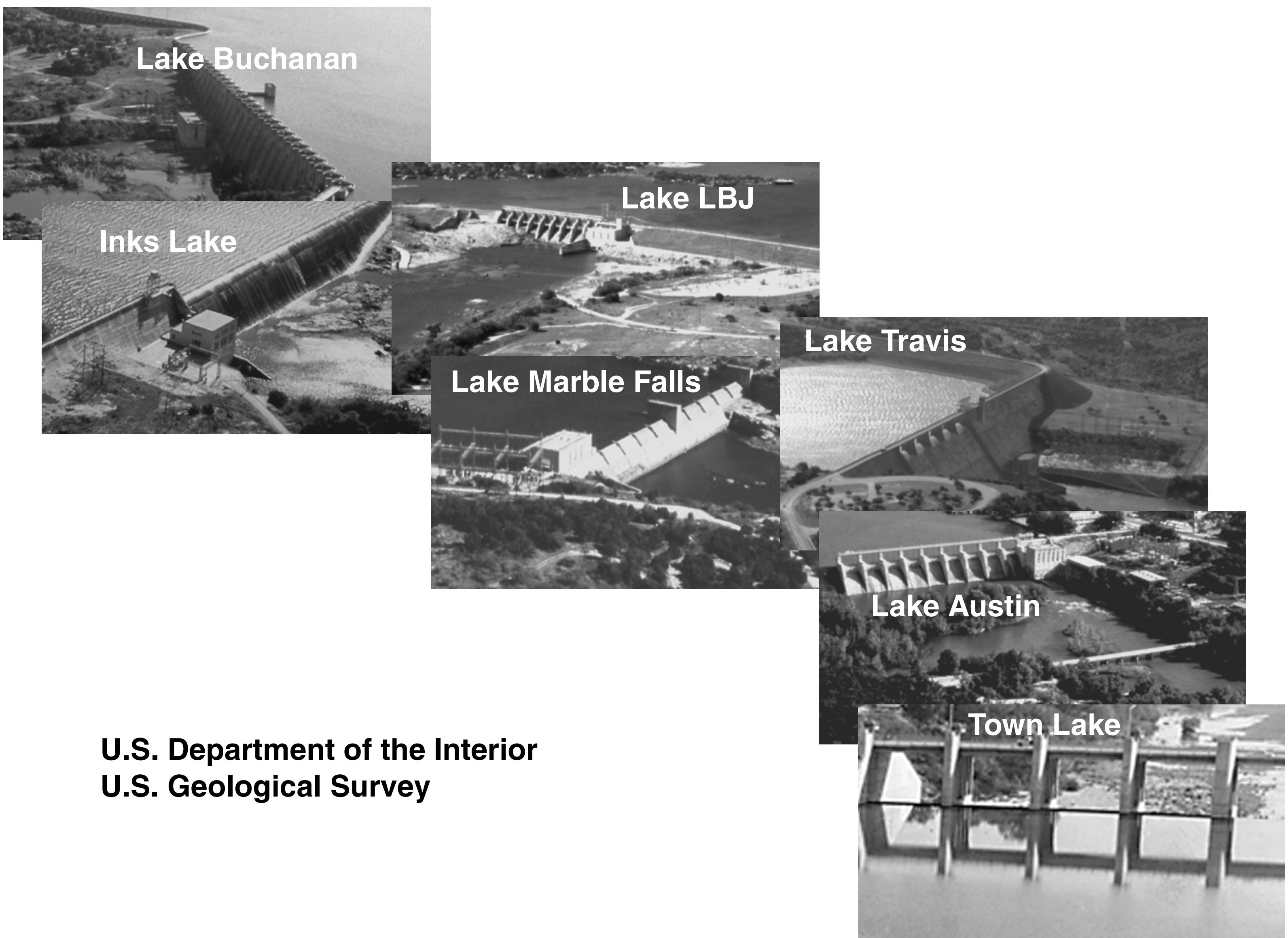
In cooperation with the Lower Colorado River Authority
and the City of Austin

Characterization and Simulation of the Quantity and Quality of Water in the Highland Lakes, Texas, 1983–92

Water-Resources Investigations Report 99–4087



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

Characterization and Simulation of the Quantity and Quality of Water in the Highland Lakes, Texas, 1983–92

By Timothy H. Raines and Walter Rast

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 99–4087

In cooperation with the Lower Colorado River Authority
and the City of Austin

Austin, Texas
1999

U.S. DEPARTMENT OF THE INTERIOR

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Characterization and Simulation of the Quantity and Quality of Water in the Highland Lakes, Texas, 1983–92

By Timothy H. Raines *and* Walter Rast

Abstract

The Highland Lakes, located in central Texas, are a series of seven reservoirs on the Colorado River (Lake Buchanan, Inks Lake, Lake Lyndon B. Johnson, Lake Marble Falls, Lake Travis, Lake Austin, and Town Lake). The reservoirs provide hydroelectric power for the area. In addition, Lake Austin and Town Lake also provide the public water supply for the Austin metropolitan area. Saline water released from Natural Dam Salt Lake during 1987–89 caused increased concern among water managers that high-salinity water entering the Highland Lakes could result in water-quality problems, necessitating additional treatment of the water.

The maximum dissolved solids concentrations for the reservoirs after the saline inflow were about two to three times the average concentrations before the inflow. The maximum concentrations of chloride and sulfate after the inflow were about three to five times the average concentrations before the inflow. The concentrations of dissolved solids, chloride, and sulfate in Lake Buchanan, Inks Lake, Lake Lyndon B. Johnson, and Lake Marble Falls were less than the concentrations of the applicable water-quality standards by the end of 1990. Concentrations of these constituents in Lake Travis, Lake Austin, and Town Lake did not decrease to previous levels, which were less than the concentrations of the applicable water-quality standards, until the end of 1991. Constituent concentrations for Lake Buchanan and Inks Lake; for Lake Lyndon B. Johnson and Lake Marble Falls; and for Lake Travis, Lake Austin, and Town Lake were similar because of the relative storage capacities and location of tributary inflows. From the initial increase in constituent concentrations in Lake Buchanan (summer 1987) in response to the saline inflow, the high-salinity water passed through the entire Highland Lakes in about 3.5 years.

A mathematical mass-balance model was used to simulate the input and movement of high-salinity water through the Highland Lakes and to estimate monthly mean concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry hydrologic conditions. The simulated median monthly concentrations during the 10-year simulation period for each reservoir generally are larger for the average condition than for the wet condition and generally are larger for the dry condition than for the average condition. The simulated concentrations of dissolved solids, chloride, and sulfate decreased to levels less than the concentrations of the applicable water-quality standards in about 2 to 5 years after the saline water inflow of 1987–89 was simulated for the three hydrologic conditions.

Results from the simulations indicate that saline inflows to the Highland Lakes similar to those of the releases from Natural Dam Salt Lake during 1987–89 are unlikely to cause large increases in future concentrations of dissolved solids, chloride, and sulfate in the Highland Lakes. The results also indicate that high-salinity water will continue to be diluted as it is transported downstream through the Highland Lakes, even during extended dry periods.

INTRODUCTION

The headwaters of the Colorado River Basin contain natural salt deposits and include active and inactive oil and gas fields. Runoff from some of these areas containing large concentrations of dissolved solids, chloride, and sulfate drain into Natural Dam Salt Lake (fig. 1). Natural Dam Salt Lake is a small but extremely saline reservoir (saline water is defined for purposes of this report as water having dissolved solids concentrations greater than 1,500 milligrams per liter (mg/L)). Water-quality data for Natural Dam Salt Lake indicate a long-term increase in dissolved solids concentrations because water primarily is lost from evaporation. Substantial amounts of precipitation during 1986–87 in parts of the contributing watersheds of Natural Dam Salt Lake and E.V. Spence Reservoir resulted in releases from these reservoirs containing thousands of tons of dissolved solids into the Colorado River and ultimately into the Highland Lakes. The Highland Lakes, a series of seven reservoirs on the Colorado River upstream from and in Austin, Tex., provide considerable natural and economic benefit to the area, including water supply, flood control, hydroelectric power generation, and recreation. The reservoirs, from upstream to downstream, are Lake Buchanan, Inks Lake, Lake Lyndon B. Johnson (LBJ), Lake Marble Falls, Lake Travis, Lake Austin, and Town Lake. Saline water has the potential to impart undesirable tastes to drinking water, interfere with fish production, reduce irrigated crop yields, and interfere with industrial water uses. Water managers are concerned that the large concentrations of dissolved solids, chloride, and sulfate entering the Highland Lakes could result in water-quality problems, necessitating additional treatment of the water prior to its use for municipal and industrial purposes.

In 1990, the U.S. Geological Survey (USGS) began an investigation in cooperation with the Lower Colorado River Authority (LCRA) and the City of Austin to characterize and simulate the quantity and quality of the Highland Lakes. The objectives of the study were to (1) characterize the recent quantity and quality of water in the Highland Lakes and (2) use a mass-balance model to simulate the quantity and quality of water in the Highland Lakes for wet, average, and dry hydrologic conditions for comparison.

Purpose and Scope

This report describes the quantity and quality of water in the Highland Lakes from January 1983 to December 1992 and presents the results from simulation of the quantity and quality of water in the Highland Lakes for three hydrologic conditions: wet, average, and dry. Measured concentrations of dissolved solids, chloride, and sulfate were compared to applicable water-quality standards. A mass-balance model was used to simulate 10 years of input and movement of water through the seven Highland Lakes and to estimate monthly mean concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry hydrologic conditions. Measured and estimated streamflow and water-quality data for the Colorado River upstream of Lake Buchanan, the Llano River, and the Pedernales River were used for inflows to the model.

Description of Study Area

The drainage basin of the Highland Lakes is characterized by rolling hills with stony soils and areas of exposed granite and limestone. Soils generally are thin, overlie hard limestone, and primarily are clay or silty clay with low permeability. More detailed geologic information is provided by Garner and Young (1976). The predominant land cover is rangeland, consisting mostly of grasses and shrubs. The local climate is characterized by short, mild winters; long, moderately hot summers; moderately high humidity; and southerly prevailing winds. The mean annual precipitation in Austin during 1928–92 is about 32 inches (in.) and ranges from about 11 to 51 in. with an average of about 80 storms annually (Miertschin and Armstrong, 1986, p. 175). The greatest precipitation typically occurs in the spring and early fall from frontal storms. Widely scattered thunderstorms produce precipitation during the summer. Major tributaries of the Highland Lakes include the Llano and Pedernales Rivers. Other smaller tributaries include Sandy, Bull, Barton, and Shoal Creeks (fig. 1).

E.V. Spence Reservoir is on the Colorado River about 315 miles (mi) upstream from Lake Buchanan (fig. 1). Natural Dam Salt Lake is located on Beals Creek, a tributary to the Colorado River upstream from E.V. Spence Reservoir, and has a drainage area of about 500 square miles (mi^2) that normally receives an average of about 18 in. of precipitation annually. Evaporation is the primary means of water loss from Natural Dam Salt Lake. During 1986–87, parts of the upper Colorado River Basin received heavy rains that resulted in releases of water that contained hundreds of thousands of tons of salt from Natural Dam Salt Lake (and subsequently from E.V. Spence Reservoir) into the Colorado River. The chloride concentration in Natural Dam Salt Lake before the 1986–87 precipitation period was estimated to be as large as 6,000 mg/L (C. Wingert, Colorado River Municipal Water District,

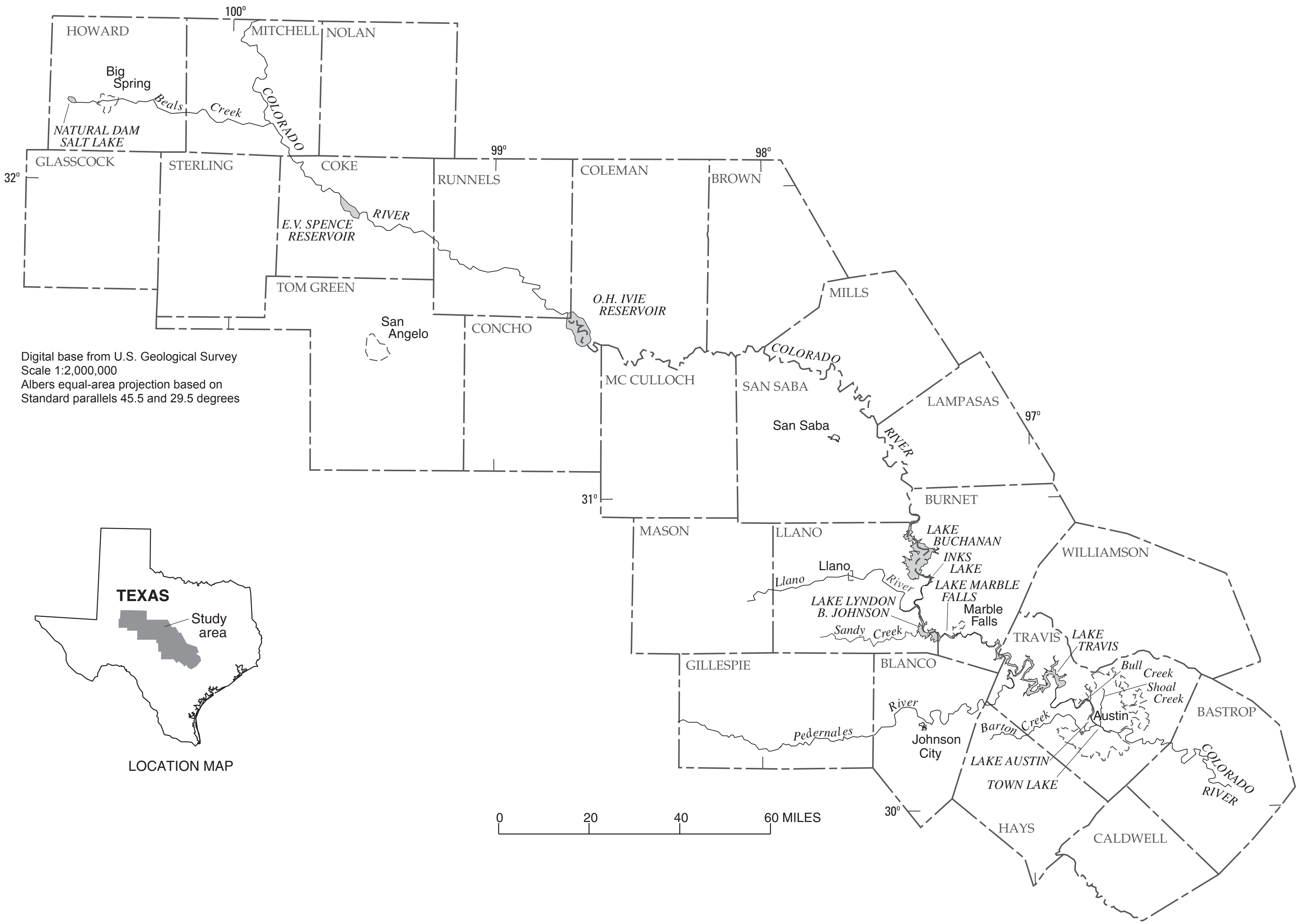


Figure 1. Location of study area.

Table 1. Selected physical and hydrologic characteristics of the Highland Lakes, Texas

Reservoir	Reservoir altitude, top of operating range[1] (feet above mean sea level)	Reservoir surface area, top of operating range[1] (acres)	Reservoir storage, top of operating range[1] (acre-feet)	Mean retention time[2] (months)
Lake Buchanan	1,020	28,400	895,000	11–130
Inks Lake	888	793	17,300	.2–2
Lake Lyndon B. Johnson	825	6,380	138,000	1–4
Lake Marble Falls	737	650	8,050	.06–.2
Lake Travis	681	18,900	1,170,000	6–19
Lake Austin	493	1,780	21,200	.1–.4
Town Lake	428	420	3,490	.02–.06

[1] Source (except for Town Lake): C.A. Riley, Lower Colorado River Authority, written commun., 1999; Town Lake data from Miertschin and Armstrong (1986).

[2] Retention times vary based on inflow and reservoir storage volumes.

written commun., 1992). By comparison, a typical chloride concentration in the downstream E.V. Spence Reservoir prior to the 1986–87 precipitation was about 700 mg/L.

The storage capacities for Lakes Buchanan, LBJ, and Travis (table 1) are appreciably larger than the storage capacities of the other four reservoirs, Inks Lake, Lake Marble Falls, Lake Austin, and Town Lake. Lakes Buchanan and Travis provide water storage to meet downstream water demands. The five other reservoirs are operated as generally constant-level reservoirs. Because of the smaller storage capacities of the reservoirs immediately downstream of Lakes Buchanan, LBJ, and Travis, inflows with large concentrations of dissolved solids, chloride, and sulfate will more quickly affect the resulting concentrations in the immediately downstream reservoirs. The rate of mixing is represented by the mean retention time for each reservoir. The maximum retention time for the four smaller reservoirs is 2 months compared to 130 months for the three larger reservoirs. The retention time for a reservoir is a function of the inflow and storage volumes. The travel time required for water to pass through all the Highland Lakes (assuming all the inflow displaces all the storage) ranges from about 18 to 160 months with an average of about 44 months (Miertschin and Armstrong, 1986, p. 51).

Description of Mass-Balance Model

The Reservoir Operating and Quality Routing program (RESOP II), developed by the Texas Water Development Board (Browder, 1978), provides detailed analyses of the annual water yield of individual reservoirs and contains a water-quality component for modeling conservative water-quality constituents. RESOP II can be used in an iterative manner to simulate multiple reservoirs in a series.The model performs a water mass balance for each month using the monthly mean storage (S), monthly inflow (I), monthly demand (D), monthly releases (R), and monthly evaporation (E). The next month $(n+1)$ storage is computed from the current month (n) values using the following equation:

$$S_{n+1} = S_n + I_n - D_n - R_n - E_n . \qquad (1)$$

RESOP II also computes concentrations of conservative constituents (dissolved solids, chloride, and sulfate) assuming uniform mixing of the reservoir. The concentrations of the reservoir demands and releases are assumed to be equal to the concentrations of the reservoir storage. The concentration of evaporation is assumed to be zero. For any constituent, the next month reservoir concentration (C_{n+1}) is a function of the current month reservoir concentration (C_n) and inflow concentration (CI_n):

$$C_{n+1} = \frac{(S_nC_n + I_nCI_n - D_nC_n - R_nC_n)}{S_{n+1}} . \qquad (2)$$

Using these variables, the model simulates monthly reservoir operation for a desired time interval (maximum of 50 years) and calculates the storage of the reservoir and concentrations of the constituents.

A limitation of the original version of RESOP II was the use of constant annual or monthly reservoir demands throughout the entire period of simulation. In reality, the measured demand varies monthly. RESOP II was modified to accept variable monthly demands from each reservoir, as measured by the LCRA, City of Austin, or USGS, to improve model simulation results.

Acknowledgments

Lewis Browder, Texas Water Development Board, provided considerable assistance in refining and updating the RESOP II model. Jeannie Wigington, Environmental Conservation Section, Water and Wastewater Department, City of Austin, compiled water-quantity and water-quality data for Town Lake. Michelle Creasy and John Wedig, Water Resources Section, LCRA, provided the water-quantity and water-quality data for the Highland Lakes. Jeff Saunders, LCRA, provided valuable comments during review of this report.

CHARACTERIZATION OF THE QUANTITY AND QUALITY OF THE HIGHLAND LAKES

During 1986–87, E.V. Spence Reservoir received runoff from substantial amounts of precipitation, resulting in massive inflows to the reservoir, including inflows from Natural Dam Salt Lake. Between July 1986 and July 1988, about 70,000 acre-feet (acre-ft) of water was released from Natural Dam Salt Lake, including major releases in July 1986 and May 1987 (J. Pickle, Colorado River Municipal Water District, oral commun., 1992). The inflows to E.V. Spence Reservoir from Natural Dam Salt Lake contained hundreds of thousands of tons of dissolved solids. About 225,000 acre-ft of water was released from E.V. Spence Reservoir downstream into the Colorado River and was estimated to contain more than 1.4 million tons of dissolved solids (C. Dvorsky, Lower Colorado River Authority, written commun., 1992). As a result, the dissolved solids load flowing into Lake Buchanan during 1987–89 represented about 40 percent of that released from Natural Dam Salt Lake during the period (Slade and Buszka, 1994).

Table 2. Applicable water-quality standards[1] for each tributary and reservoir of the Highland Lakes, Texas

[in milligrams per liter]

Reservoir	Total dissolved solids	Chloride	Sulfate
Colorado River above Lake Buchanan	875	200	155
Lake Buchanan	525	145	95
Pedernales River	525	105	50
Llano River	300	45	25
Inks Lake	525	135	95
Lake Lyndon B. Johnson	450	115	70
Lake Marble Falls	450	115	70
Lake Travis	375	85	60
Lake Austin	375	85	60
Town Lake	375	75	60
Colorado River below Town Lake	425	90	60

[1] Texas Natural Resource Conservation Commission (1997).

Monthly mean streamflow and concentrations of dissolved solids, chloride, and sulfate at the Colorado River near San Saba during 1983–92 are shown in figure 2. The dissolved solids concentration in the Colorado River increased from a mean of about 340 mg/L during 1986 to a mean of more than 1,200 mg/L during 1988–89. During this period, concentrations of dissolved solids exceeded the applicable water-quality standard for the Colorado River segment above Lake Buchanan as established by the Texas Natural Resource Conservation Commission (1997). Similarly, concentrations of chloride and sulfate exceeded the applicable water-quality standard during this period. The applicable water-quality standards are different for each tributary and reservoir of the Highland Lakes and are listed in table 2.

