Prepared in cooperation with the Oklahoma Water Resources Board

Hydrogeology and Simulated Groundwater Flow and Availability in the North Fork Red River Aquifer, Southwest Oklahoma, 1980–2013

Scientific Investigations Report 2017–5098

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

Front cover, Boat ramp at Lake Altus, Okla., during hydrologic drought conditions, December 20, 2012. Photo by Kevin A. Smith, used with permission.

Back cover, Lake Altus Dam near Lugert, Okla., January 4, 2003. Photo by S. Jerrod Smith.

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Leakance	
foot per day per foot [(ft/d)/ft]	1	meter per day per meter

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as
°F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as
°C = (°F – 32) / 1.8.

Datum

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

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

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

Supplemental Information

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

BFI	base-flow index
DEM	digital elevation model
EFRR	Elm Fork Red River inflow for Streamflow-Routing package
ELK	Elk Creek inflow for Streamflow-Routing package
EPS	equal proportionate share
ET	evapotranspiration
GHB	general-head boundary
HPT	Hydraulic Profiling Tool
IDW	inverse distance weighted
Kh	horizontal hydraulic conductivity
LAID	Lugert-Altus Irrigation District
MAY	maximum annual yield
NFRR	North Fork Red River inflow for Streamflow-Routing package
NWIS	National Water Information System
OWRB	Oklahoma Water Resources Board
RMSE	root-mean-square error
SFR	streamflow routing

SWB	soil-water balance
SWEE	Sweetwater Creek inflow for Streamflow-Routing package
Sy	specific yield
TDS	total dissolved solids
USGS	U.S. Geological Survey
WTF	water-table fluctuation

Hydrogeology and Simulated Groundwater Flow and Availability in the North Fork Red River Aquifer, Southwest Oklahoma, 1980–2013

By S. Jerrod Smith,[1] John H. Ellis,[1] Derrick L. Wagner,[2] and Steven M. Peterson[1]

Abstract

On September 8, 1981, the Oklahoma Water Resources Board established regulatory limits on the maximum annual yield of groundwater (343,042 acre-feet per year) and equal-proportionate-share (EPS) pumping rate (1.0 acre-foot per acre per year) for the North Fork Red River aquifer. The maximum annual yield and EPS were based on a hydrologic investigation that used a numerical groundwater-flow model to evaluate the effects of potential groundwater withdrawals on groundwater availability in the North Fork Red River aquifer. The Oklahoma Water Resources Board is statutorily required (every 20 years) to update the hydrologic investigation on which the maximum annual yield and EPS were based. Because 20 years have elapsed since the final order was issued, the U.S. Geological Survey, in cooperation with the Oklahoma Water Resources Board, conducted an updated hydrologic investigation and evaluated the effects of potential groundwater withdrawals on groundwater flow and availability in the North Fork Red River aquifer in Oklahoma. This report describes a hydrologic investigation of the North Fork Red River aquifer that includes an updated summary of the aquifer hydrogeology. As part of this investigation, groundwater flow and availability were simulated by using a numerical groundwater-flow model.

The North Fork Red River aquifer in Beckham, Greer, Jackson, Kiowa, and Roger Mills Counties in Oklahoma is composed of about 777 square miles (497,582 acres) of alluvium and terrace deposits along the North Fork Red River and tributaries, including Sweetwater Creek, Elk Creek, Otter Creek, and Elm Fork Red River. The North Fork Red River is the primary source of surface-water inflow to Lake Altus, which overlies the North Fork Red River aquifer. Lake Altus is a U.S. Bureau of Reclamation reservoir with the primary purpose of supplying irrigation water to the Lugert-Altus Irrigation District.

A hydrogeologic framework was developed for the North Fork Red River aquifer and included a definition of the aquifer extent and potentiometric surface, as well as a description of the textural and hydraulic properties of aquifer materials. The hydrogeologic framework was used in the construction of a numerical groundwater-flow model of the North Fork Red River aquifer described in this report. A conceptual model of aquifer inflows and outflows was developed for the North Fork Red River aquifer to constrain the construction and calibration of a numerical groundwater-flow model that reasonably represented the groundwater-flow system. The conceptual-model water budget estimated mean annual inflows to and outflows from the North Fork Red River aquifer for the period 1980–2013 and included a sub-accounting of mean annual inflows and outflows for the portions of the aquifer that were upgradient and downgradient from Lake Altus. The numerical groundwater-flow model simulated the period 1980–2013 and was calibrated to water-table-altitude observations at selected wells, monthly base flow at selected streamgages, net streambed seepage as estimated for the conceptual model, and Lake Altus stage.

