water resources data for Texas, water years 1983–92: U.S. Geological Survey Water-Data Reports TX–83–1 to TX–92–1 (published annually).

Wells, F.C., and Schertz, T.L., 1984, Computation and use of volume-weighted-average computations to determine long-term variations of selected water-quality constituents in lakes and reservoirs: U.S. Geological Survey Water-Resources Investigations Report 83–4287, 8 p.