Monthly mean reservoir storage and concentrations of dissolved solids, chloride, and sulfate for the Highland Lakes during 1983–92 are shown in

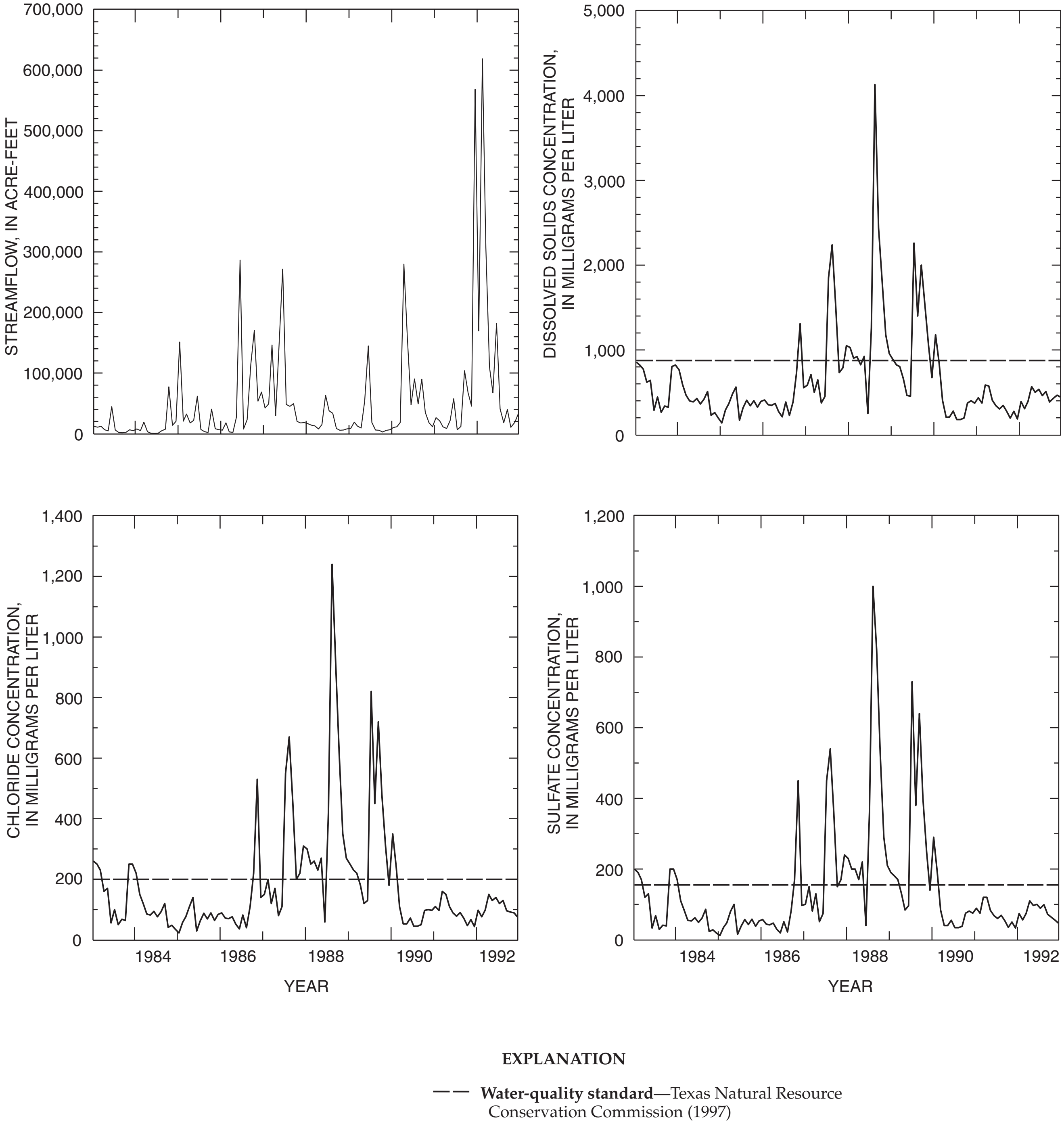


Figure 2. Measured monthly streamflow and concentrations of dissolved solids, chloride, and sulfate at Colorado River near San Saba, Texas, 1983–92.

figures 3–9. The concentrations of dissolved solids, chloride, and sulfate in Lake Buchanan began increasing during summer 1987. The concentrations in the immediately downstream, smaller Inks Lake are very similar to those of Lake Buchanan. In both reservoirs, the concentrations peaked during 1989–90 and subsequently decreased to previous levels in 1991. The concentrations in Lake LBJ and in the immediately

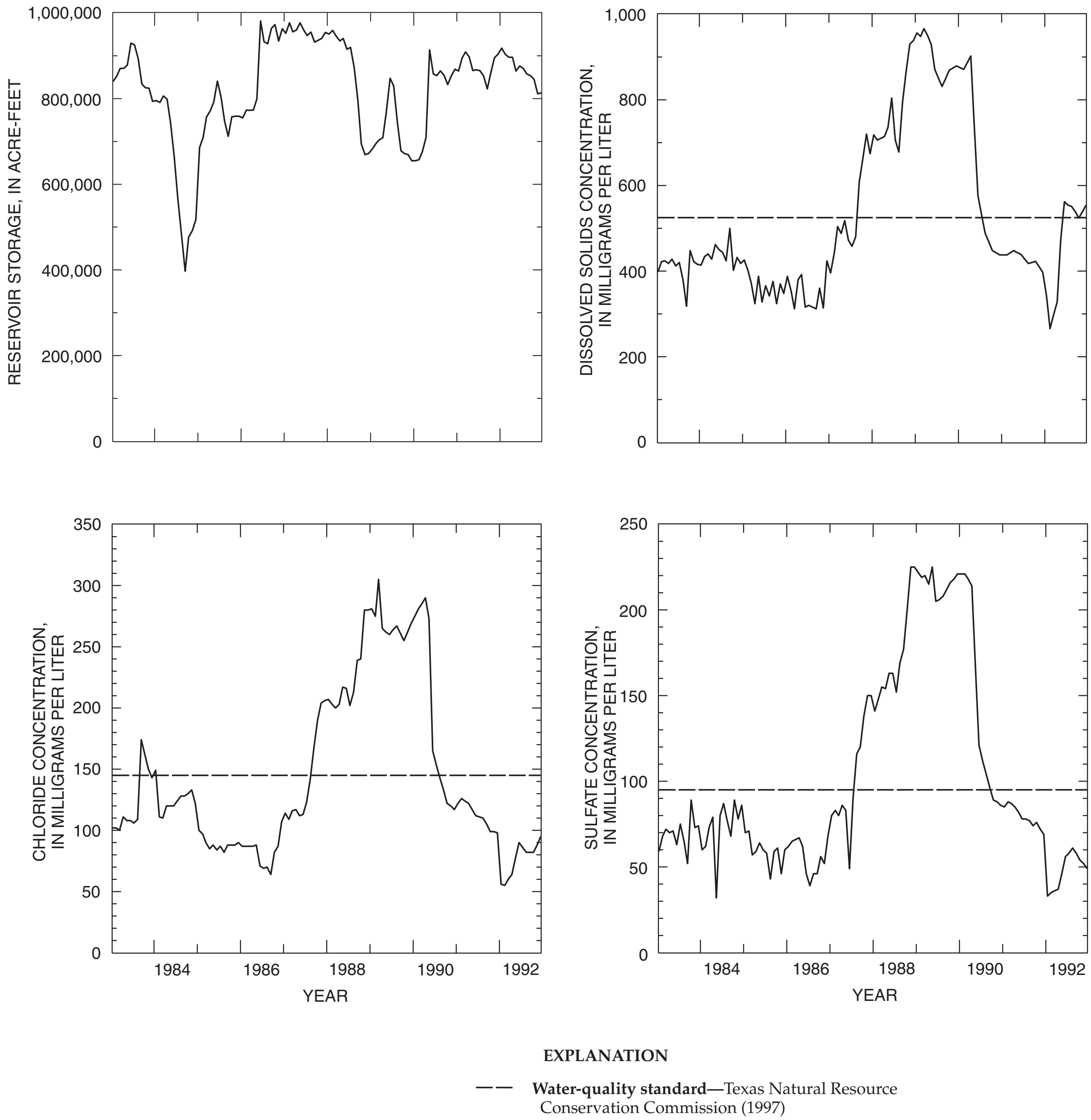


Figure 3. Measured monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Lake Buchanan, Texas, 1983–92.

downstream, smaller Lake Marble Falls began increasing in early 1988, about 1 year later than the concentrations in Lake Buchanan and Inks Lake. The concentrations peaked in late 1989, decreasing thereafter to previous levels in 1991. The concentrations in Lake Travis and in downstream Lake Austin and Town Lake began increasing by the end of 1988, more gradually than the upstream reservoir groups. The

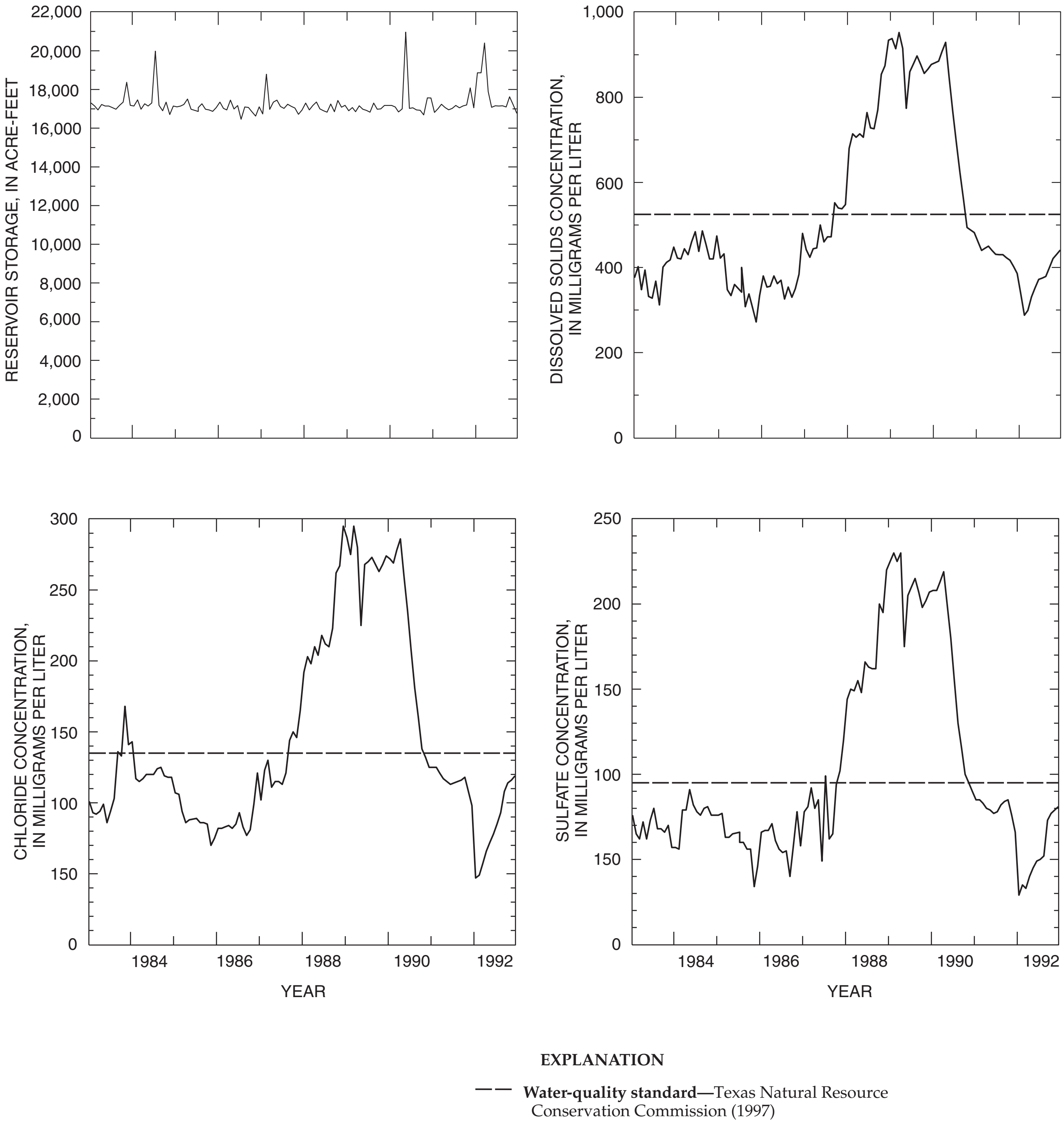


Figure 4. Measured monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Inks Lake, Texas, 1983–92.

concentrations peaked in late 1990 or early 1991 and decreased thereafter. The time required for the high-salinity water to move through all the Highland Lakes was about 42 months.The decrease in concentrations in the Highland Lakes from upstream to downstream is the result of dilution by inflows from the tributaries with lower salinity concentrations than those of water in the reservoirs during the high-salinity period.

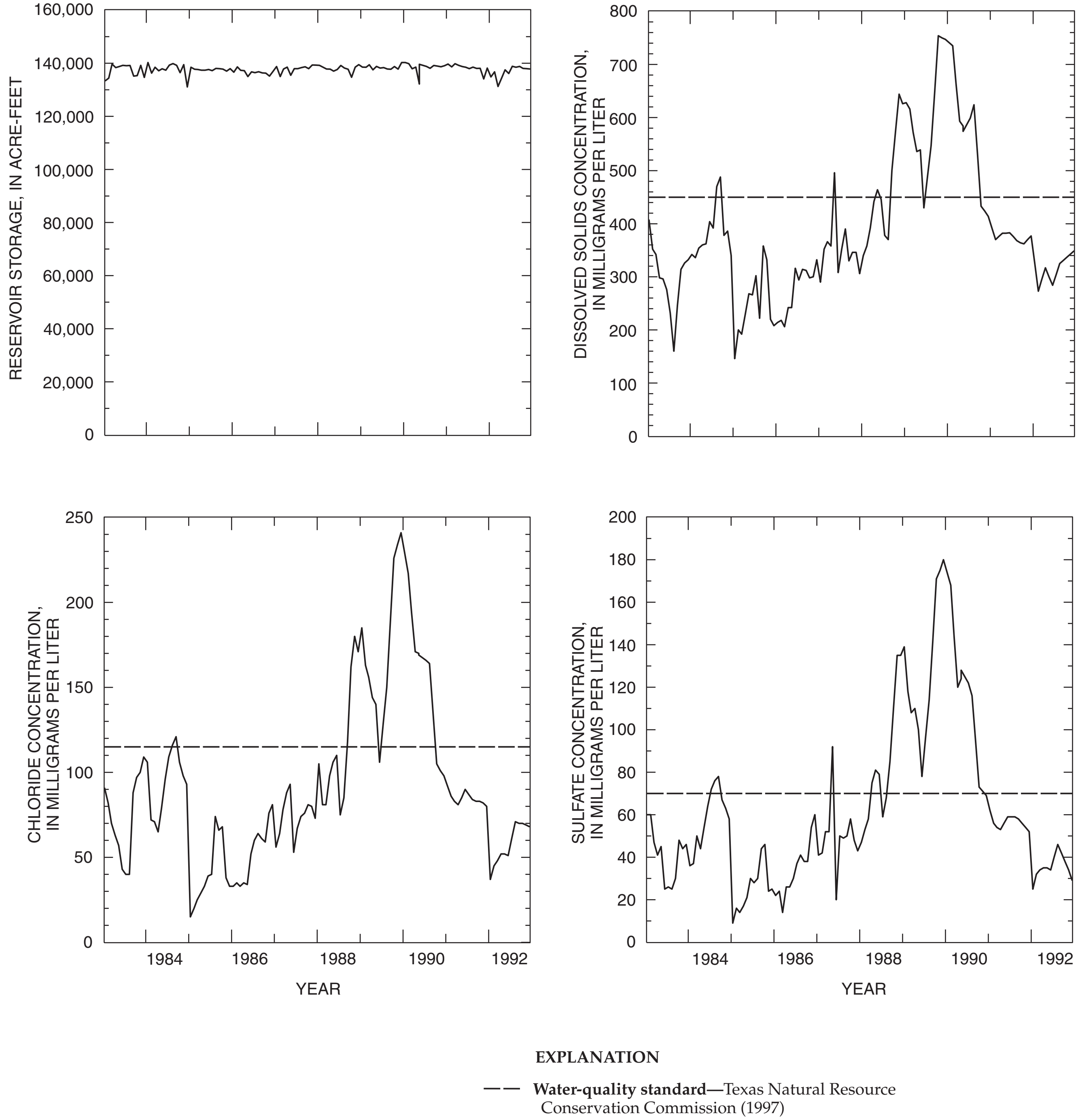


Figure 5. Measured monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Lake Lyndon B. Johnson, Texas, 1983–92.

In downstream order, the changes in the concentrations of dissolved solids, chloride, and sulfate in the Highland Lakes resulting from the saline inflows are listed in table 3. The maximum dissolved solids concentrations in the reservoirs after the saline inflows were about two to three times the mean concentrations before the saline inflows. The maximum concentrations of chloride and sulfate after the saline inflows were

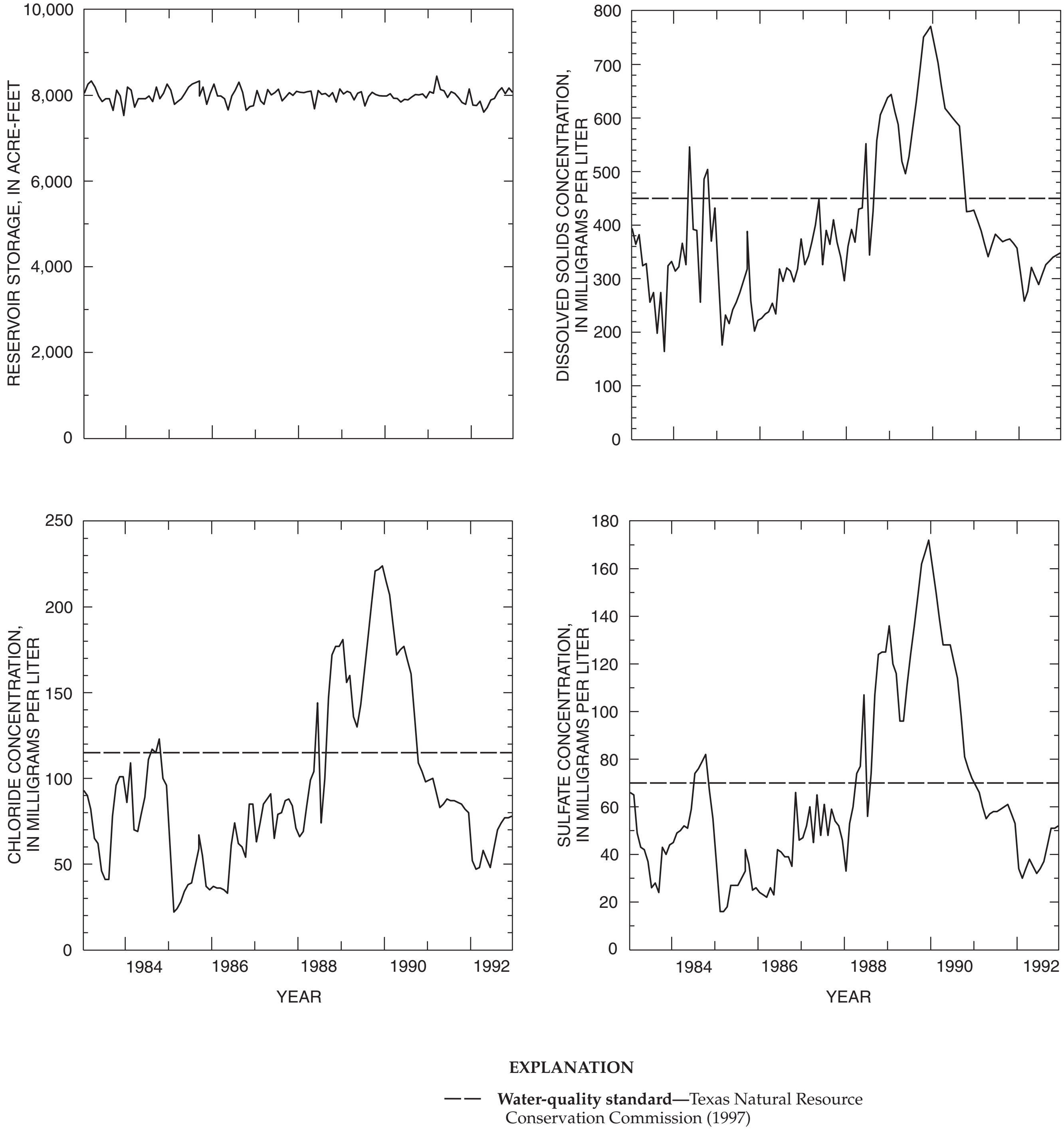


Figure 6. Measured monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Lake Marble Falls, Texas, 1983–92.

about three to five times the mean concentrations before the saline inflows. The mean concentrations of the three constituents (before the saline inflows) in the six downstream reservoirs ranged from 50 to 109 percent of the mean concentrations at Lake Buchanan, and the maximum concentrations (after the saline inflows) in the six downstream reservoirs ranged from 43 to 102 percent of the maximum concentrations at Lake Buchanan.

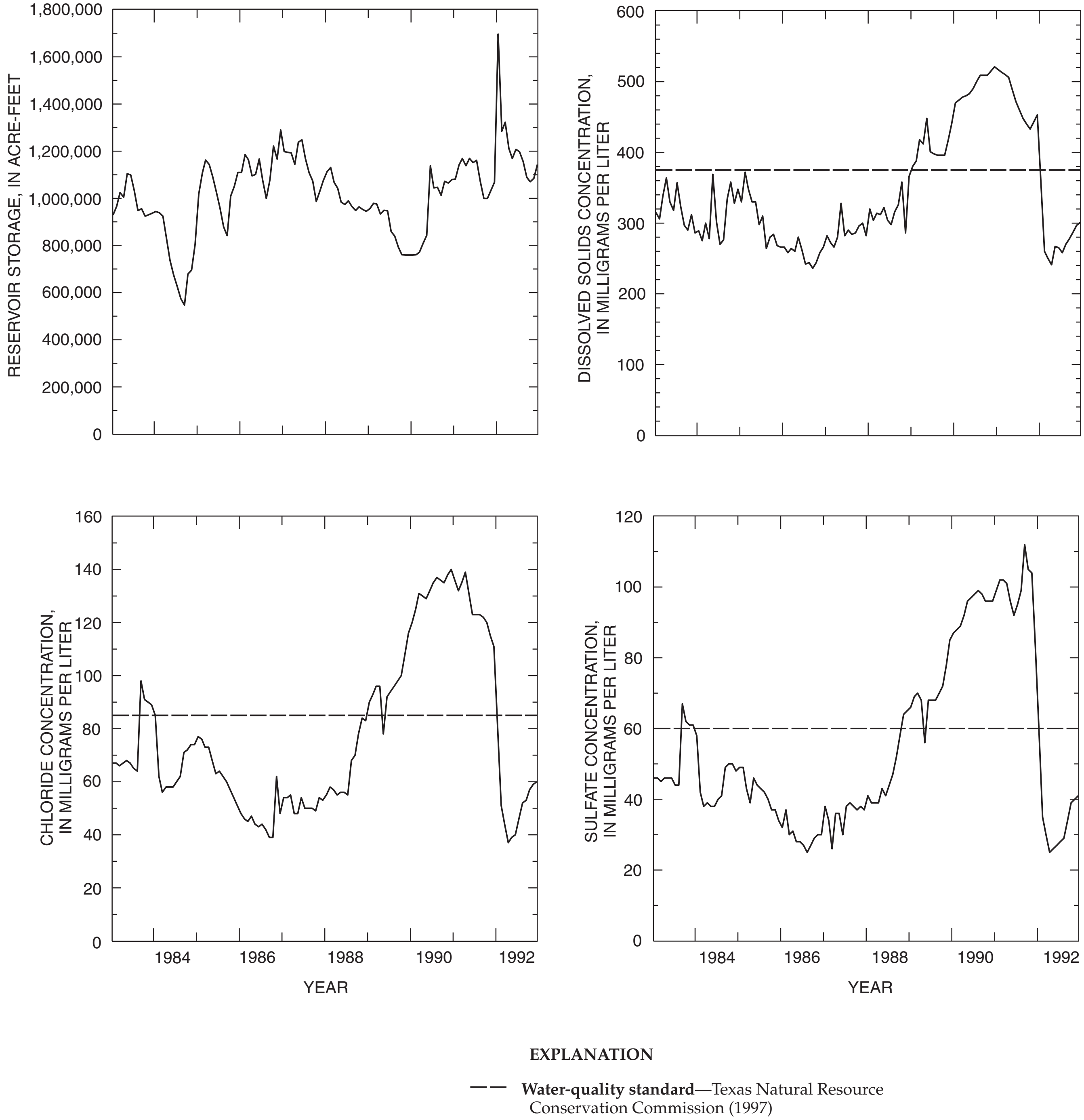


Figure 7. Measured monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Lake Travis, Texas, 1983–92.