Groundwater-availability scenarios were performed by using the calibrated numerical groundwater-flow model to (1) estimate the EPS pumping rate that guarantees a minimum 20-, 40-, and 50-year life of the aquifer, (2) quantify the potential effects of projected well withdrawals on groundwater storage over a 50-year period, and (3) simulate the potential effects of a hypothetical (10-year) drought on base flow and groundwater storage. The results of the groundwater-availability scenarios could be used by the Oklahoma Water Resources Board to reevaluate the maximum annual yield of groundwater from the North Fork Red River aquifer.

EPS scenarios for the North Fork Red River aquifer were run for periods of 20, 40, and 50 years. The 20-, 40-, and 50-year EPS pumping rates under normal recharge conditions were 0.59, 0.52, and 0.52 acre-foot per acre per year, respectively. Given the 497,582-acre aquifer area, these rates correspond to annual yields of about 294,000, 259,000, and 259,000 acre-feet per year, respectively. Groundwater storage at the end of the 20-year EPS scenario was about 951,000 acre-feet, or about 1,317,000 acre-feet (58 percent) less than the starting EPS scenario storage. This decrease in storage was equivalent to a mean water-level decline of about 22 feet. Most areas of the active alluvium near the North Fork

[1]U.S. Geological Survey.

[2]Oklahoma Water Resources Board.

Red River, Elk Creek, and Elm Fork Red River remained partially saturated through the end of the EPS scenario because of streambed seepage. Lake Altus storage was reduced to zero after 6–7 years of EPS pumping in each scenario.

Projected 50-year pumping scenarios were used to simulate the effects of selected well withdrawal rates on groundwater storage of the North Fork Red River aquifer and base flows in the North Fork Red River upstream from Lake Altus. The effects of well withdrawals were evaluated by comparing changes in groundwater storage and base flow between four 50-year scenarios using (1) no groundwater pumping, (2) mean pumping rates for the study period (1980–2013), (3) 2013 pumping rates, and (4) increasing demand pumping rates. The increasing demand pumping rates assumed a 20.4-percent increase in pumping over 50 years based on 2010–60 demand projections for southwest Oklahoma.

Groundwater storage after 50 years with no pumping was about 2,606,000 acre-feet, or 137,000 acre-feet (5.5 percent) greater than the initial groundwater storage; this groundwater storage increase is equivalent to a mean water-level increase of 2.3 feet. Groundwater storage after 50 years with the mean pumping rate for the study period (1980–2013) was about 2,476,000 acre-feet, or about 7,000 acre-feet (0.3 percent) greater than the initial groundwater storage; this groundwater storage increase is equivalent to a mean water-level increase of 0.1 foot. Groundwater storage at the end of the 50-year period with 2013 pumping rates was about 2,398,000 acre-feet, or about 70,000 acre-feet (2.8 percent) less than the initial storage; this groundwater storage decrease is equivalent to a mean water-level decline of 1.2 feet. Groundwater storage at the end of the 50-year period with increasing demand pumping rates was about 2,361,000 acre-feet, or about 107,000 acre-feet (4.3 percent) less than the initial storage; this groundwater storage decrease is equivalent to a mean water-level decline of 1.8 feet. Mean annual base flow simulated at the Carter streamgage (07301500) on North Fork Red River increased by about 4,000 acre-feet (10 percent) after 50 years with no pumping and decreased by about 5,400 acre-feet (13 percent) after 50 years with increasing demand pumping rates. Mean annual base flow simulated at the North Fork Red River inflow to Lake Altus increased by about 7,400 acre-feet (15 percent) after 50 years with no pumping and decreased by about 5,800 acre-feet (12 percent) after 50 years with increasing demand pumping rates.

A hypothetical 10-year drought scenario was used to simulate the effects of a prolonged period of reduced recharge on groundwater storage and Lake Altus stage and storage. Drought effects were quantified by comparing the results of the drought scenario to those of the calibrated numerical model (no drought). To simulate the hypothetical drought, recharge in the calibrated numerical model was reduced by 50 percent during the simulated drought period (1984–1993). Groundwater storage at the end of the drought period was about 2,271,000 acre-feet, or about 426,000 acre-feet (15.8 percent) less than the groundwater storage of the calibrated numerical model. This decrease in groundwater storage is equivalent to a mean water-table-altitude decline of 7.1 feet. At the end of the 10-year hypothetical drought period, base flows at the Sweetwater (07301420), Carter (07301500), Headrick (07305000), and Snyder (07307010) streamgages had decreased by about 37, 61, 44, and 45 percent, respectively. The minimum Lake Altus storage simulated during the drought period was 403 acre-feet, which was a decline of 92 percent from the nondrought storage. Reduced base flows in the North Fork Red River were the primary cause of Lake Altus storage declines.

Introduction

The 1973 Oklahoma Water Law (82 OK Stat § 82-1020.5) requires the Oklahoma Water Resources Board (OWRB) to conduct hydrologic investigations of the State's aquifers (called groundwater basins) to support a determination of the maximum annual yield (MAY) for each groundwater basin. The MAY is defined as the amount of fresh groundwater that can be withdrawn annually while ensuring a minimum 20-year life of the groundwater basin (OWRB, 2010). For alluvium and terrace aquifers, the groundwater-basin-life requirement is satisfied if, after 20 years of MAY withdrawals, 50 percent of the groundwater basin retains a saturated thickness of at least 5 ft. When a MAY has been established, the amount of land owned or leased by a permit applicant determines the annual volume of water allocated to that permit applicant. The annual volume of water allocated per acre of land is known as the equal-proportionate-share (EPS) pumping rate.

The OWRB issued a final order on September 8, 1981, that established the MAY (343,042 acre-feet per year [acre-ft/yr]) and EPS pumping rate (1.0 acre-foot per acre per year) for the North Fork Red River aquifer (OWRB, 2015a). The MAY and EPS were based on hydrologic investigations by Kent (1980) and Paukstaitis (1981) that used a numerical groundwater-flow model (Trescott and others, 1976) to evaluate the effects of potential groundwater withdrawals on groundwater availability in the North Fork Red River aquifer. Every 20 years, the OWRB is statutorily required to update the hydrologic investigation on which the MAY and EPS were based. Because 20 years have elapsed since the final order was issued, the U.S. Geological Survey (USGS), in cooperation with the OWRB, conducted an updated hydrologic investigation and evaluated the effects of potential groundwater withdrawals on groundwater flow and availability in the North Fork Red River aquifer.

Purpose and Scope

The purpose of this report is to describe a hydrologic investigation of the North Fork Red River aquifer that includes an updated summary of the aquifer hydrogeology and results of the simulation of groundwater flow and availability obtained by using a numerical groundwater-flow model. The numerical groundwater-flow model was calibrated to observed data and used to compute a mean annual water budget for the study period 1980–2013. Groundwater-availability scenarios were performed by using the calibrated numerical groundwater-flow model to (1) estimate the EPS pumping rate that guarantees a minimum 20-, 40-, and 50-year life of the aquifer, (2) quantify the potential effects of projected well withdrawals on groundwater storage over a 50-year period, and (3) simulate the potential effects of a hypothetical (10-year) drought on groundwater storage and lake storage. The results of the groundwater-availability scenarios could be used by the OWRB to reevaluate the MAY of groundwater from the North Fork Red River aquifer in Oklahoma. The calibrated numerical groundwater-flow model and groundwater-availability scenarios were archived and released in Smith and others (2017).