The concentrations of dissolved solids, chloride, and sulfate in the Highland Lakes exceeded the concentrations of the applicable water-quality standards (Texas Natural Resource Conservation Commission, 1997) from 25 to 42 months during 1987–91. The concentrations of dissolved solids, chloride, and sulfate in Lake Buchanan, Inks Lake, Lake LBJ, and Lake Marble Falls decreased to less than the concentrations of the

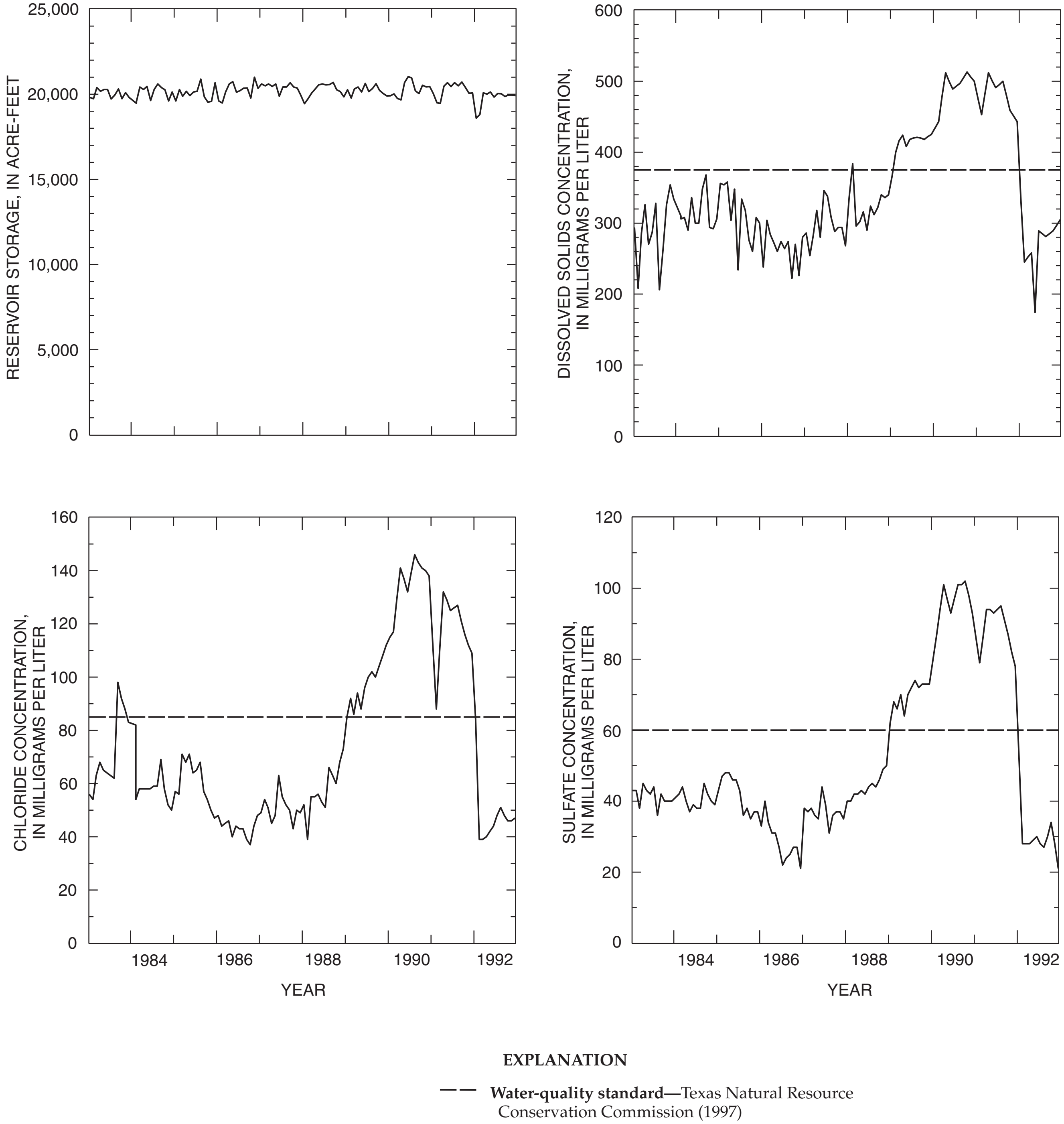
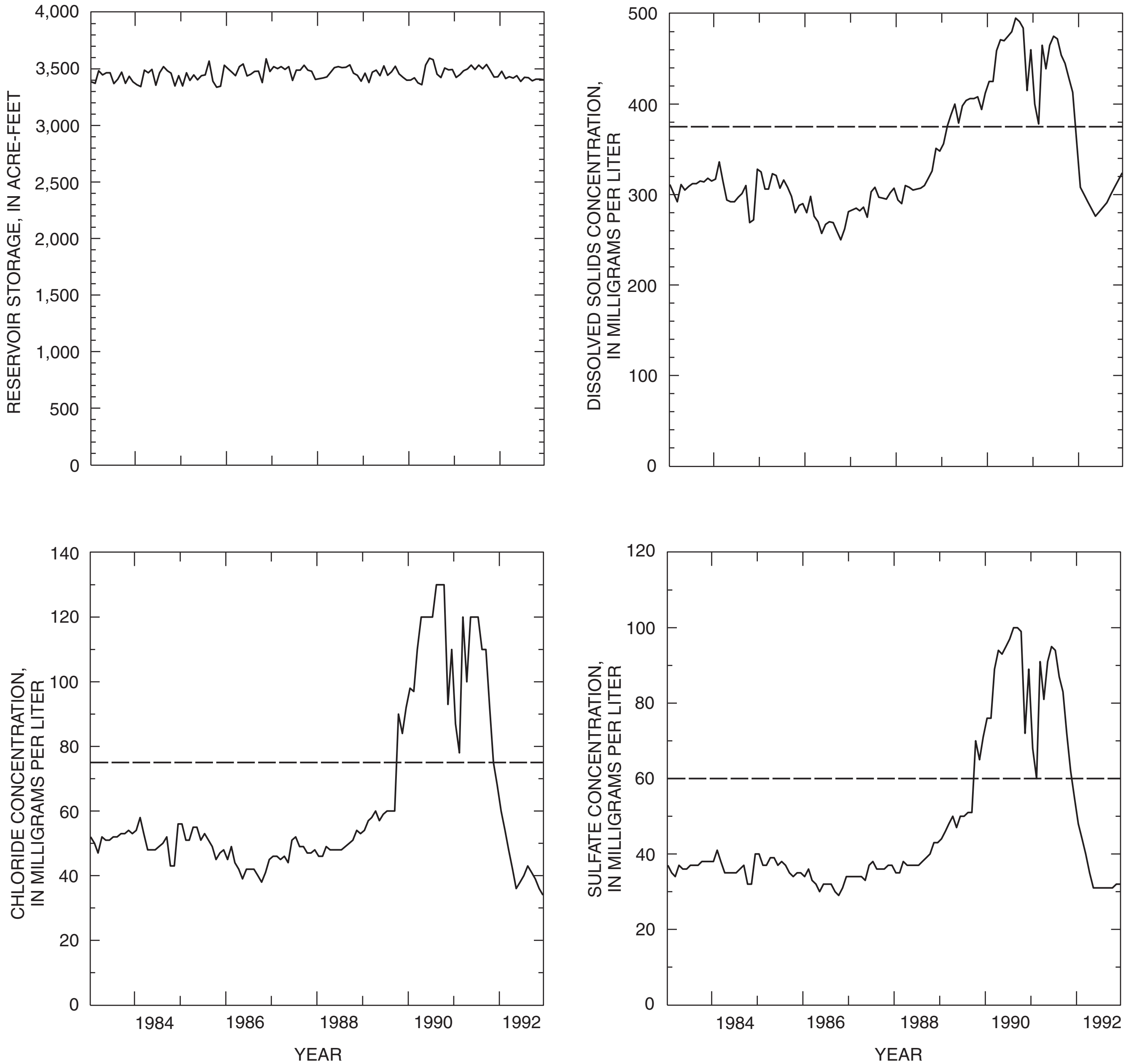


Figure 8. Measured monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Lake Austin, Texas, 1983–92.

applicable water-quality standards by the end of 1990. The concentrations in Lake Travis, Lake Austin, and Town Lake did not decrease to previous levels, which were less than the concentrations of the applicable water-quality standards, until the end of 1991.

SIMULATION OF THE QUANTITY AND QUALITY OF THE HIGHLAND LAKES

The saline inflows were simulated for three different hydrologic conditions—wet, average, and dry—



EXPLANATION

—— **Water-quality standard**—Texas Natural Resource Conservation Commission (1997)

Figure 9. Measured monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Town Lake, Texas, 1983–92.

to determine a range in monthly concentrations of dissolved solids, chloride, and sulfate for each of the three conditions in the Highland Lakes.

Because reservoir inflows are proportional to precipitation in each drainage basin, the period of record for each major tributary to the Highland Lakes

Table 3. Measured concentrations of dissolved solids, chloride, and sulfate in the Highland Lakes, Texas, 1983–92

[mg/L, milligrams per liter; --, not applicable]

Reservoir	1986 monthly mean concentration before saline inflow (mg/L)	Maximum concentration after saline inflow (mg/L)	Ratio of maximum concentration to mean concentration	Ratio of mean concentration to Lake Buchanan concentration	Ratio of maximum concentration to Lake Buchanan concentration	Number of months exceeding water-quality standard[1] during 1983–92	Period in which water-quality standards exceeded from saline inflow
Dissolved solids							
Lake Buchanan	350	965	2.8	--	--	35	9/87–7/90
Inks Lake	370	950	2.6	1.06	0.98	37	9/87–9/90
Lake Lyndon B. Johnson	275	755	2.7	.79	.78	28	9/88–9/90
Lake Marble Falls	285	770	2.7	.81	.80	29	9/88–9/90
Lake Travis	255	520	2.0	.73	.54	36	1/89–12/91
Lake Austin	265	515	1.9	.76	.53	36	2/89–12/91
Town Lake	270	495	1.8	.77	.51	34	2/89–11/91
Chloride							
Lake Buchanan	80	305	3.8	--	--	39	9/87–7/90
Inks Lake	85	295	3.5	1.06	.97	42	9/87–10/90
Lake Lyndon B. Johnson	50	240	4.8	.62	.79	25	9/88–9/90
Lake Marble Falls	55	225	4.1	.69	.74	29	9/88–9/90
Lake Travis	45	140	3.1	.56	.46	41	1/89–12/91
Lake Austin	45	145	3.2	.56	.48	39	1/89–12/91
Town Lake	40	130	3.2	.50	.43	26	10/89–11/91
Sulfate							
Lake Buchanan	55	225	4.1	--	--	38	9/87–7/90
Inks Lake	60	230	3.8	1.09	1.02	38	8/87–9/90
Lake Lyndon B. Johnson	35	180	5.1	.64	.80	31	11/88–11/90
Lake Marble Falls	35	170	4.9	.64	.76	36	9/88–11/90
Lake Travis	30	112	4.2	.55	.56	42	8/89–12/91
Lake Austin	30	100	3.3	.55	.44	36	11/88–12/91
Town Lake	30	100	3.3	.55	.44	26	10/89–11/91

[1] Water-quality standard established by the Texas Natural Resource Conservation Commission (1997).

was analyzed for the concurrent period of record, 1944–95, to compute the maximum, mean, and minimum 7-year period of cumulative streamflow. The consecutive 7-year period with the maximum storage was considered to represent the wet hydrologic condition, the consecutive 7-year period with the storage most comparable to the mean storage for 1944–95 was considered to represent the average hydrologic condition, and the consecutive 7-year period with the minimum storage was considered to represent the dry hydrologic condition. Available water-quality data were used to estimate inflow concentrations. Available reservoir demands, releases, and evaporation data were used for the simulations.

Model Development

The major tributaries for the Highland Lakes are the Colorado, Llano, and Pedernales Rivers, and additional tributaries include Sandy, Bull, Barton, and

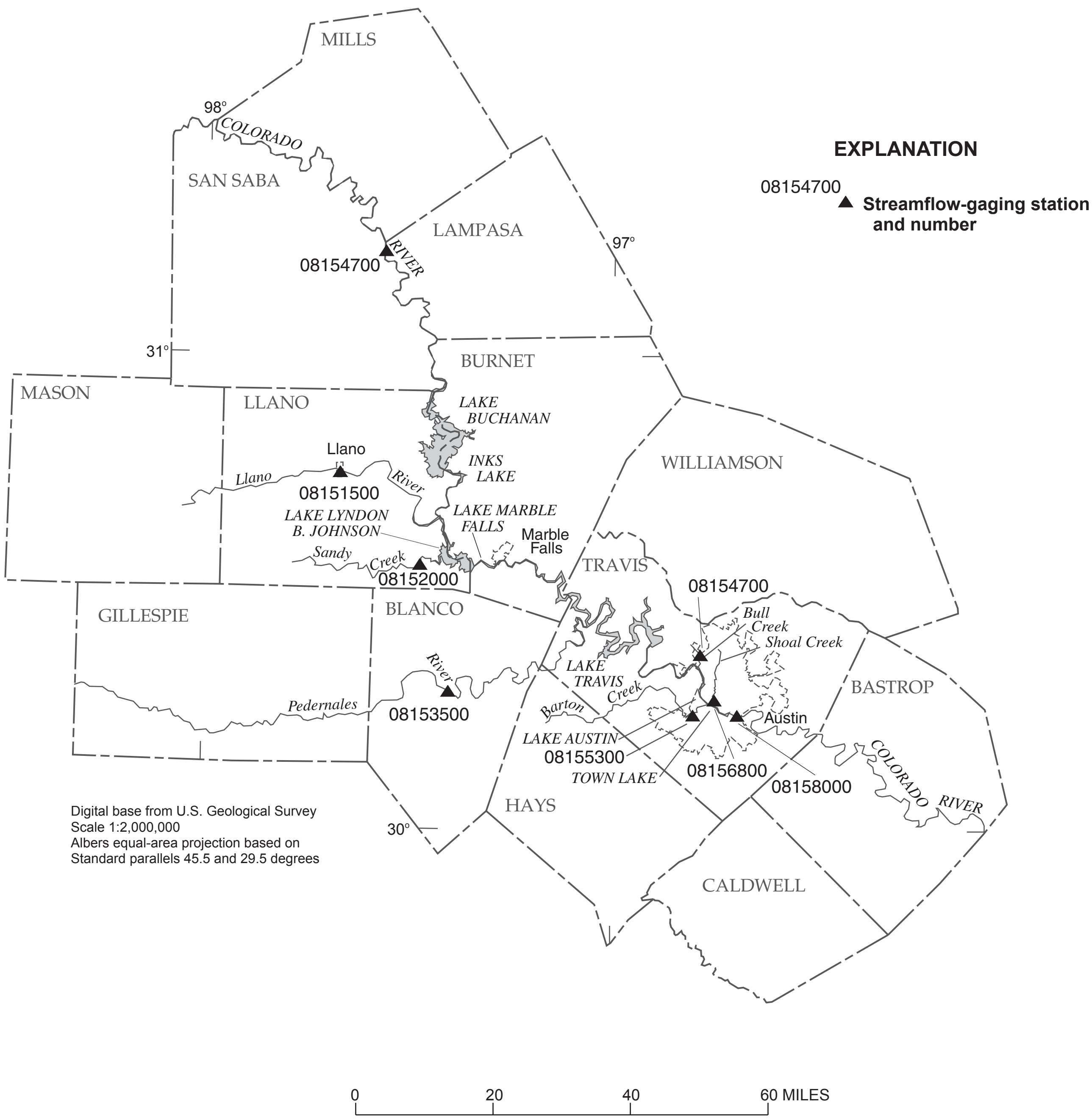


Figure 10. Location of selected streamflow-gaging stations near the Highland Lakes, Texas.

Shoal Creeks (fig. 10). Drainage areas of these tributaries account for about 26,800 of the 27,600 mi^2 or about 97 percent of the contributing drainage area to Town Lake (table 4). The remaining area comprises intervening drainage from local tributaries to the Highland Lakes. Of the 26,800 mi^2, about 25,400 mi^2 or 95 percent is measured at USGS streamflow-gaging stations. Of the 25,400 mi^2 gaged area, about 24,900 mi^2 or 98 percent of the area is gaged at the Colorado River near San Saba, Llano River at Llano, and Pedernales River near Johnson City streamflow-gaging stations. More than 50 years of data are available from each of these stations to define the hydrologic conditions for the three major tributaries as compared to about 20 years or less

Table 4. Characteristics of selected tributary and outlet streams of the Highland Lakes, Texas

[mi^2, square miles; --, not available]

Stream	Stream contributing drainage area[1] (mi^2)	Station number	Station location	Station contributing drainage area (mi^2)	Period of record	1983–92 mean annual streamflow (acre-feet)	Ratio of stream to station drainage areas
Tributary							
Colorado River at Lake Buchanan	20,512	08147000	near San Saba	19,819	1941–present	621,000	1.03
Colorado River at Inks Lake	20,552	--	--	--	--	--	--
Llano River	4,450	08151500	at Llano	4,192	1939–present	308,000	1.06
Sandy Creek	391	08152000	near Kingsland	346	1966–present	53,700	1.13
Colorado River at Lake Lyndon B. Johnson	25,523	--	--	--	--	--	--
Colorado River at Marble Falls	25,605	--	--	--	--	--	--
Pedernales River	1,281	08153500	near Johnson City	901	1940–present	186,000	1.42
Colorado River at Lake Travis	27,352	--	--	--	--	--	--
Bull Creek	31.6	08154700	at Loop 360 near Austin	22.3	1979–present	11,100	1.42
Colorado River at Lake Austin	27,443	--	--	--	--	--	--
Barton Creek	120	08155300	at Loop 360, Austin	116	1975–present	42,700	1.03
Shoal Creek	13.6	08156800	at 12th Street, Austin	12.3	1984–present	5,450	1.11
Total	27,577			25,409		1,228,000	1.09
Outlet							
Colorado River at Town Lake	27,600	08158000	at Austin	27,606	1898–present	1,550,000	1.00

[1] Tovar and Maldonado, 1981.

Table 5. Measured and simulated water gains and losses of the Highland Lakes, Texas

Reservoir	Measured		Simulated	
	Water gains	Water losses	Water gains	Water losses
Lake Buchanan	Colorado River	Evaporation; downstream releases to Inks Lake	Colorado River	Evaporation; downstream releases to Inks Lake
Inks Lake	Lake Buchanan releases; local tributaries	Evaporation; downstream releases to Lake Lyndon B. Johnson	Lake Buchanan releases	Evaporation; downstream releases to Lake Lyndon B. Johnson
Lake Lyndon B. Johnson	Inks Lake releases; Llano River; local tributaries	Evaporation; downstream releases to Lake Marble Falls	Inks Lake releases; Llano River	Evaporation; downstream releases to Lake Marble Falls
Lake Marble Falls	Lake Lyndon B. Johnson releases; local tributaries	Evaporation; downstream releases to Lake Travis	Lake Lyndon B. Johnson releases	Evaporation; downstream releases to Lake Travis
Lake Travis	Lake Marble Falls releases; Pedernales River; local tributaries	Evaporation; downstream releases to Lake Austin	Lake Marble Falls releases; Pedernales River	Evaporation; downstream releases to Lake Austin
Lake Austin	Lake Travis releases; Bull Creek; local tributaries	Evaporation; downstream releases to Town Lake; public water supply withdrawals by City of Austin	Lake Travis releases	Evaporation; downstream releases to Town Lake; public water supply withdrawals by City of Austin
Town Lake	Lake Austin releases; Barton Creek; Shoal Creek; local tributaries	Evaporation; downstream releases to lower Colorado River; public water supply withdrawals by City of Austin	Lake Austin releases	Evaporation; downstream releases to lower Colorado River; public water supply withdrawals by City of Austin

for the smaller tributaries. The three major tributaries account for about 91 percent of the 1983–92 mean annual inflow to the Highland Lakes but only about 72 percent of the 1983–92 annual streamflow released from the Highland Lakes measured at Colorado River at Austin. The net change in storage from 1983–92 was a decrease of about 27,000 acre-ft in Lake Buchanan and an increase of about 210,000 acre-ft in Lake Travis.

A list of the sources of the measured and simulated water gains and losses for each reservoir of the Highland Lakes is shown in table 5. The water gains for the Highland Lakes include tributary inflows and releases from upstream reservoirs. The water losses include evaporation, reservoir releases, and water supply withdrawals. The primary difference between the measured and simulated water gains and losses is that the simulated water gains include only tributary inflows from the Colorado, Llano, and Pedernales Rivers with no additional tributary contributions. The three major tributaries provide most of the annual inflow to the Highland Lakes and have an adequate amount of data to represent the wet, average, and dry periods for simulations.