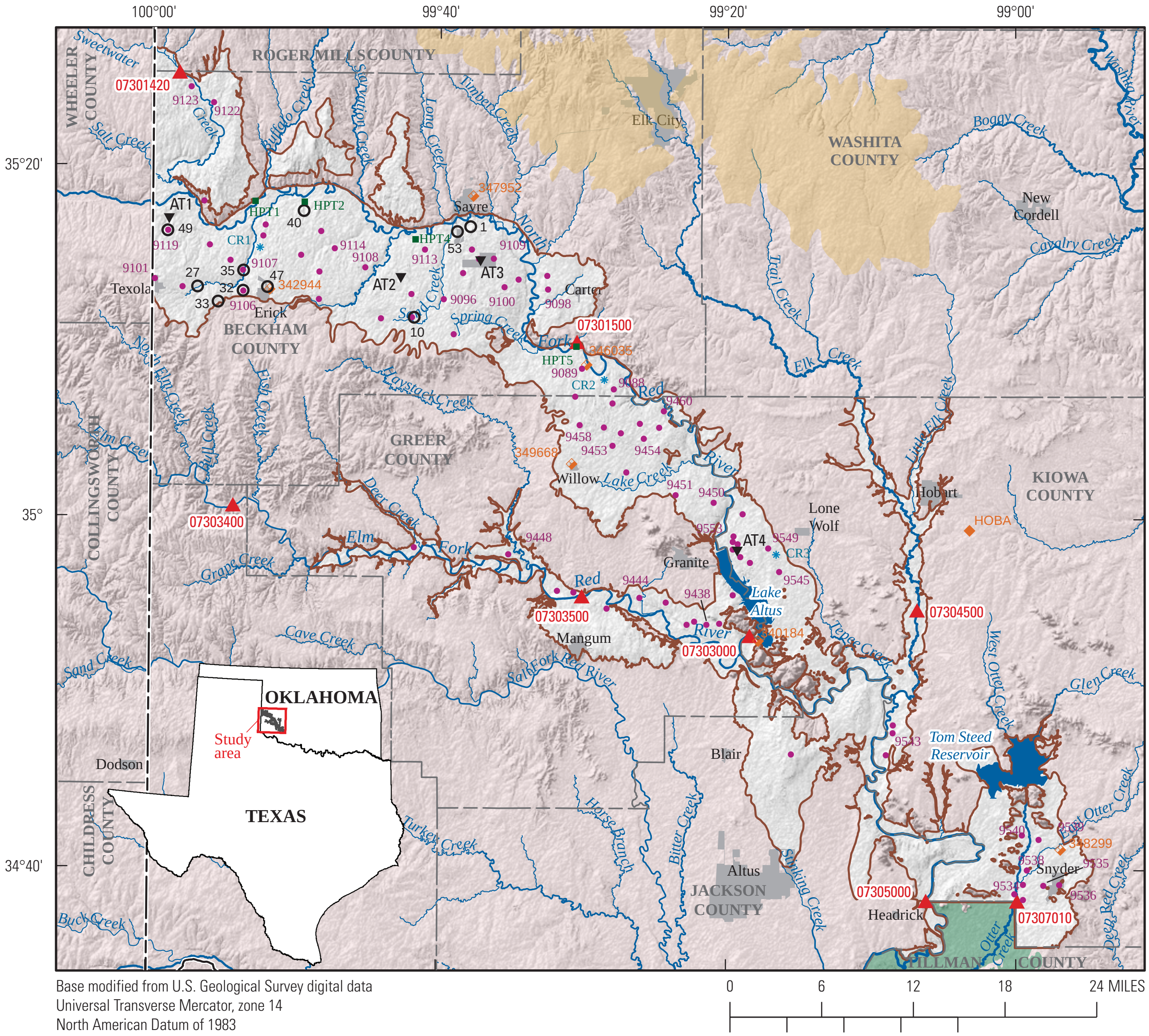
The geographic scope of the hydrologic investigation is the alluvium and terrace deposits of the North Fork Red River aquifer and the underlying Permian bedrock units. Though the alluvium and terrace deposits of the North Fork Red River and Sweetwater Creek extend west into Texas, this investigation was focused on the OWRB jurisdictional extent of the North Fork Red River aquifer in Beckham, Greer, Jackson, Kiowa, and Roger Mills Counties of southwest Oklahoma (fig. 1). The alluvium and terrace deposits of the North Fork Red River also extend south into Tillman County, Oklahoma, where they are known as the Tillman Terrace aquifer (fig. 1); the Tillman Terrace aquifer was not included in the investigation described in this report because the OWRB manages that aquifer separately from the North Fork Red River aquifer.

Description of Study Area

The North Fork Red River aquifer in Beckham, Greer, Jackson, Kiowa, and Roger Mills Counties in Oklahoma is composed of about 777 square miles (mi^2) (497,582 acres) of alluvium and terrace deposits along the North Fork Red River. This area includes alluvium and terrace deposits along several major tributaries to the North Fork Red River including Sweetwater Creek, Elk Creek, Otter Creek, and Elm Fork Red River in southwest Oklahoma (fig. 1). The North Fork Red River and tributaries, which compose the North Fork Red River watershed, drain about 4,500 mi^2 of land area in Texas and Oklahoma before connecting with the Red River (fig. 2). Groundwater discharge from the North Fork Red River aquifer sustains streamflow to the North Fork Red River during most of the year (Smith and Wahl, 2003); however, some gaged reaches of the North Fork Red River and tributaries commonly have no flow (defined as streamflow less than 1 cubic foot per second [ft^3/s]) in the late summer when water demands for irrigation, public supply, and evapotranspiration (ET) are greatest. The Carter streamgage (07301500; fig. 1, table 1, at end of report) on the North Fork Red River, for example, recorded no flow from June 6, 2011, to January 6, 2012, during a 7-month period of exceptional drought (USGS, 2015a). Though a few storms in that period produced enough runoff to sustain streamflow for a few hours, no day in that period had daily streamflow greater than 1 ft^3/s.