Because only periodic water-quality data were available for the stations on the Llano and Pedernales Rivers and monthly water-quality data were not available for the Colorado River at San Saba prior to 1980, regression equations were developed from the available water-quality data and daily mean streamflows to estimate loads for dissolved solids, chloride, and sulfate for the Colorado, Llano, and Pedernales Rivers using ordinary least-squares regression (Helsel and Hirsch, 1992). The regression equations were log-transformed to make the variance of the regression residuals approximately constant (constant variance is a necessary assumption of least-squares regression). The equations to estimate loads of dissolved solids, chloride, and sulfate as a function of streamflow (table 6) contain bias correction

Table 6. Regression equations for estimating concentrations of dissolved solids, chloride, and sulfate for selected tributaries of the Highland Lakes, Texas

[LOAD, load in kilograms per day; EXP, e = 2.71828; Q, streamflow in cubic feet per second; 0.5 SE^2, bias correction factor[1]; CONC, concentration in milligrams per liter]

Tributary	Equation		Coefficient of determination (R^2)	Standard error in log units (SE)	Number of observations
Dissolved solids					
Colorado River near San Saba	LOAD = EXP(7.35 + 0.909Q + 0.5 SE^2)	CONC = LOAD/2.446Q	0.93	0.390	81
Llano River at Llano	LOAD = EXP(6.23 + 1.01Q + 0.5 SE^2)	CONC = LOAD/2.446Q	.98	.129	46
Pedernales River near Johnson City	LOAD = EXP(7.07 + 0.904Q + 0.5 SE^2)	CONC = LOAD/2.446Q	.98	.207	54
Chloride					
Colorado River near San Saba	LOAD = EXP(5.82 + 0.922Q + 0.5 SE^2)	CONC = LOAD/2.446Q	.89	.514	81
Llano River at Llano	LOAD = EXP(4.59 + 0.894Q + 0.5 SE^2)	CONC = LOAD/2.446Q	.94	.223	46
Pedernales River near Johnson City	LOAD = EXP(5.84 + 0.756Q + 0.5 SE^2)	CONC = LOAD/2.446Q	.90	.359	54
Sulfate					
Colorado River near San Saba	LOAD = EXP(5.37 + 0.936Q + 0.5 SE^2)	CONC = LOAD/2.446Q	.86	.608	81
Llano River at Llano	LOAD = EXP(3.06 + 1.11Q + 0.5 SE^2)	CONC = LOAD/2.446Q	.96	.224	46
Pedernales River near Johnson City	LOAD = EXP(4.96 + 0.851Q + 0.5 SE^2)	CONC = LOAD/2.446Q	.93	.323	54

[1] Helsel and Hersch (1992).

factors (Helsel and Hirsch, 1992, p. 256). Bias correction factors were used in the equations because the estimated loads from log-transformed equations, when retransformed back to original units, are biased low and thus underestimate the actual loads. The data related to the saline inflow during 1987–89 were not used in the regression analysis for the Colorado River. The coefficients of determination ranged from 0.86 to 0.98, and the standard errors ranged from 0.129 to 0.608 log units for the three major tributaries (table 6). The daily mean streamflow in relation to the load for each of the three constituents in the Colorado, Llano, and Pedernales Rivers are shown in figures 11–13. The estimated monthly mean concentration is computed using the equations in table 6 and the monthly mean streamflow.

The monthly mean streamflow and estimated monthly mean concentrations of dissolved solids, chloride, and sulfate at the Llano River at Llano and the Pedernales River near Johnson City streamflow-gaging stations are shown in figures 14–15. The measured streamflows for those two streams and for the Colorado River near San Saba were adjusted for simulation by the corresponding ratio of stream to station drainage area (table 4) to account for the intervening drainages between the streamflow-gaging stations and the reservoirs.

Model Testing

Measured inflow quantity and estimated quality data for the Colorado River, Llano River, and Pedernales River for 1983–92; measured evaporation data; actual reservoir demands and releases; and initial reservoir capacities and concentrations were used as input to RESOP II to determine if the simulated results are comparable to measured values. The measured and simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate for the Highland Lakes are shown in figures 16–22.

The simulated reservoir storages are similar to the measured reservoir storages. The simulated dissolved solids, chloride, and sulfate concentrations generally are larger than the measured concentrations, especially in the downstream reservoirs. The pattern of the simulated concentrations tracks the pattern of the measured concentrations fairly well. The absolute error and the error between the measured and simulated reservoir storage, dissolved solids concentrations, chloride concentrations, and sulfate concentrations are listed in table 7 (at end of report). The mean absolute errors of monthly reservoir storage in the Highland Lakes range from 0.9 to 4.7 percent with a minimum error of 0 to a maximum error of 55.0 percent. The mean errors of monthly reservoir storage range from –2.8 to 2.2 percent with a minimum error of –32.2 percent to a maximum error of 55.0 percent.

The mean absolute errors of monthly concentrations of dissolved solids in the Highland Lakes range from 14.1 to 35.7 percent, and the mean errors range from 11.3 to 35.7 percent. The mean absolute errors of monthly concentrations of chloride range from 16.0 to 63.5 percent, and the mean errors range from 13.1 to 63.5 percent. The mean absolute errors of monthly concentrations of sulfate range from 20.3 to 51.5 percent, and the mean errors range from 18.0 to 51.5 percent.

The absolute errors and errors of monthly concentrations of dissolved solids, chloride, and sulfate generally increase in downstream order, which probably is the result of intervening, unaccounted inflow from other tributaries. The errors accumulate as the water moves downstream. The difference between the total measured and simulated streamflow at Colorado River at Austin is –33.7 percent (fig. 23). The negative difference between the measured and simulated streamflow indicates that an insufficient amount of water (only about two-thirds of the actual amount) is added to the system from the three major tributaries to balance the water quantity. As a result, the error between measured and simulated water quality increases as the water moves through the Highland Lakes because of the lack of water (in the simulated system) to dilute the concentrations of dissolved solids, chloride, and sulfate.

The model errors could be reduced if the quantity and quality of water from minor tributaries and other intervening inflow to the Highland Lakes were accounted for in the simulations. An adequate amount of water quantity and quality data are not available for the minor tributaries to represent the three hydrologic conditions. However, the results of the model testing are judged acceptable to determine the relative differences in the quantity and quality of the Highland Lakes from simulations of wet, average, and dry conditions after the saline inflow.

Model Simulation

From an analysis of the annual streamflow measured at the Colorado River near San Saba, Llano

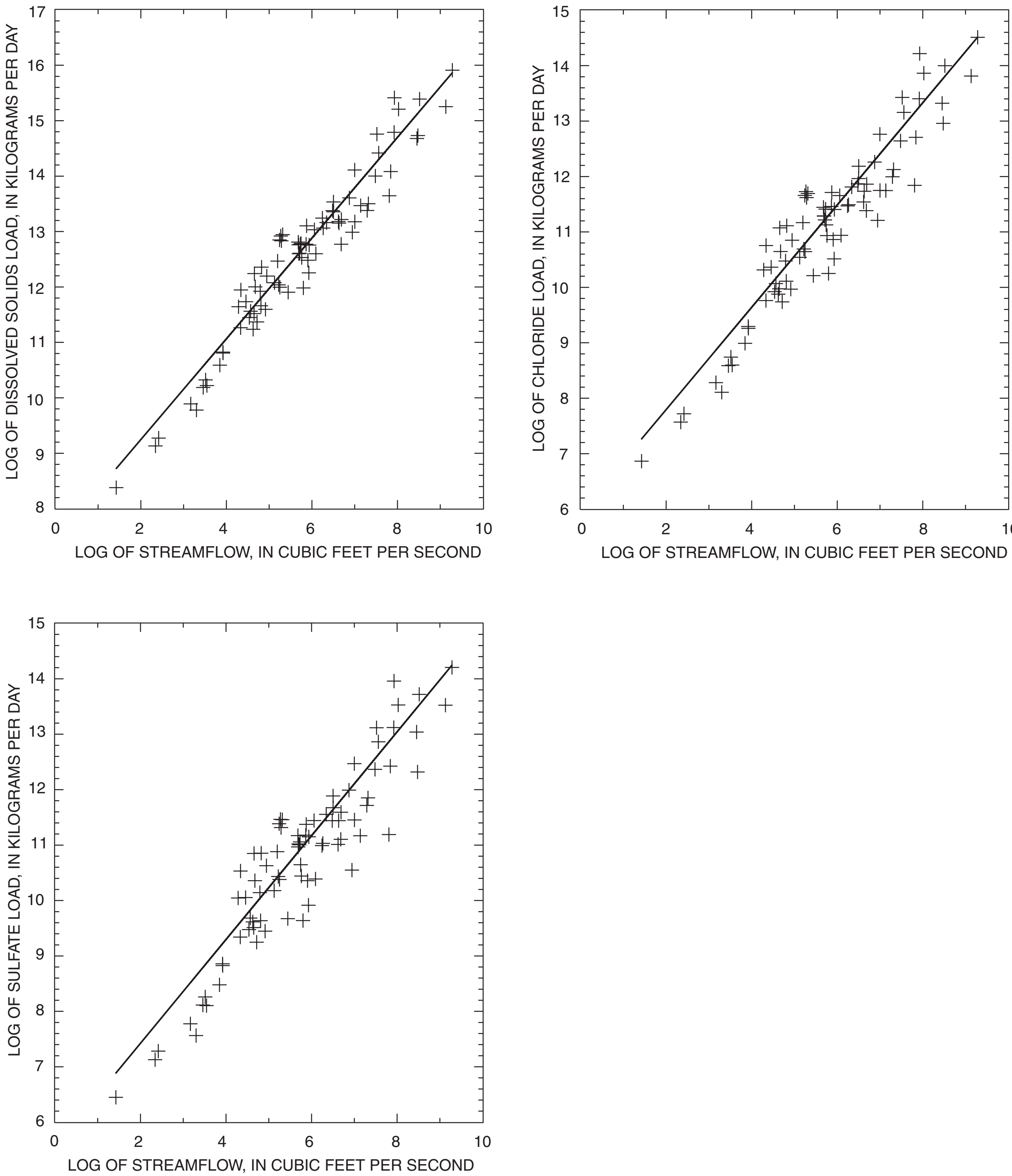


Figure 11. Daily mean streamflow in relation to dissolved solids, chloride, and sulfate loads at Colorado River near San Saba, Texas.

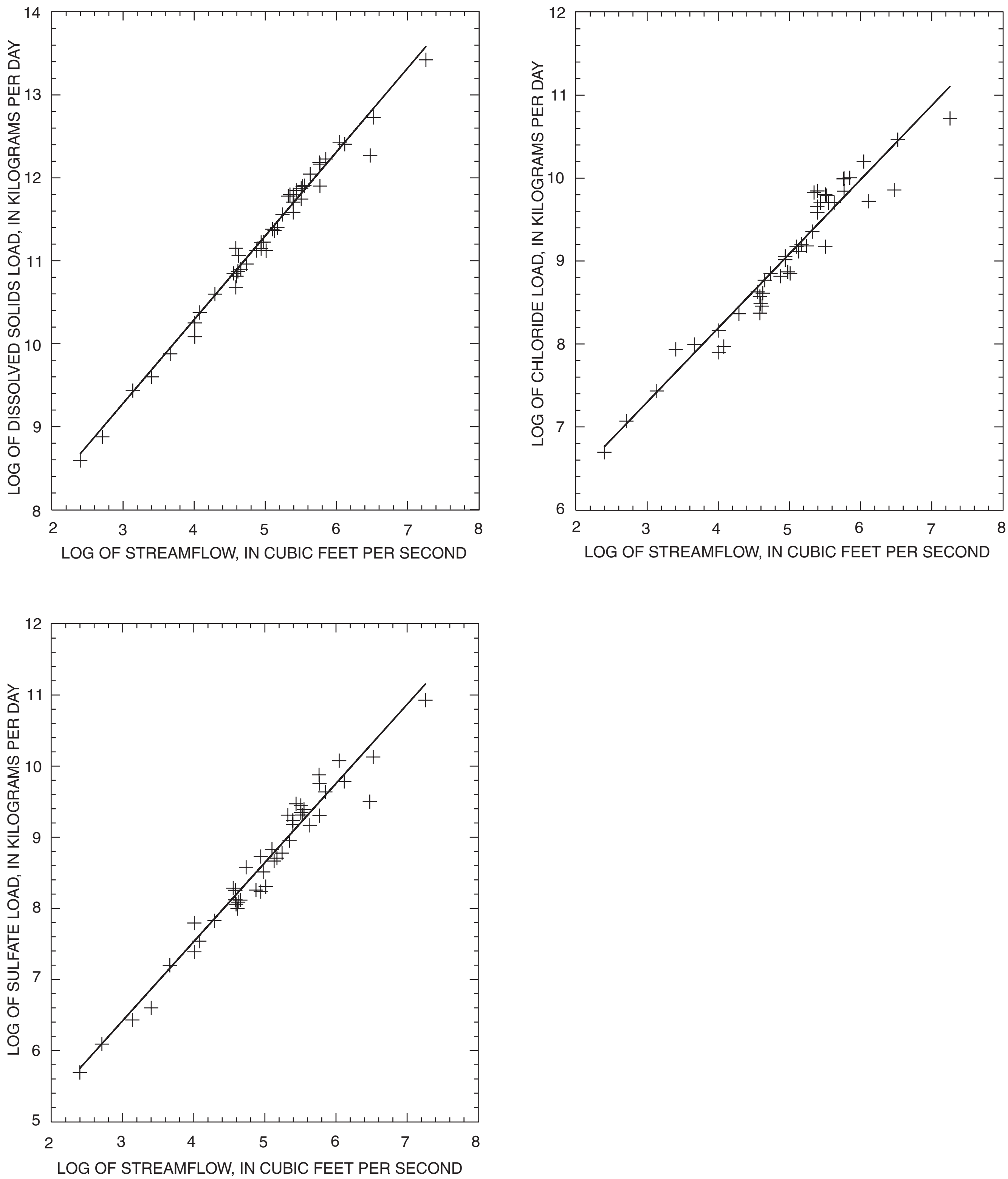


Figure 12. Daily mean streamflow in relation to dissolved solids, chloride, and sulfate loads at Llano River at Llano, Texas.

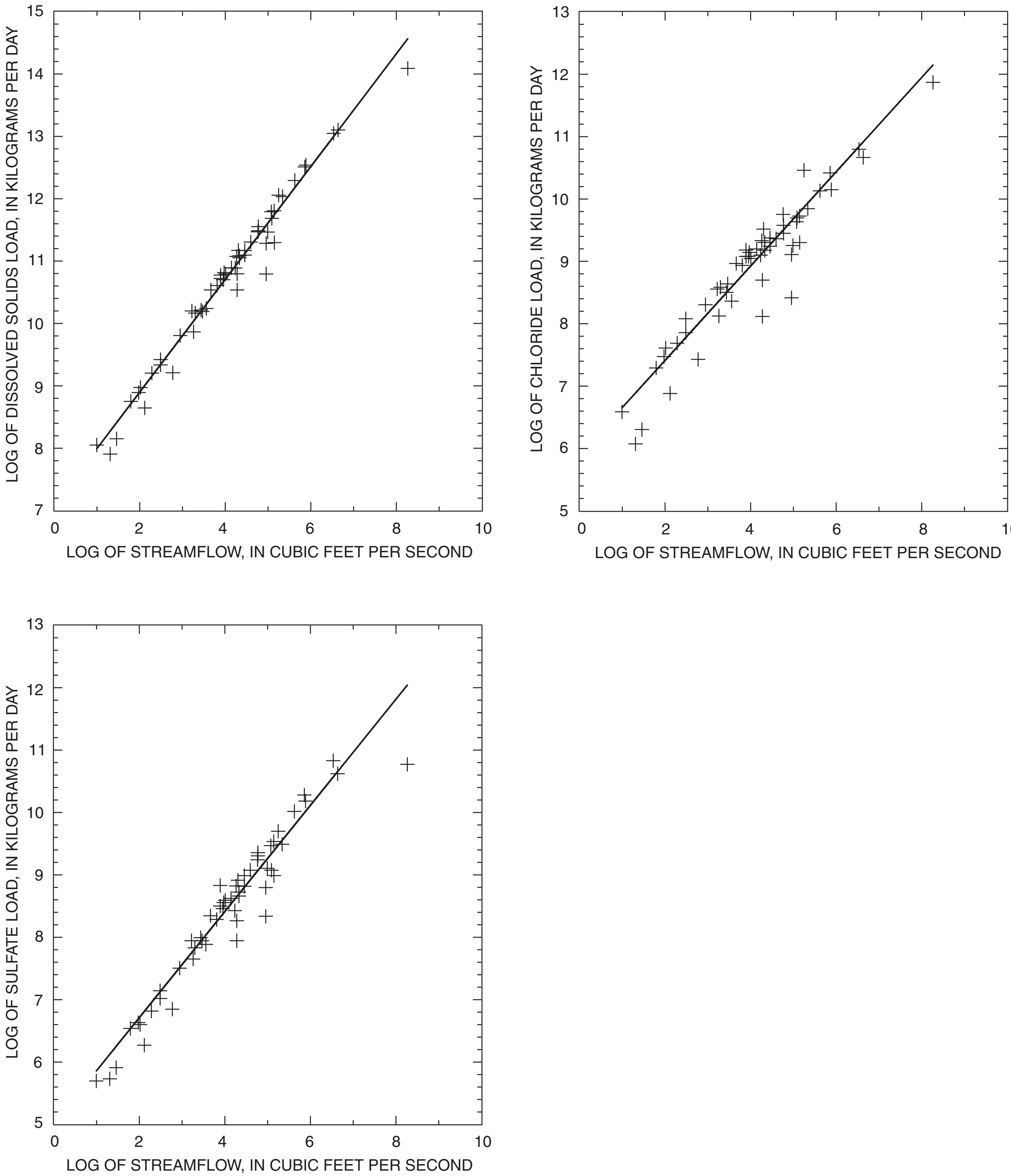
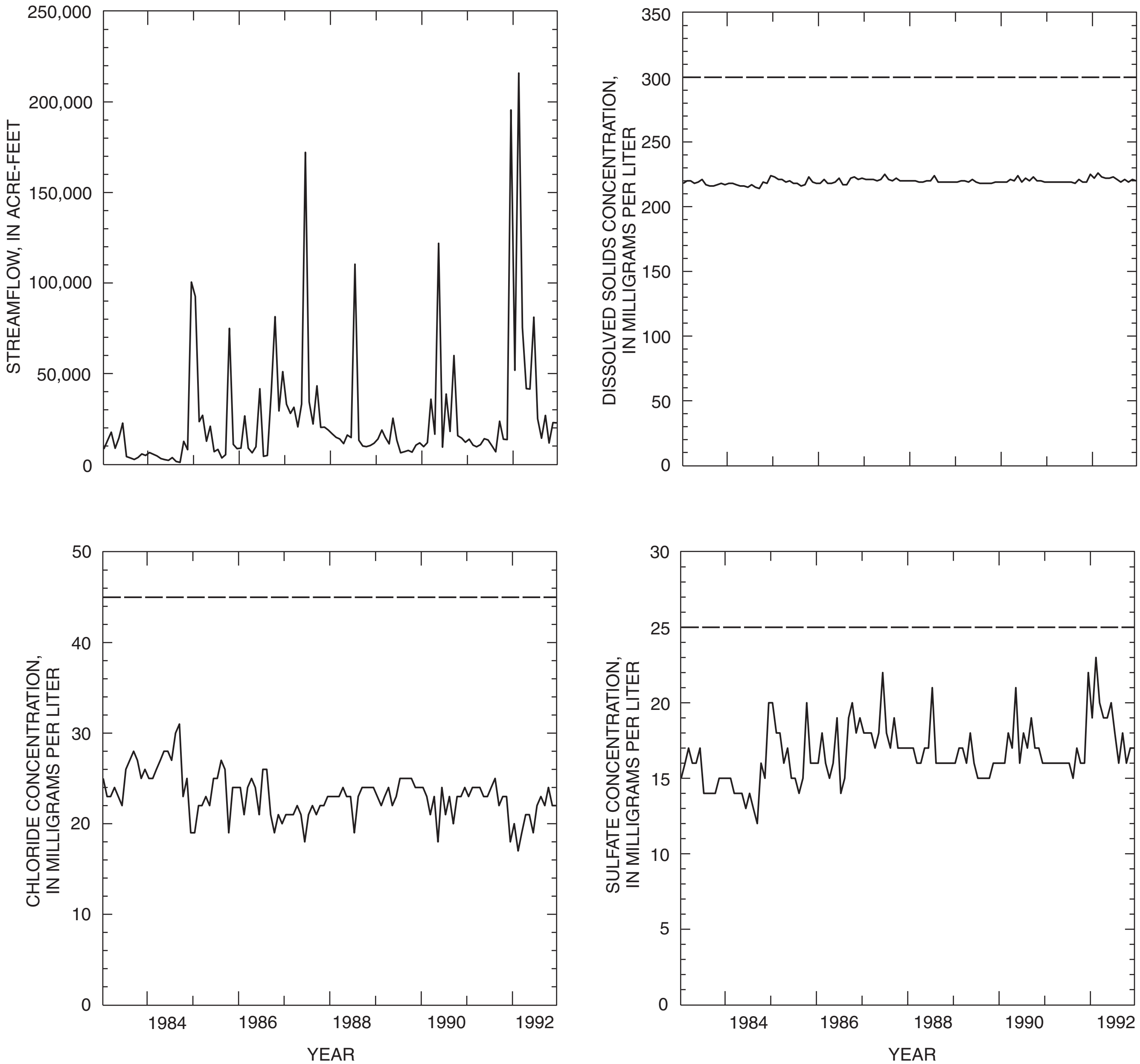


Figure 13. Daily mean streamflow in relation to dissolved solids, chloride, and sulfate loads at Pedernales River near Johnson City, Texas.



EXPLANATION

— — **Water-quality standard**—Texas Natural Resource Conservation Commission (1997)

Figure 14. Measured monthly streamflow and estimated monthly concentrations of dissolved solids, chloride, and sulfate at Llano River at Llano, Texas, 1983–92.

River at Llano, and Pedernales River near Johnston City during 1944–95, the wet, average, and dry 7-year periods were selected from a 7-year moving average of the cumulative annual streamflow volumes. The 7-year period with the maximum average annual storage, about 1,570,000 acre-ft during 1955–61, represents the wet hydrologic condition, the 7-year period with the storage most comparable to the mean of the average annual

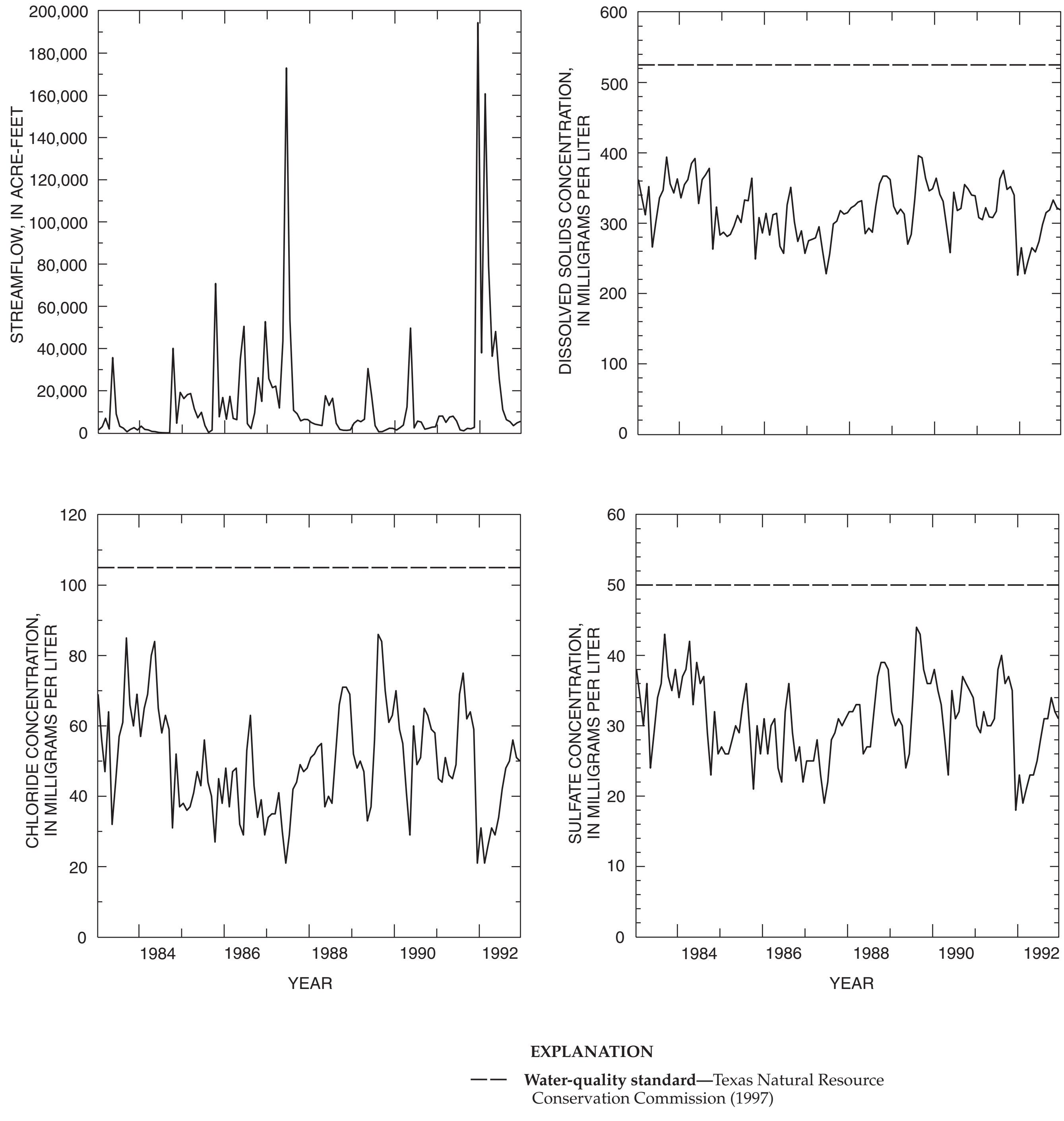


Figure 15. Measured monthly streamflow and estimated monthly concentrations of dissolved solids, chloride, and sulfate at Pedernales River near Johnson City, Texas, 1983–92.

storages, about 1,010,000 acre-ft during 1972–78, represents the average hydrologic condition, and the 7-year period with the minimum average annual storage, about 682,000 acre-ft during 1978–84, represents the dry hydrologic condition.