The North Fork Red River is the primary source of surface-water inflow to Lake Altus, a U.S. Bureau of Reclamation reservoir with the primary purpose of supplying irrigation water to the Lugert-Altus Irrigation District (LAID) (fig. 2). Lake Altus supplies a dependable annual yield of 47,100 acre-ft/yr but is over-allocated with permitted surface-water withdrawals of 85,630 acre-ft/yr to the LAID and 4,800 acre-ft/yr to the city of Altus (OWRB, 2012a). For the study period 1980–2013, about half of the annual surface-water inflow to Lake Altus was supplied by base flow (as observed at the Carter streamgage [07301500] and computed by using the USGS Groundwater Toolbox [Barlow and others, 2015]), which is the component of streamflow supplied by the discharge of groundwater to streams (Barlow and Leake, 2012) (table 2). However, the total annual base flow and the base-flow index (the ratio of total annual base flow to total annual streamflow) generally have been increasing (while peak flows generally have been decreasing) since the 1960s at the Carter streamgage (07301500), just upstream from Lake Altus (Smith and Wahl, 2003; Esralew and Lewis, 2010). The reasons for these increasing trends in base flow and base-flow index are not clear but could include increases in the number of impoundments (stock ponds and floodwater-retarding structures) or changes in agricultural practices that reduce runoff and promote artificial recharge to the aquifer (Smith and Wahl, 2003). In recent years (2000–13) at the Carter streamgage (07301500), the base-flow index exceeded 60 percent in 4 out of 14 years with a maximum base-flow index of 81.1 percent in 2011 (table 2).

Elk Creek (through Bretch Canal) and West Otter Creek supply inflow to Tom Steed Reservoir, a U.S. Bureau of Reclamation reservoir that provides water (16,100 acre-ft/yr, permitted) to the Oklahoma cities of Altus, Snyder, and Frederick, as well as the Hackberry Flat Wildlife Management Area (U.S. Bureau of Reclamation, 2015a; fig. 2). During times of runoff, surplus water is diverted from Elk Creek through the Bretch Canal to augment supply at Tom Steed Reservoir (fig. 2). Unlike Lake Altus, which is dependent on base flows from the North Fork Red River aquifer for replenishment, Tom Steed Reservoir is near the edge of the aquifer and primarily is replenished by surface-water runoff from areas outside of the North Fork Red River aquifer. Base flows in Elk Creek originate from several sources including the Elk City aquifer, the North Fork Red River aquifer, and, following periods of runoff, numerous floodwater-retarding structures in the Elk Creek watershed (figs. 1–2).



Base modified from U.S. Geological Survey digital data
Universal Transverse Mercator, zone 14
North American Datum of 1983

EXPLANATION

- Incorporated area (U.S. Census Bureau, 2000)
- North Fork Red River aquifer boundary (modified from Oklahoma Water Resources Board, 2015b)
- Tillman Terrace aquifer (Oklahoma Water Resources Board, 2015b)
- Elk City aquifer (Oklahoma Water Resources Board, 2015b)
- Climate station (table 1)
  - National Climatic Data Center (2015)
  - Oklahoma Mesonet (2015)
- Continuous water-level recorder well (U.S. Geological Survey, 2015a; table 1)
- Multi-well aquifer test location (table 1)
- Geoprobe hydraulic profiling tool test hole (table 1)
- Water-table-altitude observation and Mass Measurement Program well (Oklahoma Water Resources Board, 2015b; table 1, only wells discussed in this report are labeled)
- Historical water-table altitude observation well (U.S. Geological Survey, 2015a; table 1)
- Streamgage (U.S. Geological Survey, 2015a; table 1)

Figure 1. The North Fork Red River aquifer study area, southwest Oklahoma.

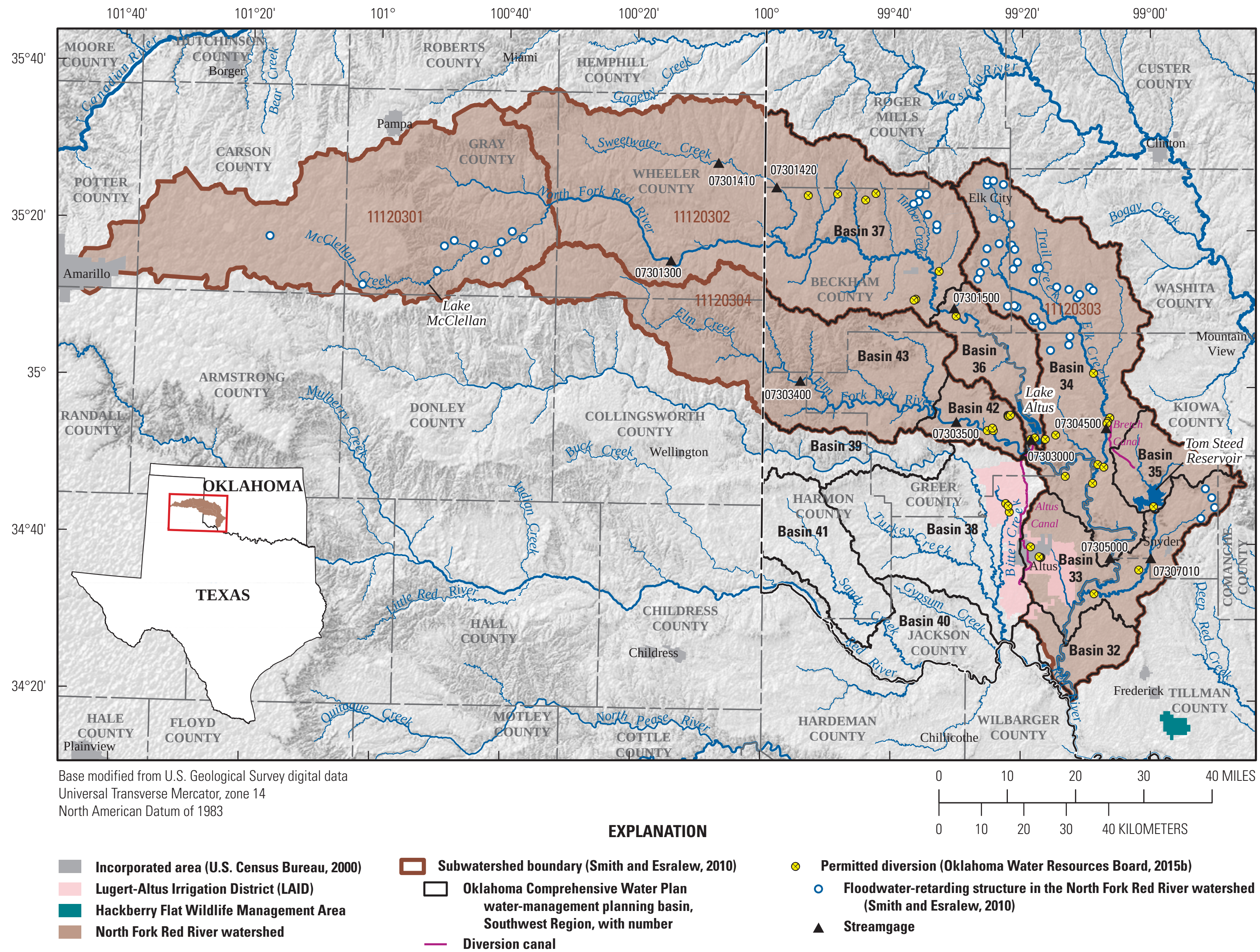


Figure 2. Major geographic and surface-water features in and near the North Fork Red River watershed, southwest Oklahoma and northwest Texas.

Table 2. Mean annual streamflow and mean annual base flow for selected streamgages in and near the North Fork Red River aquifer study area, 1980–2013.