The time series of streamflow for model input for 1987–96 for the Colorado, Llano, and Pedernales Rivers for each of the three hydrologic conditions consisted of the measured streamflow for the period 1987–89, adjusted by the corresponding ratio listed in table 4

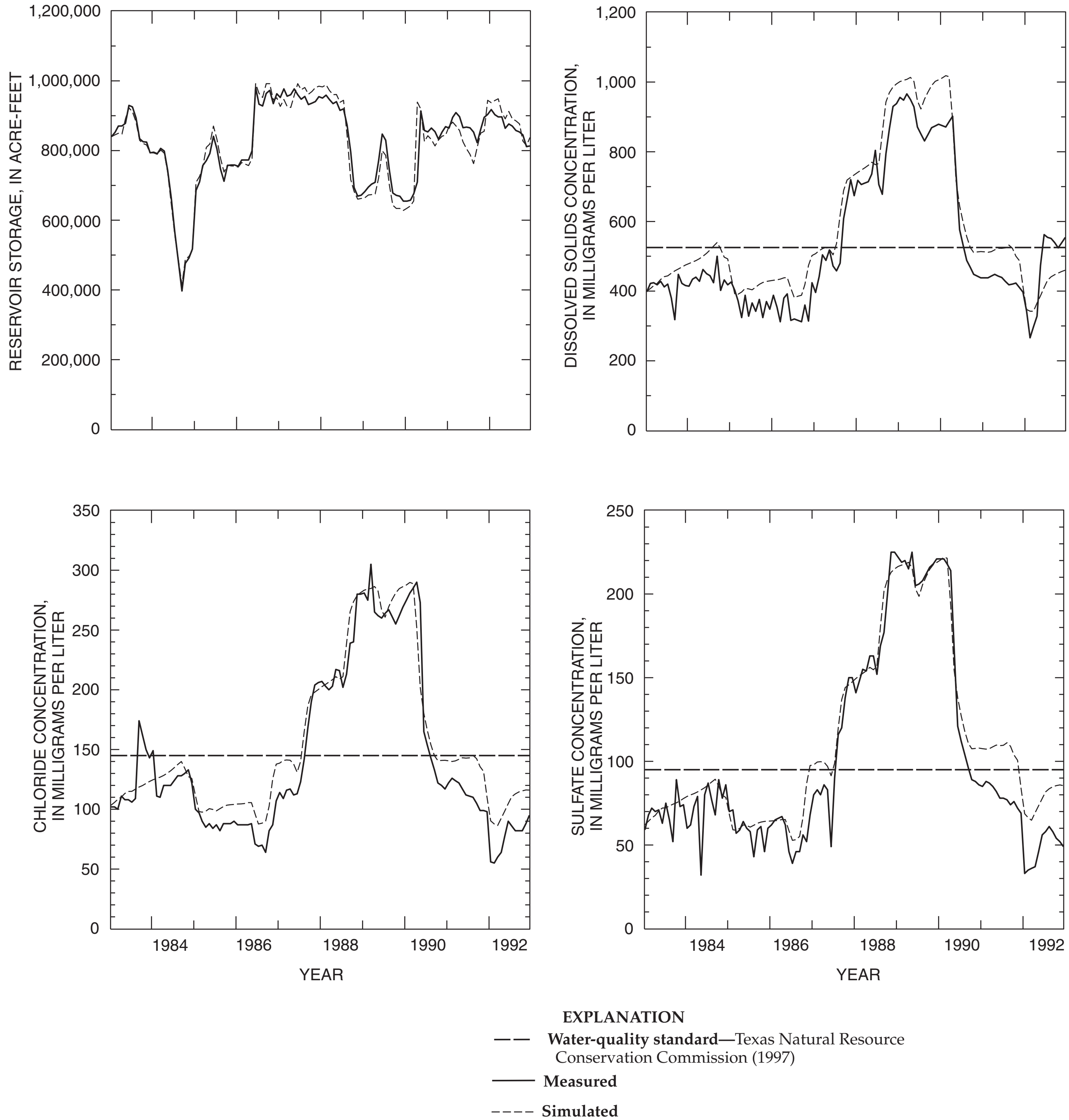


Figure 16. Measured and simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Lake Buchanan, Texas, 1983–92.

to account for additional intervening inflow between the streamflow-gaging station and the reservoir, followed by the representative 7-year wet-period streamflow, average-period streamflow, or dry-period streamflow.

The simulated monthly streamflow and concentrations of dissolved solids, chloride, and sulfate for major inflows to the Highland Lakes are shown in figures 24–26. The concentrations of dissolved solids, chloride, and

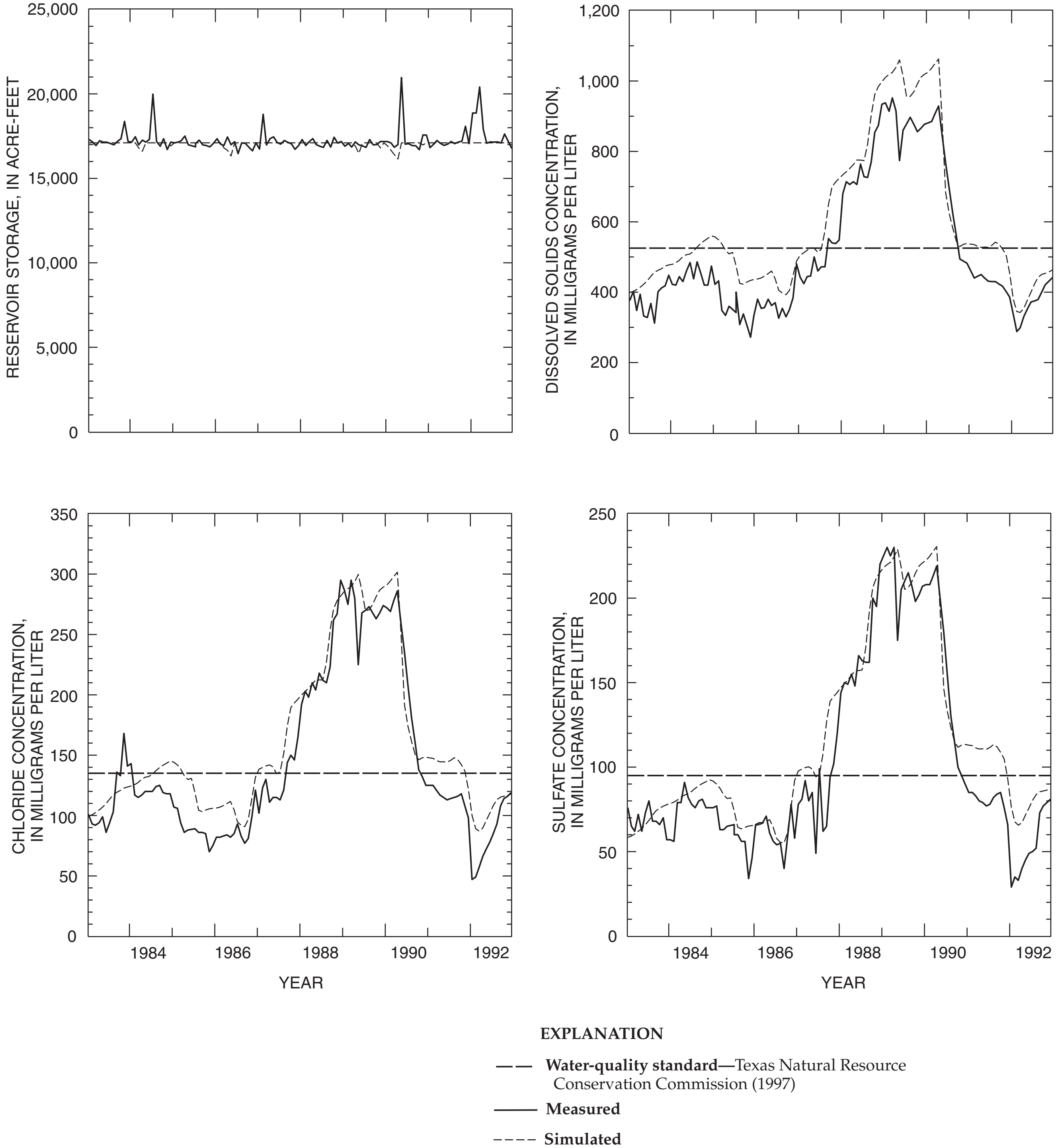


Figure 17. Measured and simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Inks Lake, Texas, 1983–92.

sulfate were estimated from the regression equations (table 6).

Because actual releases and demands were not available for the simulated hydrologic conditions, the annual demand and monthly distribution factors (percentages of annual demand) for Lake Travis were needed for input to the simulation model (table 8 at end of report). The Highland Lakes are operated as a system

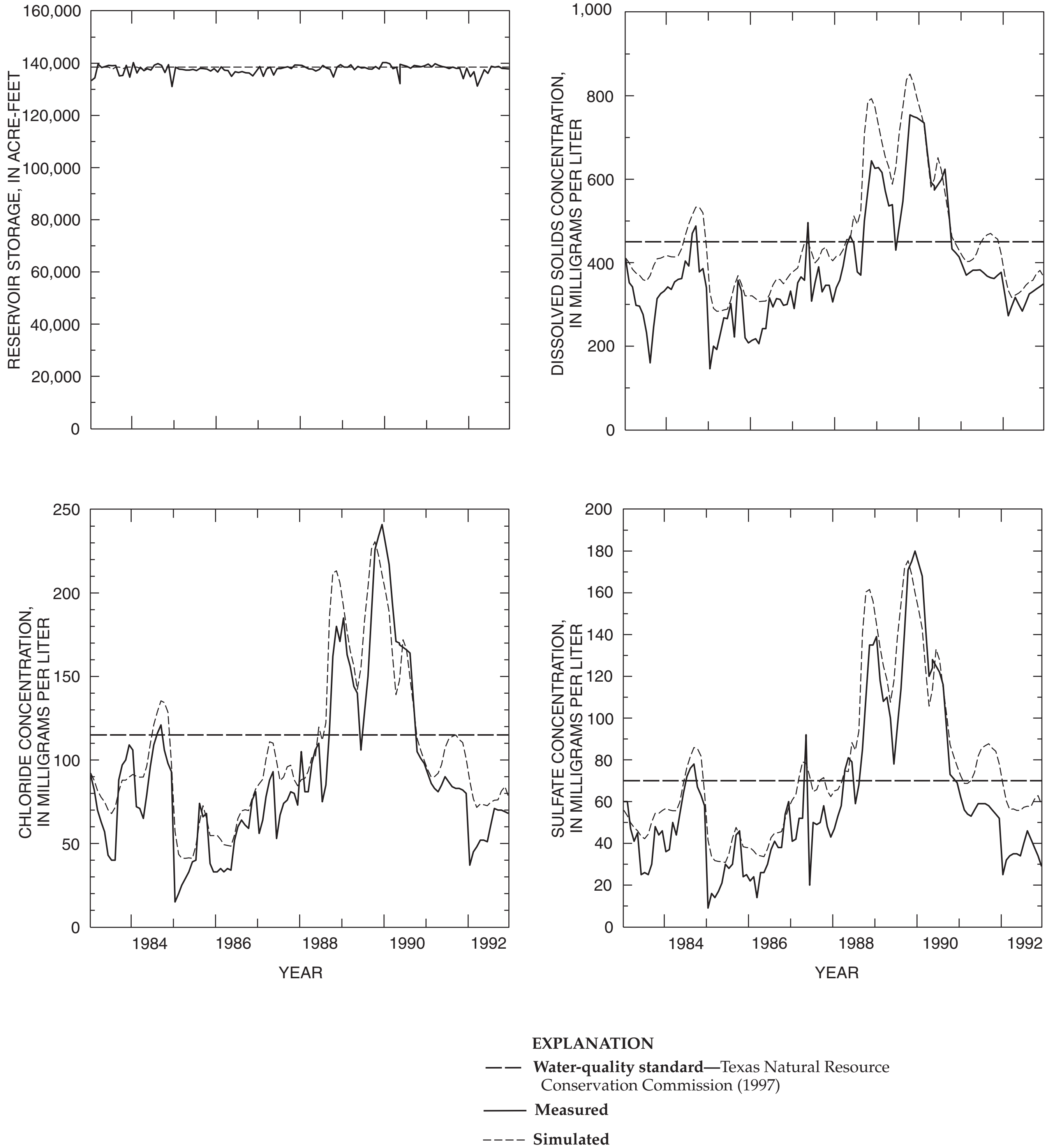


Figure 18. Measured and simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Lake Lyndon B. Johnson, Texas, 1983–92.

with demand being met by Lake Buchanan and Lake Travis (Lower Colorado River Authority, 1993). Until the storage of Lake Travis falls below 850,000 acre-ft, the demand is met by Lake Travis. When the storage of Lake Travis is between 850,000 and 700,000 acre-ft, 35 percent of the demand is met by Lake Buchanan and

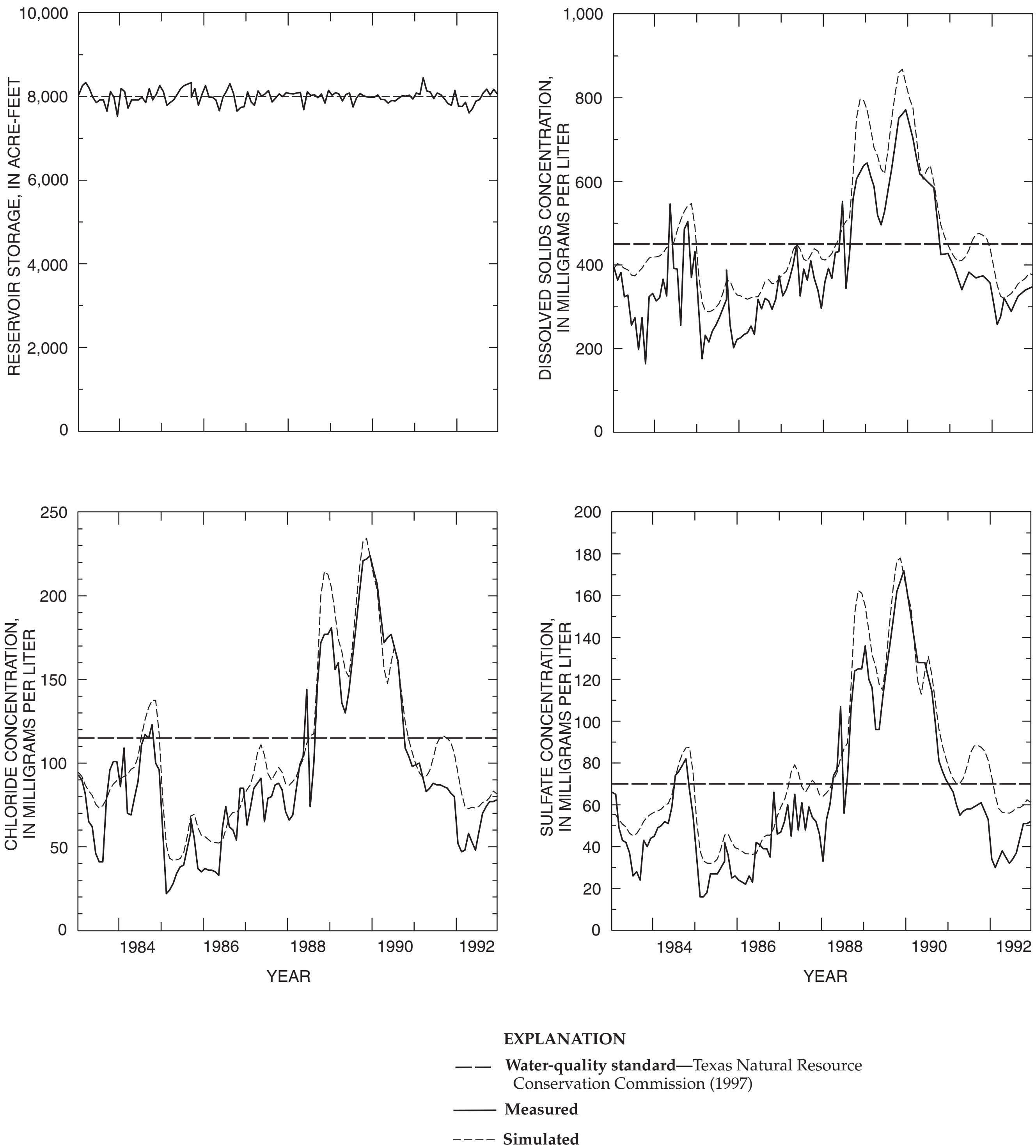


Figure 19. Measured and simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Lake Marble Falls, Texas, 1983–92.

65 percent by Lake Travis. When the storage of Lake Travis is below 700,000 acre-ft, 90 percent of the demand is met by Lake Buchanan until the storage of Lake Buchanan is below 150,000 acre-ft. When the storage of Lake Buchanan is between 50,000 and 150,000 acre-ft, 35 percent of the demand is met by

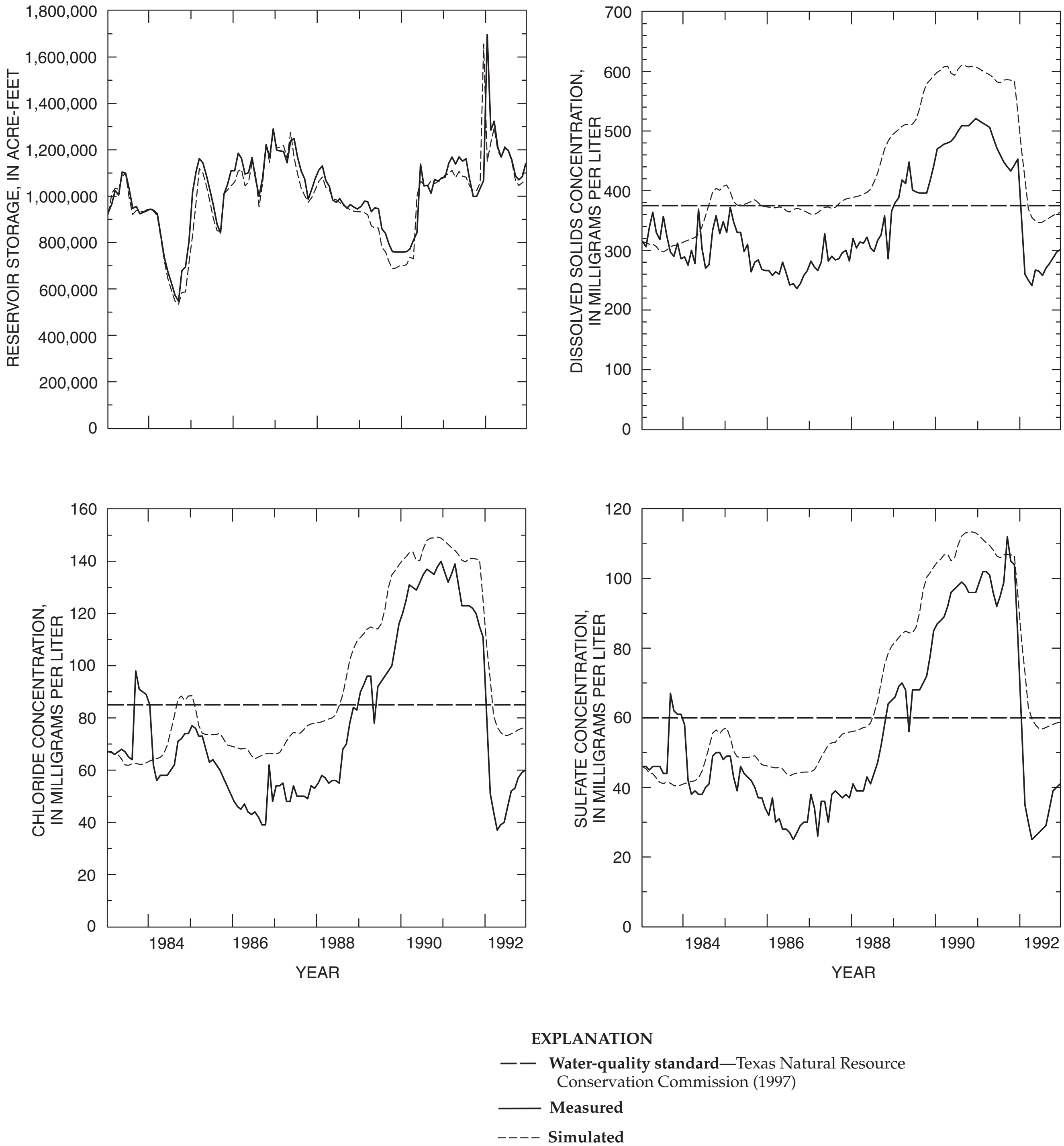


Figure 20. Measured and simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Lake Travis, Texas, 1983–92.

Lake Buchanan. Finally, when the storage of Lake Buchanan is below 50,000 acre-ft, all downstream demands are met by Lake Travis.

Simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry conditions in the Highland Lakes

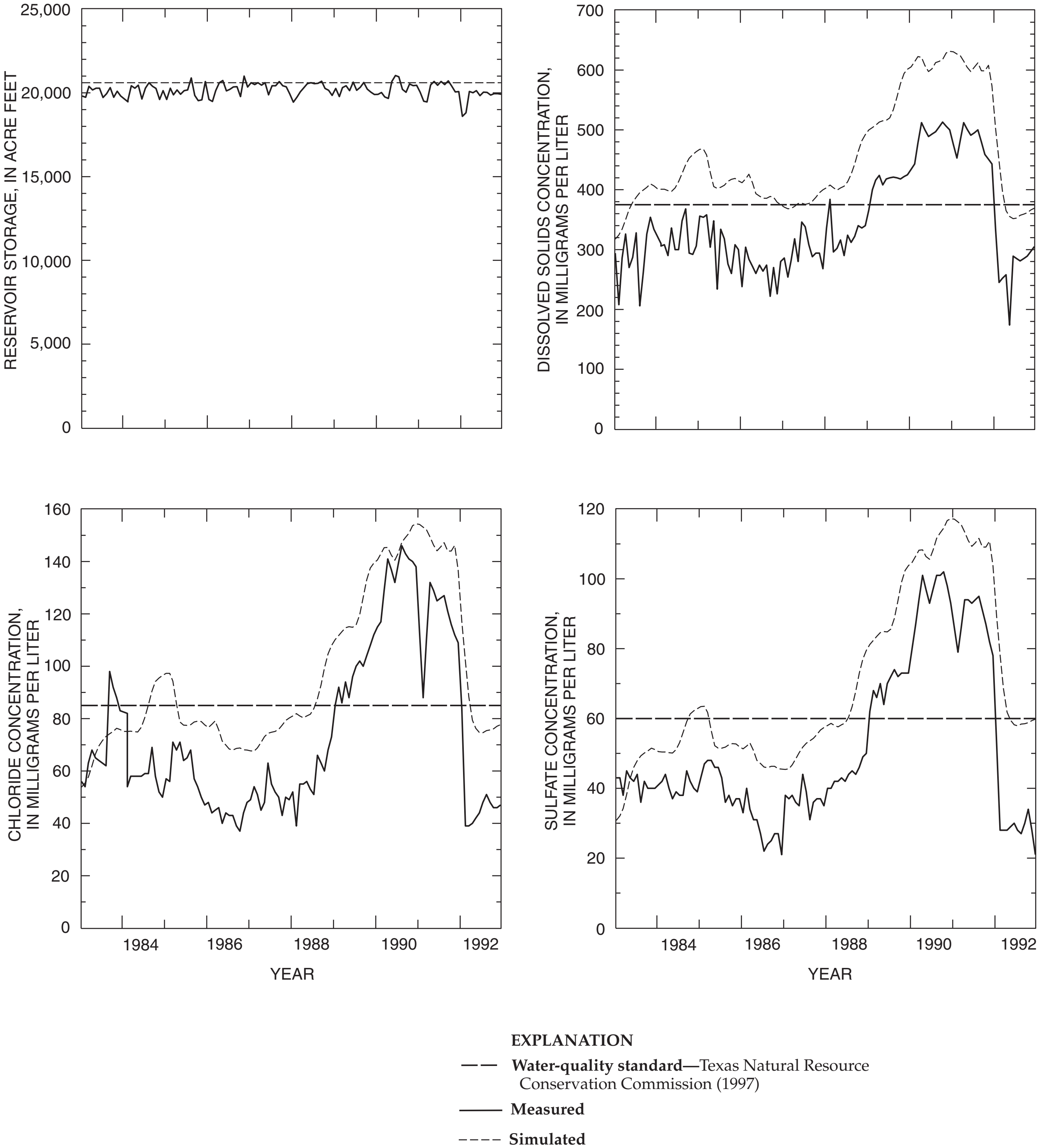


Figure 21. Measured and simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Lake Austin, Texas, 1983–92.

are shown in figures 27–33. For Lake Buchanan, the simulated reservoir storage for the wet condition was at or near the reservoir storage at the top of operating range during much of the simulation period (fig. 27). Simulated storage in Lake Buchanan for the average and dry conditions was less than storage at the top of

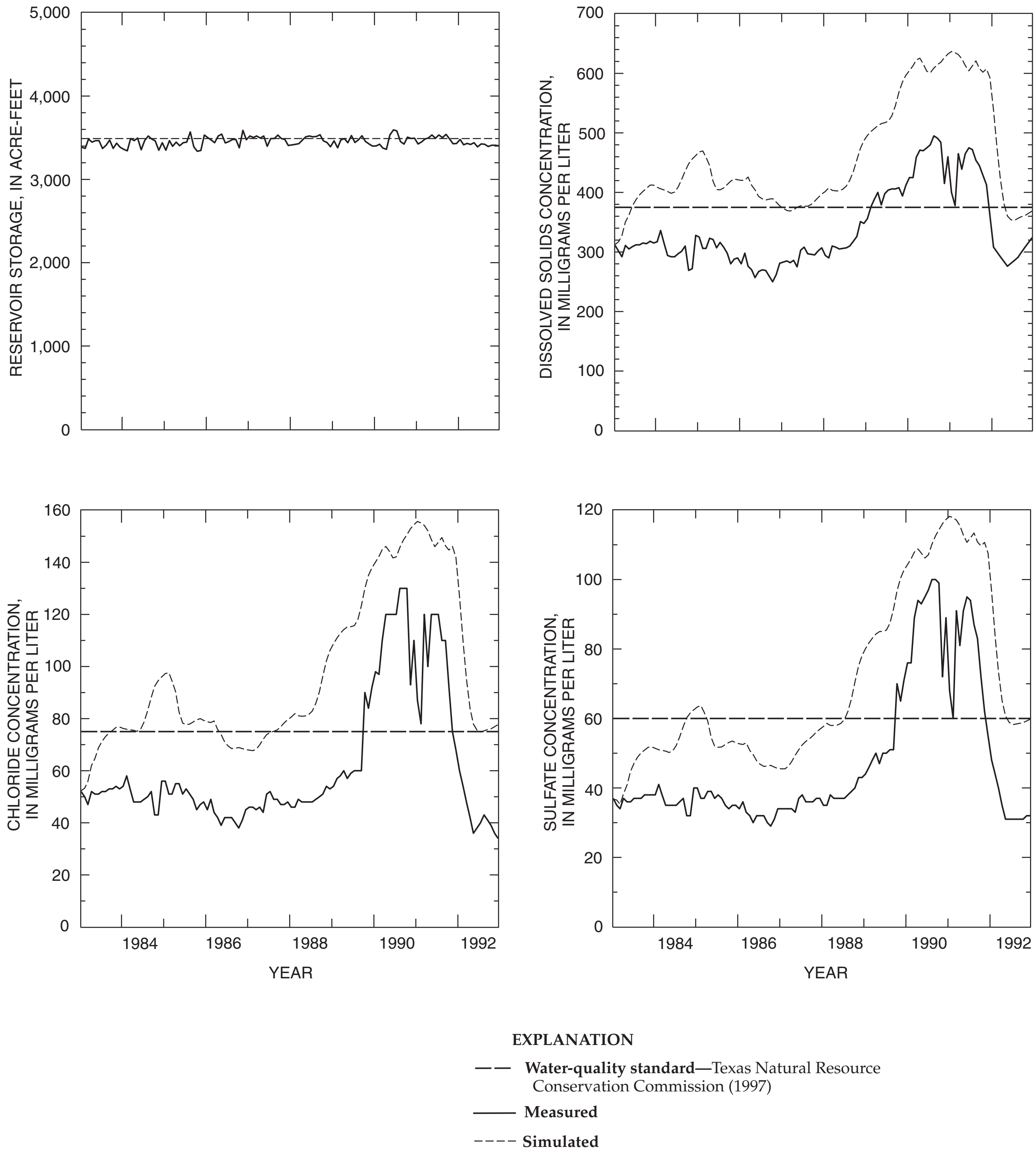


Figure 22. Measured and simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate at Town Lake, Texas, 1983–92.

operating range. For Lake Travis, the simulated reservoir storage for the wet condition was greater than the reservoir storage at the top of operating range, but less than the reservoir storage at spillway altitude, for part of the simulation period (fig. 31). Simulated storage in Lake Travis for the average and dry conditions did not reach storage at the top of operating range. Simulated storages for all three conditions at the five other

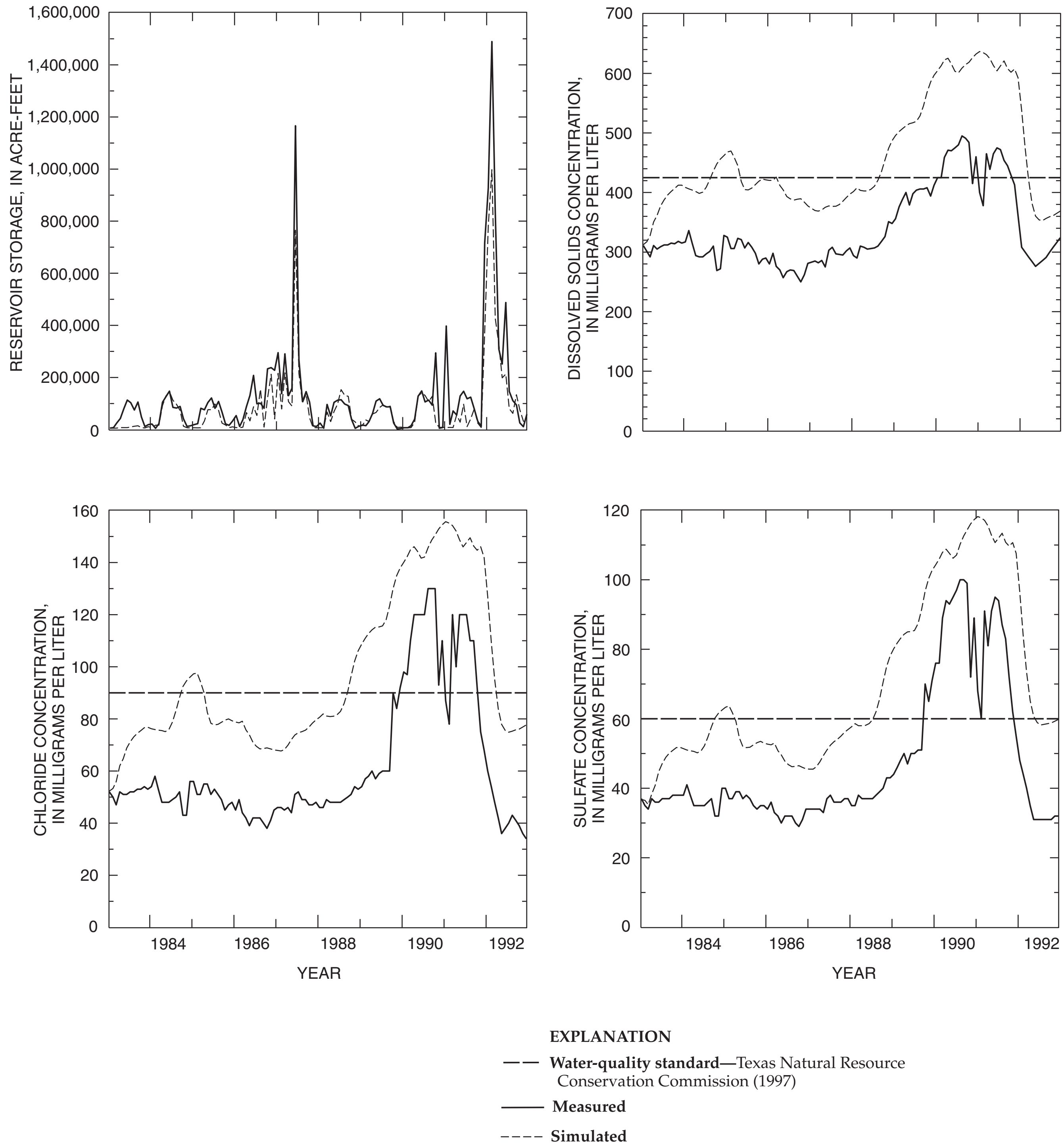


Figure 23. Measured and simulated monthly streamflow and concentrations of dissolved solids, chloride, and sulfate at Colorado River at Austin, Texas, 1983–92.

reservoirs were equal to their respective reservoir storages at the top of operating range (figs. 28–30, 32–33).

The simulated concentrations of dissolved solids, chloride, and sulfate in Lake Buchanan (fig. 27) and Inks Lake (fig. 28) decreased to pre-saline-inflow levels

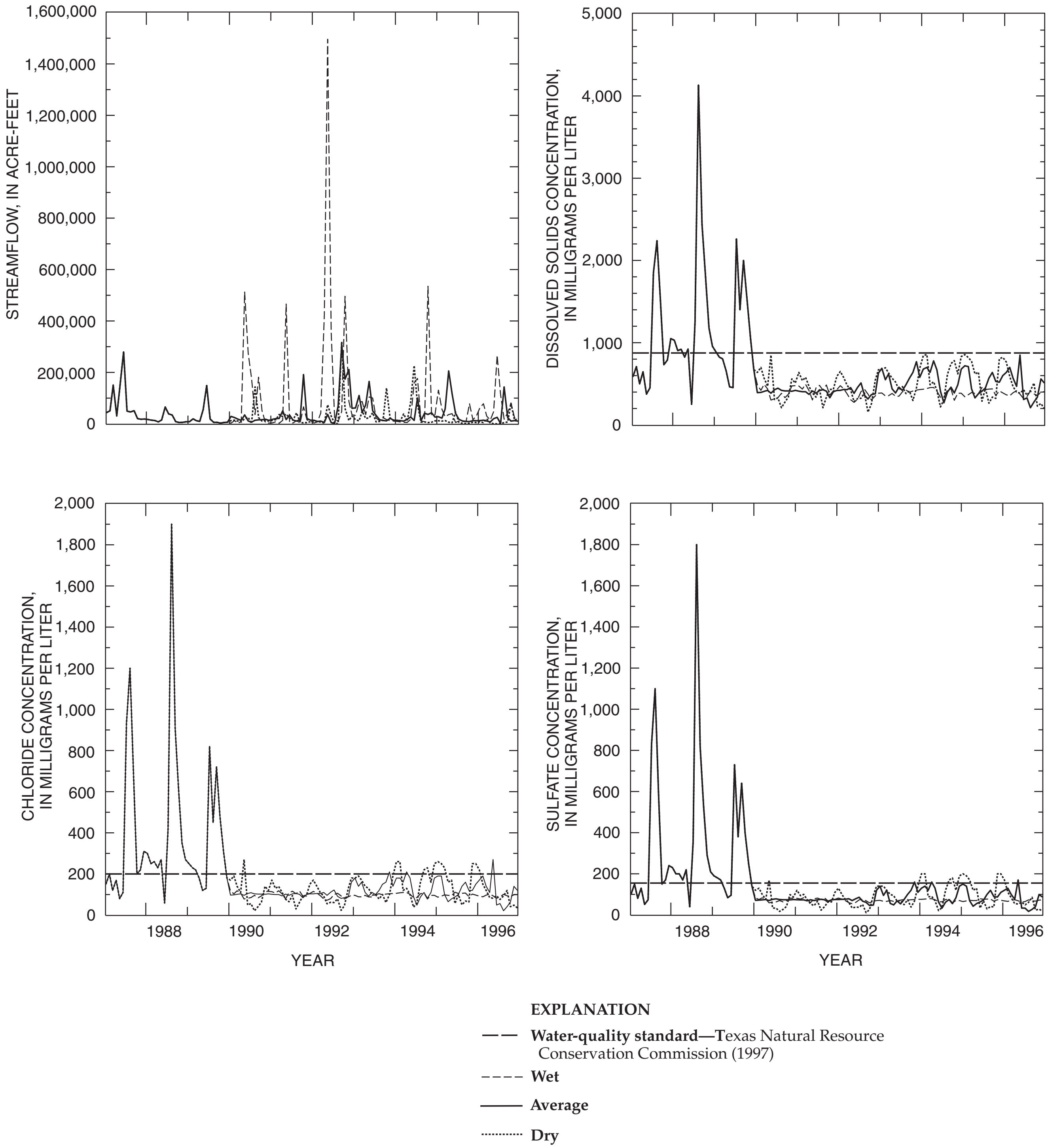


Figure 24. Simulated monthly streamflow and concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry hydrologic conditions at Colorado River above Lake Buchanan, Texas, 1987–96.

less than or near the concentrations of the applicable water-quality standards during 1990–91 for the wet condition and in 1992 for the average and dry conditions. As the reservoir storage in Lake Buchanan neared zero for the dry condition simulation, the simulated concentrations increased. The simulated concentrations of dissolved solids, chloride, and sulfate in Lake LBJ (fig. 29) and Lake Marble Falls (fig. 30) decreased to

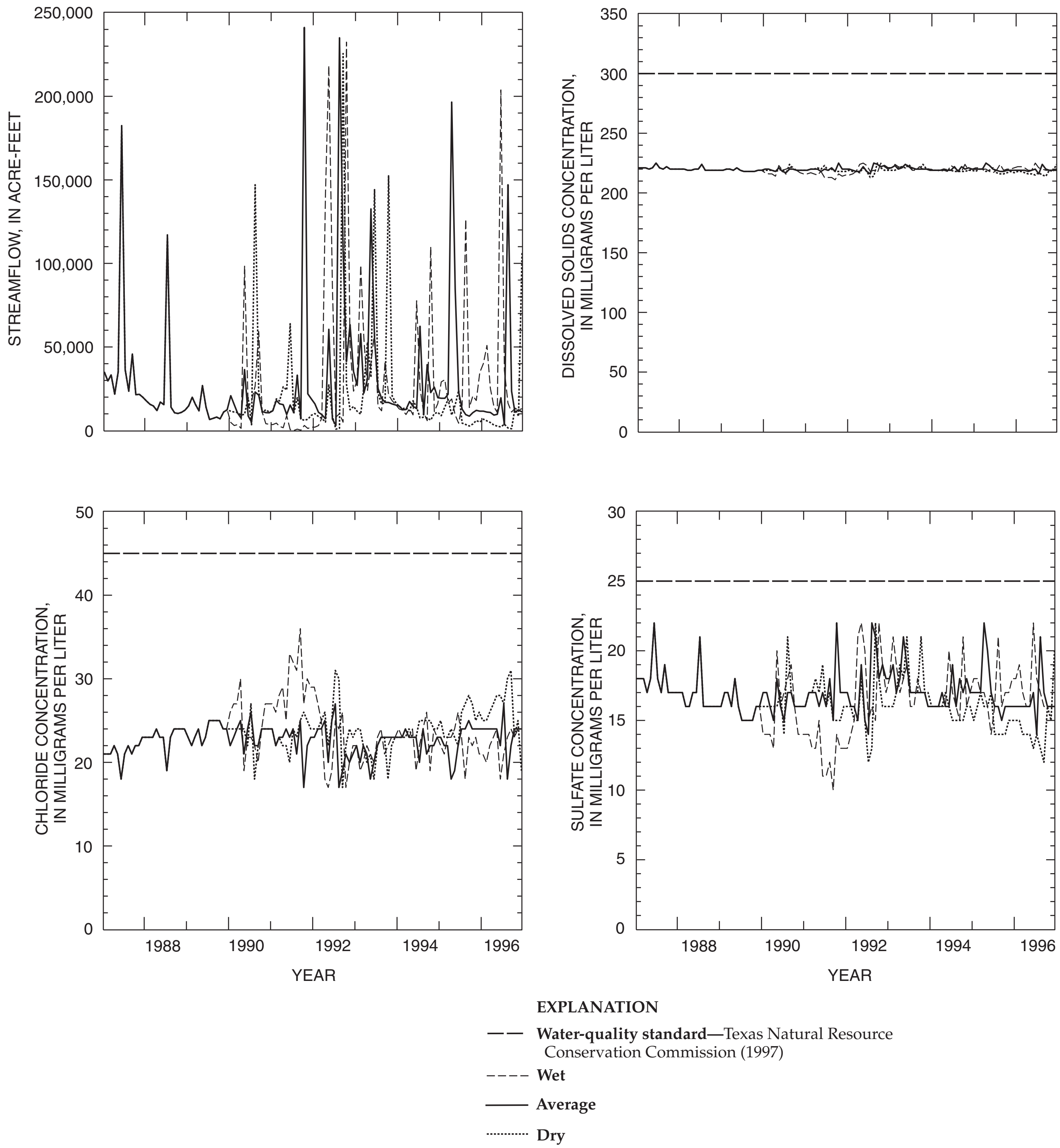


Figure 25. Simulated monthly streamflow and concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry hydrologic conditions at Llano River above Lake Lyndon B. Johnson, Texas, 1987–96.

levels less than or near the concentrations of the applicable water-quality standards in 1993 for the three conditions. The simulated concentrations of dissolved solids, chloride, and sulfate in Lake Travis (fig. 31), Lake Austin (fig. 32), and Town Lake (fig. 33) peaked during 1990–92. The simulated concentrations for the wet condition peaked first, followed by the average and then dry conditions. The simulated concentrations for

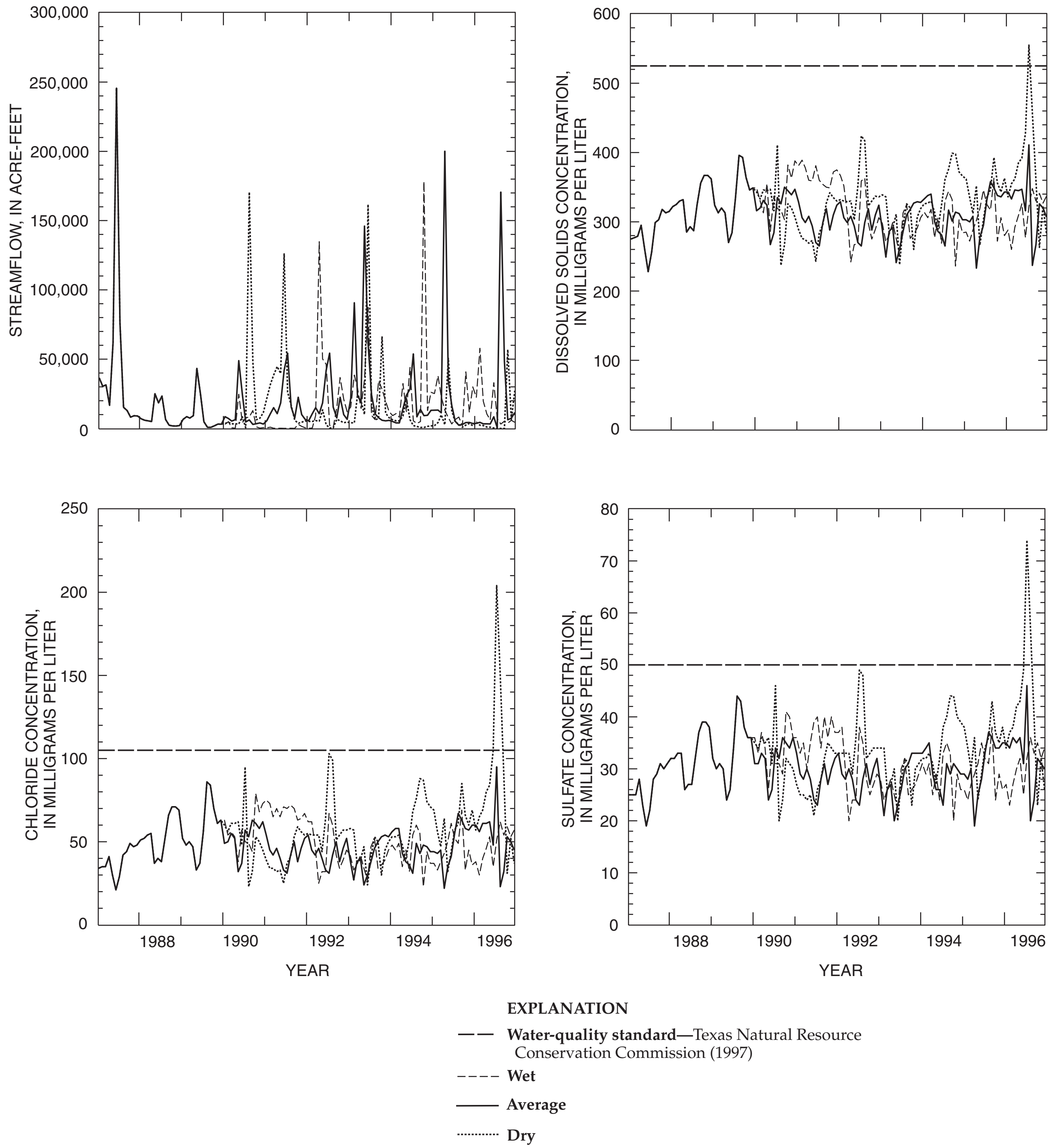


Figure 26. Simulated monthly streamflow and concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry hydrologic conditions at Pedernales River above Lake Travis, Texas, 1987–96.

the three conditions decreased to less than or near the pre-saline-inflow levels during 1993–94.