[Base flow computed by using BFI method in the U.S. Geological Survey Groundwater Toolbox (Barlow and others, 2015; streamflow data from U.S. Geological Survey, 2015a); Mean Lake Altus releases were assumed to be the same as mean streamflow at the Lugert streamgage; ft^3/s, cubic feet per second; acre-ft/yr, acre-feet per year; %, percent; BFI, base-flow index; --, data not available or not applicable]

Year	Shamrock streamgage (07301300) on North Fork Red River			Kelton streamgage (07301410) on Sweetwater Creek			Sweetwater streamgage (07301420) on Sweetwater Creek		
	Mean streamflow (ft^3/s)	Mean base flow		Mean streamflow (ft^3/s)	Mean base flow		Mean streamflow (ft^3/s)	Mean base flow	
		ft^3/s	% (BFI)		ft^3/s	% (BFI)		ft^3/s	% (BFI)
1980	12.0	1.3	11.1	8.1	5.7	71.0	--	--	--
1981	13.1	0.7	5.1	10.1	5.7	55.7	--	--	--
1982	48.1	0.8	1.6	13.3	8.0	60.7	--	--	--
1983	29.5	1.1	3.6	8.0	6.1	76.1	--	--	--
1984	11.8	0.4	3.0	5.1	3.8	74.2	--	--	--
1985	43.9	3.9	8.8	15.6	7.0	45.2	--	--	--
1986	36.3	9.8	26.9	17.2	9.9	57.7	--	--	--
1987	28.3	9.7	34.4	16.9	12.2	72.0	31.5	22.0	69.8
1988	46.5	11.3	24.3	17.8	11.7	65.8	28.8	18.8	65.2
1989	58.6	3.8	6.5	18.4	12.1	65.6	25.8	18.2	70.3
1990	28.0	5.5	19.7	12.5	9.9	79.5	19.6	15.3	78.0
1991	--	--	--	9.8	7.6	77.0	16.1	11.7	72.8
1992	--	--	--	11.4	8.8	77.1	19.4	14.3	73.6
1993	--	--	--	10.0	7.8	77.9	17.7	13.3	75.1
1994	--	--	--	5.9	4.4	73.6	9.9	7.2	72.7
1995	--	--	--	17.3	8.9	51.4	28.8	14.2	49.3
1996	--	--	--	16.5	10.5	63.7	26.0	18.6	71.5
1997	--	--	--	34.9	18.8	54.0	55.5	33.1	59.6
1998	--	--	--	14.9	11.6	78.0	29.8	21.7	72.8
1999	--	--	--	13.4	9.8	73.4	24.6	17.2	70.0
2000	--	--	--	12.2	6.5	52.9	29.9	16.8	56.3
2001	29.9	15.0	50.1	14.4	10.2	70.7	31.9	21.3	66.8
2002	26.1	11.4	43.6	10.5	7.9	75.2	20.4	14.8	72.4
2003	27.0	9.7	36.0	9.0	7.7	85.0	16.8	12.1	72.3
2004	31.3	10.5	33.6	9.6	6.2	64.5	16.9	10.4	61.7
2005	26.6	11.8	44.4	8.4	6.3	74.8	14.5	10.4	71.7
2006	20.6	3.7	17.9	5.5	3.8	68.4	8.9	5.2	57.8
2007	45.8	19.9	43.5	14.2	8.8	61.8	25.6	16.0	62.6
2008	30.6	15.1	49.5	16.3	10.6	64.8	24.8	15.5	62.5
2009	22.9	12.5	54.6	11.9	9.6	80.5	20.5	14.0	68.0
2010	61.5	18.9	30.7	14.0	9.1	64.5	27.8	15.1	54.4
2011	8.2	4.5	55.0	4.0	3.5	89.1	8.3	6.7	80.7
2012	11.4	5.0	44.2	2.5	1.4	55.3	5.3	2.8	52.4
2013	15.1	5.7	37.9	3.3	1.8	52.5	9.5	3.9	41.3
Mean	29.7	8.0	28.6	12.1	8.0	67.9	22.0	14.5	66.0
Mean, in acre-ft/yr	21,526	5,794		8,798	5,827		15,954	10,480	

Table 2. Mean annual streamflow and mean annual base flow for selected streamgages in and near the North Fork Red River aquifer study area, 1980–2013.—Continued

[Base flow computed by using BFI method in the U.S. Geological Survey Groundwater Toolbox (Barlow and others, 2015; streamflow data from U.S. Geological Survey, 2015a); Mean Lake Altus releases were assumed to be the same as mean streamflow at the Lugert streamgage; ft^3/s, cubic feet per second; acre-ft/yr, acre-feet per year; %, percent; BFI, base-flow index; --, data not available or not applicable]