Selected results of simulated storages and concentrations of dissolved solids, sulfate, and chloride for wet, average, and dry conditions in the Highland Lakes are presented in table 9 (at end of report). The reservoir storage in Lake Buchanan ranged from 442,000 to 992,000 acre-ft for the wet simulation, from 39,900 to

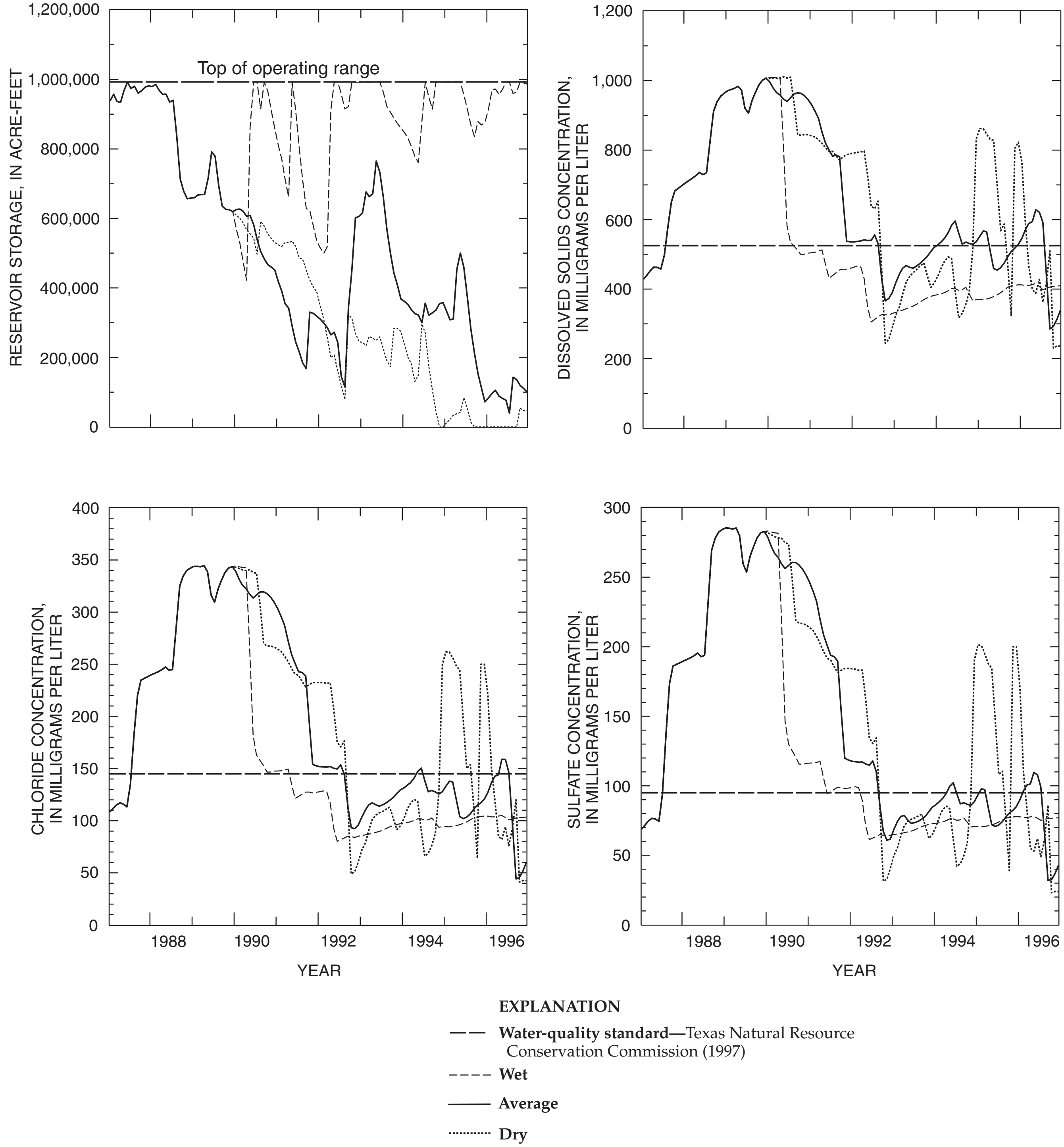


Figure 27. Simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry hydrologic conditions at Lake Buchanan, Texas, 1987–96.

992,000 acre-ft for the average simulation, and from 0 to 992,000 acre-ft for the dry simulation. The reservoir storage in Lake Travis ranged from 644,000 to 1,350,000 acre-ft for the wet simulation, from 30,800 to 1,270,000 acre-ft for the average simulation, and from 0 to 1,270,000 acre-ft for the dry simulation. The simulated reservoir storage in Lake Buchanan and Lake Travis during the dry condition decreased to zero

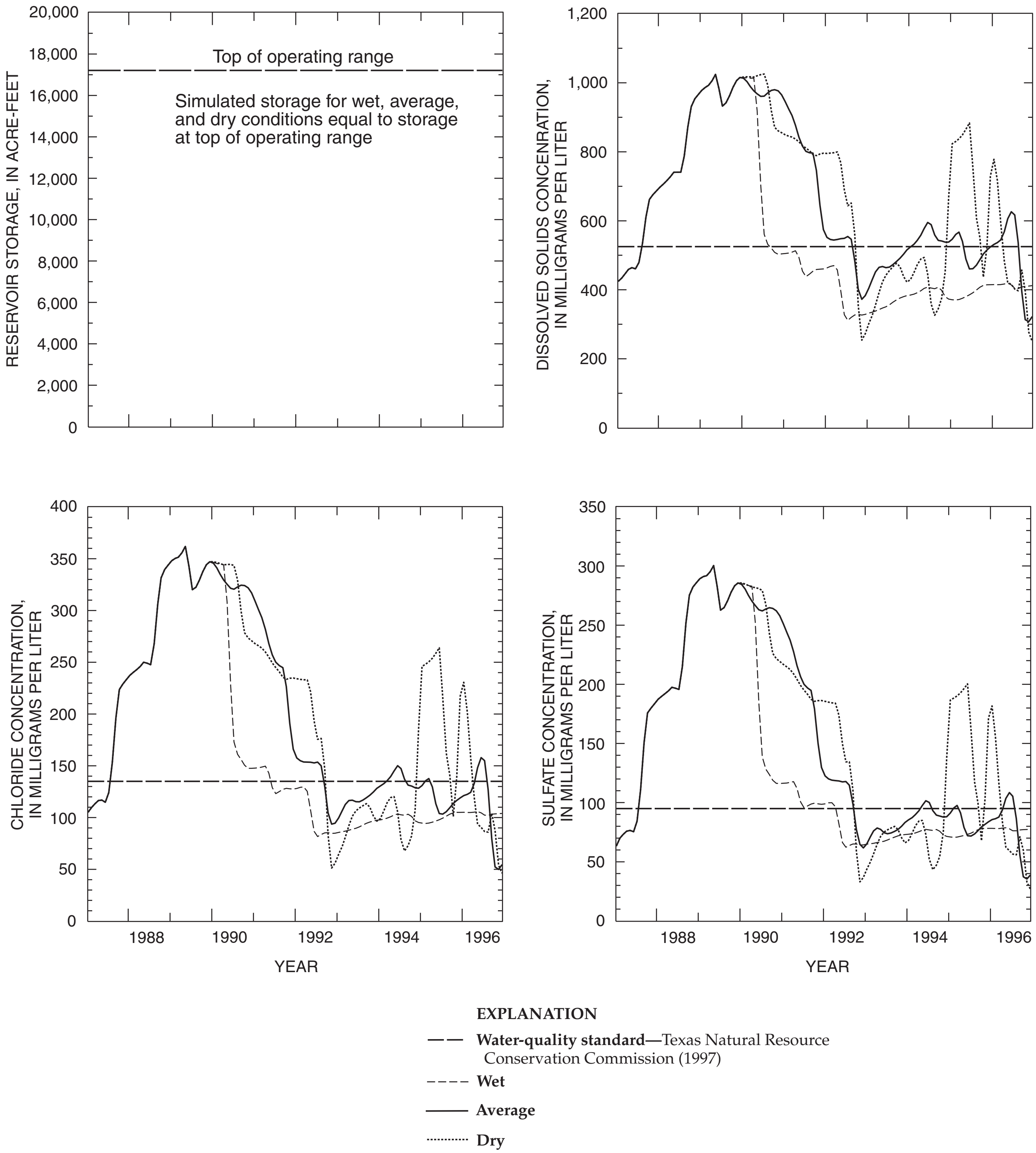


Figure 28. Simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry hydrologic conditions at Inks Lake, Texas, 1987–96.

during the 10-year simulation because the annual demand exceeded the annual inflow from the three major tributaries and the storage in Lake Buchanan and Lake Travis. Because the measured inflow to the Highland Lakes from the three major tributaries accounted only for about 72 percent of the measured streamflow released during 1983–92, the simulated inflow from the three major tributaries probably

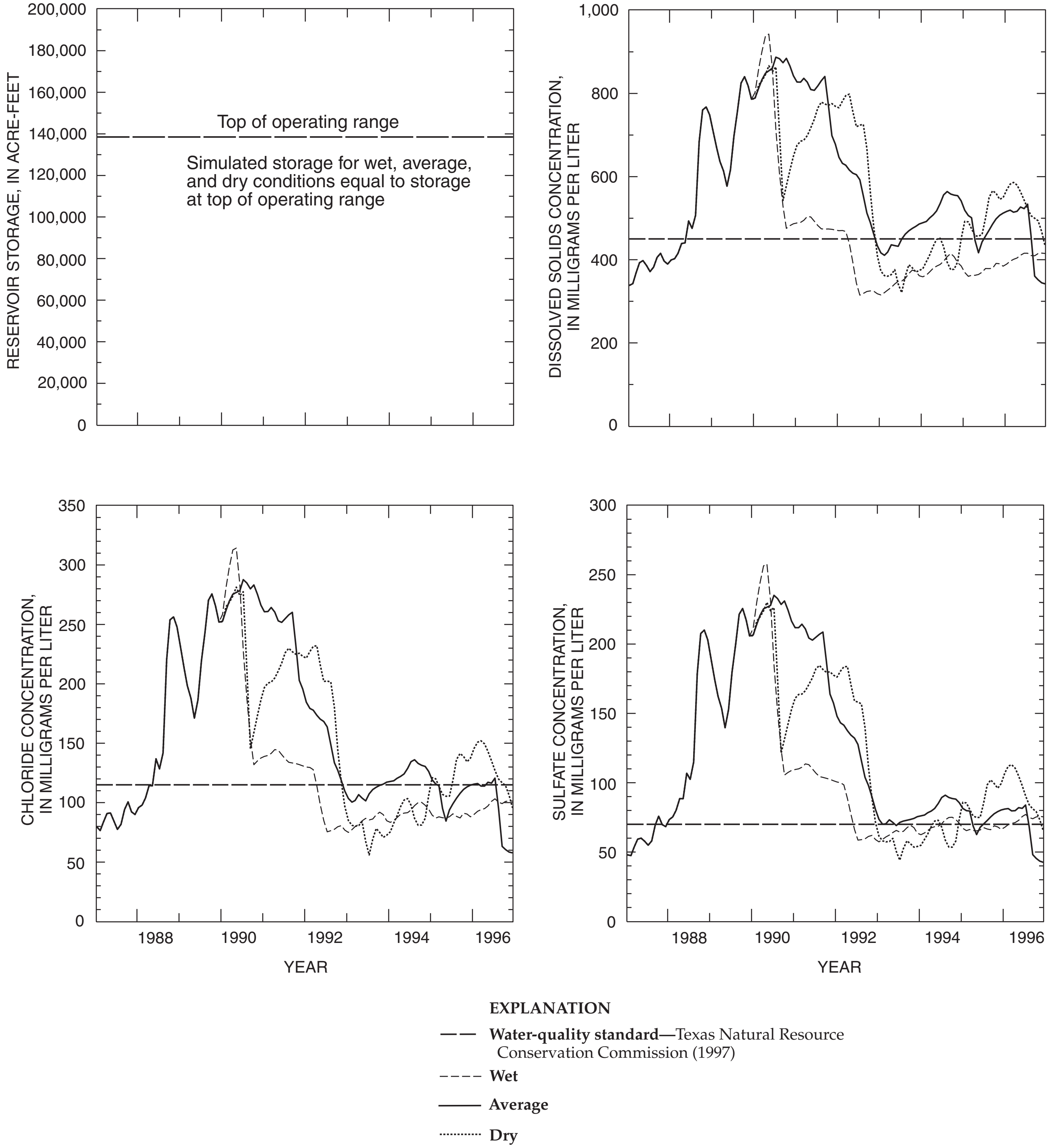


Figure 29. Simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry hydrologic conditions at Lake Lyndon B. Johnson, Texas, 1987–96.

accounts for a similar fraction of total inflow to the Highland Lakes. Therefore, it is unlikely that Lake Buchanan and Lake Travis would be depleted during the 7-year period.

The median monthly concentrations of dissolved solids, chloride, and sulfate during the 10-year simulation period for each reservoir generally are larger for the average condition than for the wet condition and are

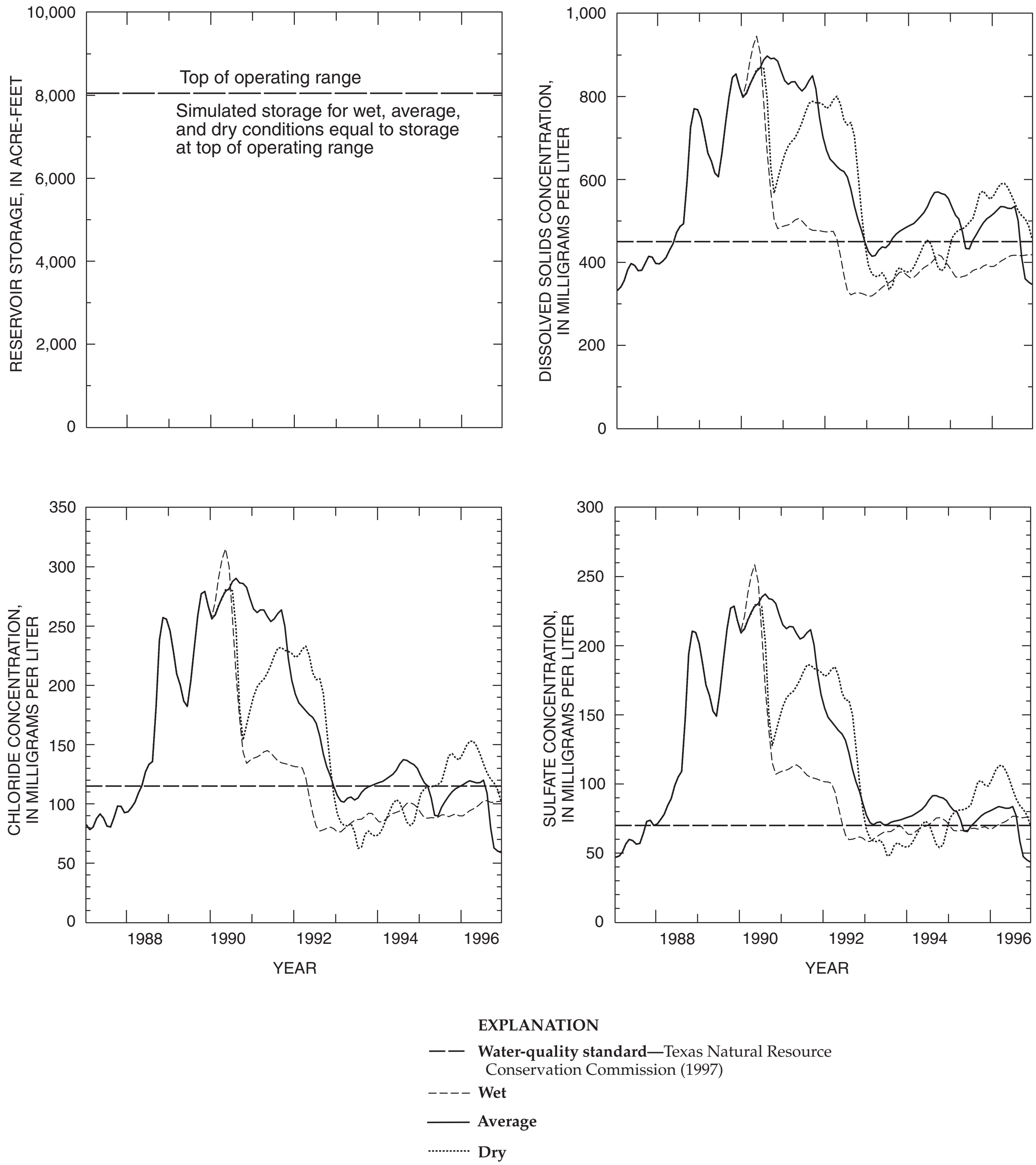


Figure 30. Simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry hydrologic conditions at Lake Marble Falls, Texas, 1987–96.

larger for the dry condition than for the average condition. The maximum concentrations for the reservoirs are comparable for the three simulations. The simulated ending concentrations of dissolved solids, chloride, and sulfate in all reservoirs for the three simulations are smaller than simulated maximum concentrations. The results indicate that the continuing inputs of large volumes of water (even with large constituent loads)

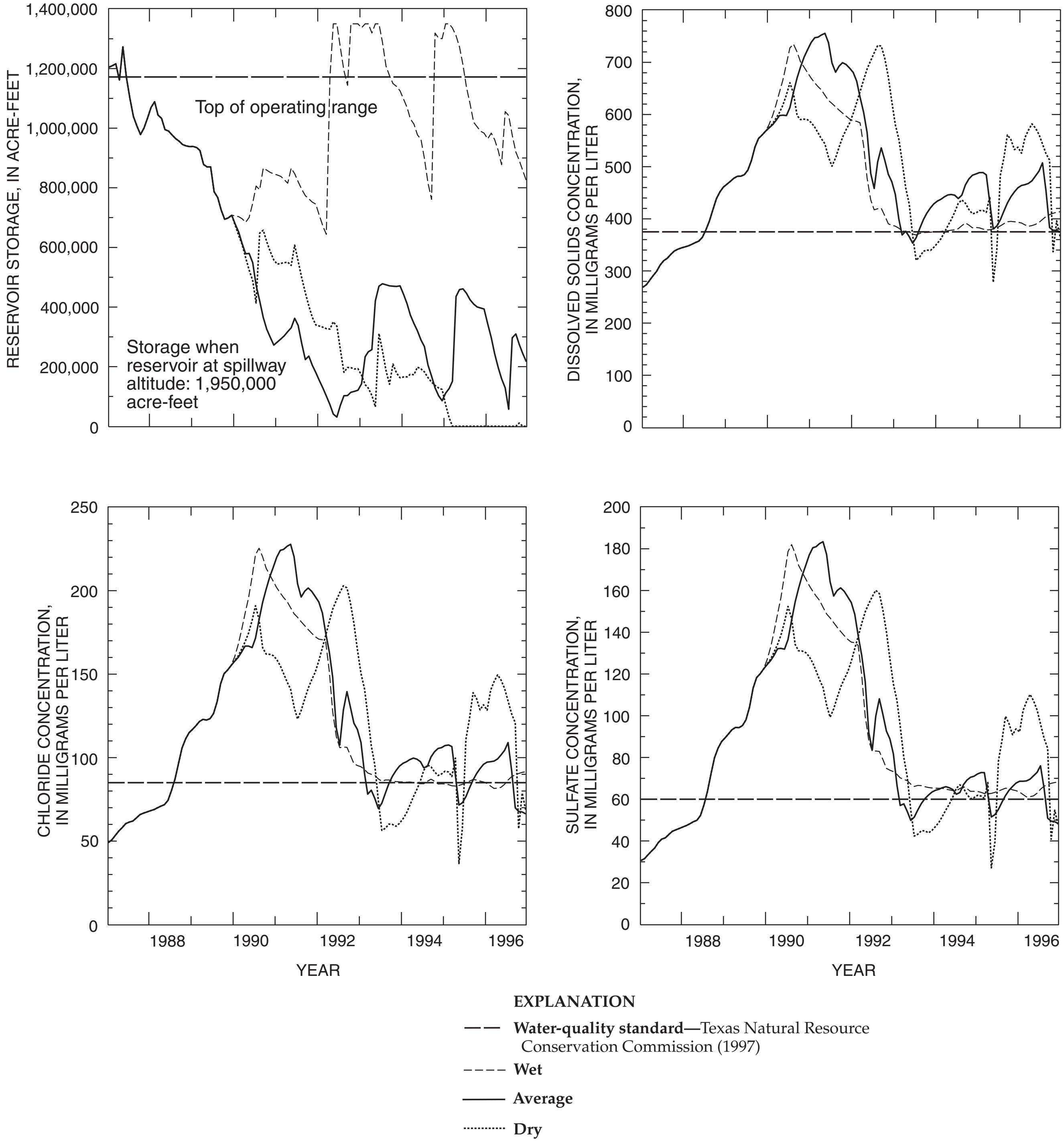


Figure 31. Simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry hydrologic conditions at Lake Travis, Texas, 1987–96.

after the saline inflow during 1987–89 tend to have a diluting effect on the constituent concentrations in the reservoirs. Generally, the larger the inflow volume, the less time required to dilute the increased concentrations in the reservoirs.

The simulated monthly streamflow and concentrations of dissolved solids, sulfate, and chloride for wet, average, and dry hydrologic conditions at the Colorado River at Austin, downstream of Town Lake, are shown in figure 34. The simulated concentrations

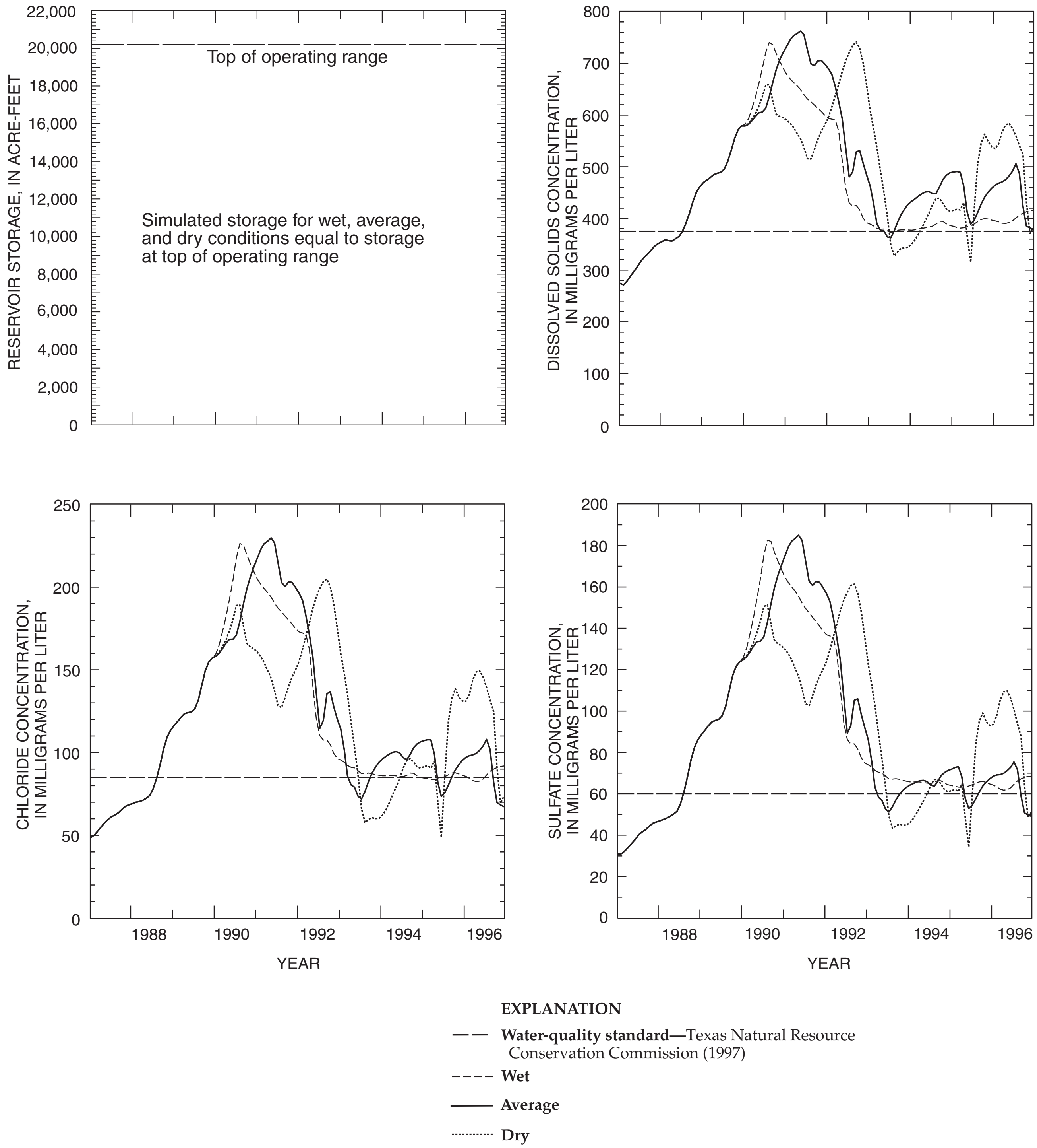


Figure 32. Simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry hydrologic conditions at Lake Austin, Texas, 1987–96.

decreased to levels less than the concentrations of the applicable water-quality standards during 1992–93 for the three hydrologic conditions but exceeded the standards again during 1996 for the dry condition. Simulated concentrations for the dry condition exceeded concentrations of the water-quality standards during 1996 because the amount of water stored in Lake Buchanan and Lake Travis and the amount of tributary inflow were insufficient to dilute the concentrations before the water was released downstream.

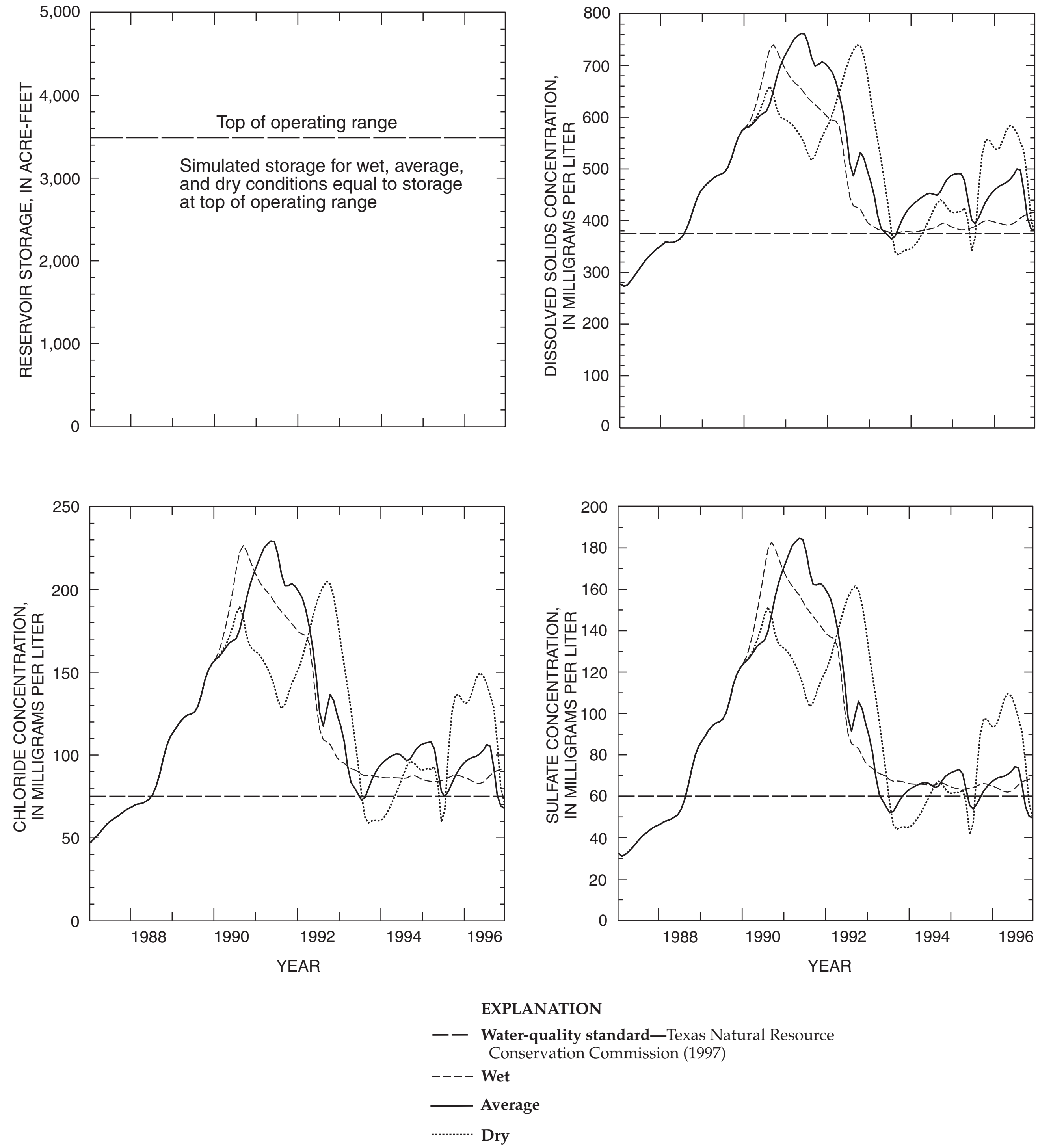


Figure 33. Simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry hydrologic conditions at Town Lake, Texas, 1987–96.

Results from the simulations indicate that saline inflows to the Highland Lakes similar to those during 1987–89 are unlikely to cause extremely large increases in concentrations of dissolved solids, chloride, and sulfate in the Highland Lakes. The results also indicate that saline water will continue to be diluted as it is transported downstream through the Highland Lakes, even during extended dry periods.

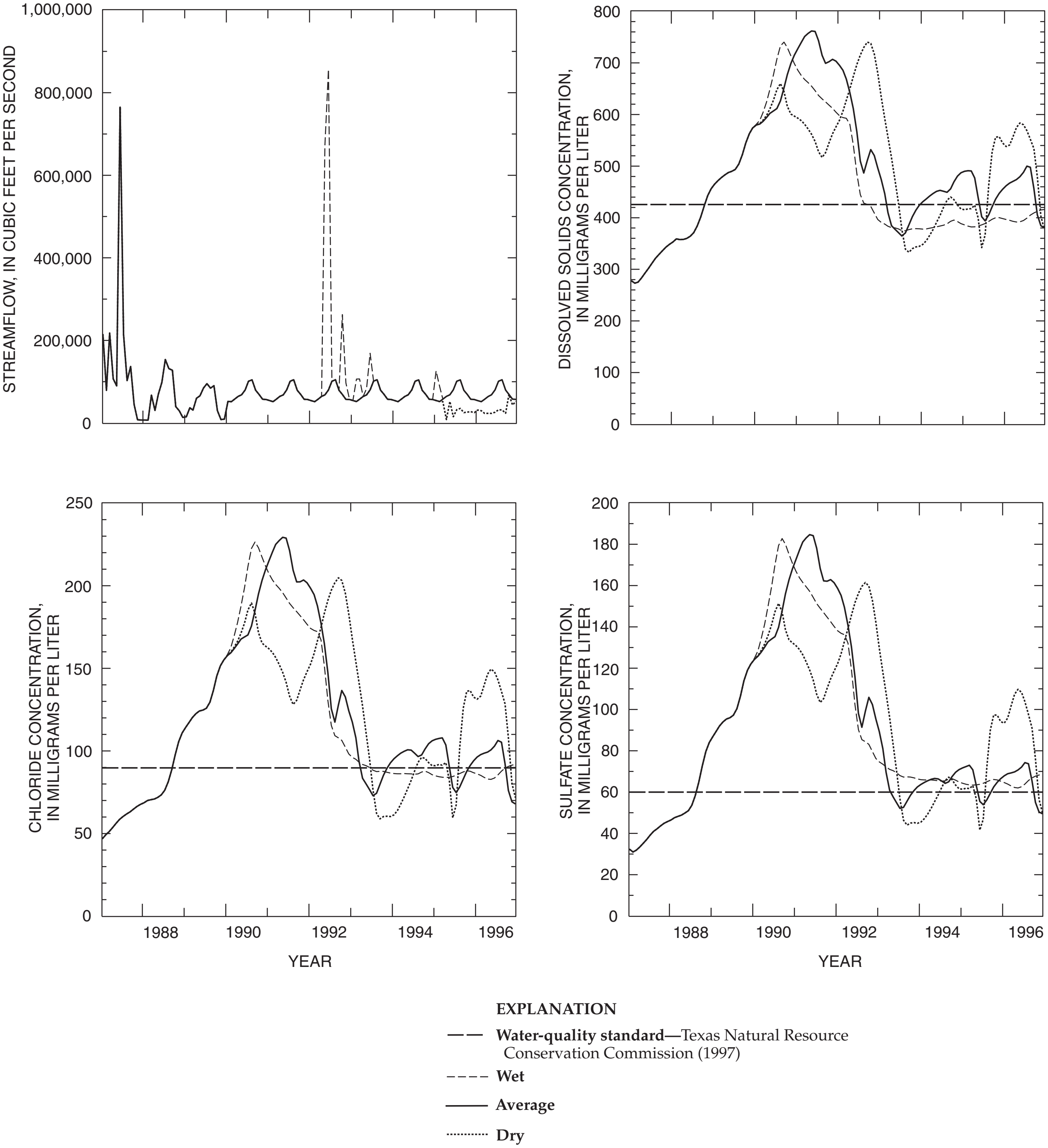


Figure 34. Simulated monthly streamflow and concentrations of dissolved solids, chloride, and sulfate for wet, average, and dry hydrologic conditions at Colorado River at Austin, Texas, 1987–96.

SUMMARY

The Highland Lakes are a series of seven reservoirs on the Colorado River in Central Texas. The reservoirs provide hydroelectric power and also provide the public water supply for the Austin metropolitan area. The saline water released from Natural Dam Salt Lake into the Highland Lakes during 1987–89 created the potential for water-quality problems that would necessitate additional treatment of the water.

The maximum dissolved solids concentrations for the reservoirs after the saline inflow were about two to three times the average concentrations before the inflow. The maximum concentrations of chloride and sulfate after the inflow were about three to five times the average concentrations before the inflow. The concentrations of dissolved solids, chloride, and sulfate after the saline inflow decreased from dilution by tributary inflow. The concentrations of dissolved solids, chloride, and sulfate in Lake Buchanan, Inks Lake, Lake LBJ, and Lake Marble Falls decreased to less than the concentrations of the applicable water-quality standards by the end of 1990. The concentrations in Lake Travis, Lake Austin, and Town Lake did not decrease to previous levels, which were less than the concentrations of the applicable water-quality standards until the end of 1991. Constituent concentrations for Lake Buchanan and Inks Lake, Lake LBJ and Lake Marble Falls, and Lake Travis, Lake Austin, and Town Lake were similar because of the relative storage capacities and location of tributary inflows. From the initial increase in concentrations in Lake Buchanan (summer 1987) in response to the period of saline inflow, the high-salinity water passed through the entire Highland Lakes series in about 3.5 years.

A mathematical mass-balance model was used to simulate 10 years of inflow and movement of water through the Highland Lakes and to estimate the concentrations of dissolved solids, chloride, and sulfate for each of three hydrologic conditions—wet, average, and dry. Simulated tributary inflow comprised the Colorado River, Llano River, and Pedernales River. The model was tested with 1983–92 data for each of the Highland Lakes to determine the adequacy for simulating the three hydrologic conditions. The errors increased in downstream order for each reservoir, but the model was judged to be acceptable for comparing differences in simulated concentrations of dissolved solids, chloride, and sulfate during the three conditions.

The model results could be improved by accounting for the additional quantity and quality of the minor tributaries and intervening areas to the Highland Lakes. The mass balance of the water quantity would be improved from an increase in the simulated water added to the system, which would provide more water to dilute the simulated concentrations of dissolved solids, chloride, and sulfate.

The simulated median monthly concentrations during the 10-year simulation period for each reservoir generally are larger for the average condition than for the wet condition and generally are larger for the dry condition than for the average condition. The simulated concentrations of dissolved solids, chloride, and sulfate decreased to less than the concentrations of the applicable water-quality standards in about 2 to 5 years after the saline-water inflow for the three hydrologic conditions.

Results from the simulations indicate that saline inflows to the Highland Lakes similar to those of 1987–89 are unlikely to cause large increases in concentrations of dissolved solids, chloride, and sulfate in the Highland Lakes. The results also indicate that high-salinity water will continue to be diluted as it is transported downstream through the Highland Lakes, even during extended dry periods.

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Table 7. Absolute error and error between measured and simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate in the Highland Lakes, Texas, 1983–92

[absolute error = |(simulated – measured)/measured|*100; error = (simulated – measured)/measured)*100]

Reservoir	Absolute error (percent)				Error (percent)			
	Mean	Median	Minimum	Maximum	Mean	Median	Minimum	Maximum
Reservoir storage								
Lake Buchanan	3.0	2.7	0	32.4	–0.3	–0.6	–10.6	32.4
Inks Lake	1.8	.9	0	18.4	–1.0	–.3	–18.4	3.9
Lake Lyndon B. Johnson	.9	.5	0	5.7	.6	.4	–1.3	5.7
Lake Marble Falls	1.6	1.1	0	6.2	.1	–.1	–5.3	6.2
Lake Travis	4.7	2.9	0	55.0	–2.8	–2.5	–32.2	55.0
Lake Austin	2.4	2.1	0	10.8	2.2	2.1	–2.0	10.8
Town Lake	1.6	1.3	0	4.6	1.0	.9	–2.9	4.6
Dissolved solids								
Lake Buchanan	14.1	14.2	.4	50.9	11.3	12.2	–27.0	50.9
Inks Lake	17.6	16.0	.1	59.4	17.1	16.0	–11.0	59.9
Lake Lyndon B. Johnson	21.5	16.3	.8	131	21.0	16.3	–9.6	131
Lake Marble Falls	21.3	16.3	.3	147	20.7	16.1	–18.6	147
Lake Travis	27.0	27.5	.1	69.0	25.8	27.5	–16.7	69.0
Lake Austin	34.2	31.2	6.2	104	34.2	31.2	6.2	104
Town Lake	35.7	34.3	.4	74.6	35.7	34.3	.4	74.6
Chloride								
Lake Buchanan	16.0	13.6	.4	61.3	13.1	11.3	–31.8	61.3
Inks Lake	18.7	15.8	.1	113	16.3	13.6	–27.0	113
Lake Lyndon B. Johnson	27.2	18.3	.3	281	23.8	17.4	–18.7	281
Lake Marble Falls	23.0	16.1	.2	132	19.9	13.8	–22.4	132
Lake Travis	28.5	24.4	0	107	25.6	23.0	–36.1	107
Lake Austin	40.1	33.9	1.0	161	38.5	33.9	–24.3	161
Town Lake	63.5	64.3	.6	128	63.5	64.3	.6	128
Sulfate								
Lake Buchanan	20.3	9.8	.1	159	18.0	6.7	–16.8	159
Inks Lake	22.6	13.6	0	163	19.9	11.4	–23.2	163
Lake Lyndon B. Johnson	38.9	26.8	.4	361	36.7	26.8	–15.0	361
Lake Marble Falls	30.9	21.4	.1	138	28.9	23.3	–38.5	138
Lake Travis	32.4	25.0	0	139	28.9	23.3	–38.5	139
Lake Austin	43.5	35.2	.5	185	42.2	35.2	–28.4	185
Town Lake	51.5	51.5	.5	101	51.5	51.5	.5	101

Table 8. Monthly demand distribution for Lake Travis[1]

[acre-ft, acre-feet]

Month	Demand		Month	Demand	
	Percent of annual demand	Volume (acre-ft)		Percent of annual demand	Volume (acre-ft)
Jan.	6.4	54,900	Aug.	12.4	106,300
Feb.	6.1	52,300	Sept.	9.4	80,600
Mar.	6.8	58,300	Oct.	8.2	70,300
Apr.	7.6	65,200	Nov.	6.8	58,300
May	8.1	69,400	Dec.	6.7	57,500
June	9.5	81,400			
July	12.0	102,900	Annual	100	857,400

[1] Modified from Lower Colorado River Authority, 1993.

Table 9. Selected simulated monthly reservoir storage and concentrations of dissolved solids, chloride, and sulfate in the Highland Lakes, Texas, for wet, average, and dry hydrologic conditions, 1987–96

[acre-ft, acre-feet; mg/L, milligrams per liter]

Reservoir	Volume and concentration												
	Initial	Wet				Average				Dry			
		Min	Median	Max	Ending	Min	Median	Max	Ending	Min	Median	Max	Ending
Reservoir storage (acre-ft)													
Lake Buchanan	963,000	442,000	922,000	992,000	987,000	39,900	457,000	992,000	101,000	0	368,000	992,000	47,300
Inks Lake	17,100	17,100	17,100	17,100	17,100	17,100	17,100	17,100	17,100	17,100	17,100	17,100	17,100
Lake Lyndon B. Johnson	138,500	138,500	138,500	138,500	138,500	138,500	138,500	138,500	138,500	138,500	138,500	138,500	138,500
Lake Marble Falls	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760	8,760
Lake Travis	1,290,000	644,000	981,000	1,350,000	824,000	30,800	405,000	1,270,000	217,000	0	345,000	1,270,000	0
Lake Austin	20,600	20,600	20,600	20,600	20,600	20,600	20,600	20,600	20,600	20,600	20,600	20,600	20,600
Town Lake	3,490	3,490	3,490	3,490	3,490	3,490	3,490	3,490	3,490	3,490	3,490	3,490	3,490
Dissolved solids (mg/L)													
Lake Buchanan	424	306	440	1,010	410	286	566	1,010	340	230	716	1,010	236
Inks Lake	420	311	446	1,020	412	308	564	1,020	323	250	716	1,020	250
Lake Lyndon B. Johnson	332	315	408	943	415	338	518	887	342	321	543	867	432
Lake Marble Falls	326	318	414	946	419	332	532	898	347	338	548	870	456
Lake Travis	266	269	394	735	414	269	464	756	375	269	484	732	366
Lake Austin	280	272	397	741	415	272	469	762	379	272	491	741	383
Town Lake	281	273	398	740	416	273	470	762	381	273	489	740	378
Chloride (mg/L)													
Lake Buchanan	107	80	175	344	103	44	151	345	60	41	232	345	42
Inks Lake	102	82	116	362	104	50	153	362	54	46	230	362	46
Lake Lyndon B. Johnson	81	75	99	314	101	58	125	288	58	56	137	281	96
Lake Marble Falls	85	76	100	315	102	59	126	290	59	62	136	281	102
Lake Travis	48	49	90	225	92	49	103	228	66	37	123	203	68
Lake Austin	48	49	90	226	92	49	102	230	67	49	124	205	74
Town Lake	45	47	90	227	92	47	103	229	68	47	124	205	72
Sulfate (mg/L)													
Lake Buchanan	68	61	78	285	77	32	113	286	43	23	183	286	24
Inks Lake	58	62	79	300	78	36	113	300	39	27	181	300	27
Lake Lyndon B. Johnson	48	47	75	300	76	43	88	235	43	44	99	230	65
Lake Marble Falls	46	47	75	259	76	44	88	237	44	47	101	230	70
Lake Travis	30	31	67	182	68	31	71	183	48	27	91	160	47
Lake Austin	31	31	68	183	68	31	71	185	49	31	93	161	51
Town Lake	34	31	68	183	68	31	71	185	50	31	93	162	50