Year	Carter streamgage (07301500) on North Fork Red River			Lugert streamgage (07303000) on North Fork Red River below Lake Altus dam			Carl streamgage (07303400) on Elm Fork Red River		
	Mean streamflow (ft^3/s)	Mean base flow		Mean streamflow (ft^3/s)	Mean Lake Altus releases		Mean streamflow (ft^3/s)	Mean base flow	
		ft^3/s	% (BFI)		ft^3/s	% (BFI)		ft^3/s	% (BFI)
1980	45.7	19.7	43.1	1.0	1.0	--	--	--	--
1981	27.8	8.5	30.4	0.1	0.1	--	--	--	--
1982	174.0	42.1	24.2	0.0	0.0	--	--	--	--
1983	66.9	33.1	49.5	0.4	0.4	--	--	--	--
1984	34.3	14.2	41.6	0.2	0.2	--	--	--	--
1985	72.3	26.5	36.6	0.1	0.1	--	--	--	--
1986	205.2	48.1	23.4	0.1	0.1	--	--	--	--
1987	239.4	109.2	45.6	303.9	303.9	--	--	--	--
1988	131.5	65.6	49.9	78.9	78.9	--	--	--	--
1989	193.4	85.6	44.3	110.3	110.3	--	--	--	--
1990	132.1	56.1	42.5	98.5	98.5	--	--	--	--
1991	93.2	44.3	47.5	1.3	1.3	--	--	--	--
1992	94.4	60.7	64.4	28.2	28.2	--	--	--	--
1993	125.6	72.2	57.4	142.4	142.4	--	--	--	--
1994	36.3	21.7	59.8	1.0	1.0	--	--	--	--
1995	253.8	48.8	19.2	77.6	77.6	--	115.9	25.1	21.7
1996	155.2	76.9	49.6	41.2	41.2	--	37.7	24.2	64.1
1997	364.3	182.7	50.1	378.9	378.9	--	91.1	48.2	52.9
1998	184.2	114.2	62.0	201.8	201.8	--	50.4	33.4	66.2
1999	145.7	85.9	58.9	37.0	37.0	--	48.3	27.9	57.7
2000	134.7	60.9	45.2	4.4	4.4	--	38.2	17.6	46.1
2001	173.0	90.2	52.1	77.2	77.2	--	47.4	25.3	53.4
2002	70.4	45.2	64.2	0.5	0.5	--	15.6	12.0	77.0
2003	73.4	41.0	55.8	0.1	0.1	--	27.3	7.2	26.5
2004	95.0	50.5	53.2	0.1	0.1	--	22.2	10.6	47.4
2005	85.6	52.1	60.9	0.4	0.4	--	17.1	11.4	66.9
2006	37.8	17.2	45.5	0.4	0.4	--	10.1	4.5	44.8
2007	223.5	96.3	43.1	58.0	58.0	--	30.2	14.3	47.4
2008	92.8	54.1	58.3	1.0	1.0	--	18.3	11.3	61.7
2009	72.0	46.3	64.3	0.6	0.6	--	10.0	8.4	84.0
2010	126.9	54.3	42.8	0.8	0.8	--	18.6	7.6	40.8
2011	23.1	18.7	81.1	0.3	0.3	--	4.1	3.4	84.5
2012	12.1	7.0	58.4	0.1	0.1	--	3.1	1.7	53.2
2013	6.6	1.4	21.0	0.0	0.0	--	4.4	2.2	51.1
Mean	117.7	54.4	48.4	48.4	48.4	--	32.1	15.6	55.1
Mean, in acre-ft/yr	85,278	39,445		35,089	35,089		23,259	11,301	

Table 2. Mean annual streamflow and mean annual base flow for selected streamgages in and near the North Fork Red River aquifer study area, 1980–2013.—Continued

[Base flow computed by using BFI method in the U.S. Geological Survey Groundwater Toolbox (Barlow and others, 2015; streamflow data from U.S. Geological Survey, 2015a); Mean Lake Altus releases were assumed to be the same as mean streamflow at the Lugert streamgage; ft³/s, cubic feet per second; acre-ft/yr, acre-feet per year; %, percent; BFI, base-flow index; --, data not available or not applicable]

Year	Hobart streamgage (07304500) on Elk Creek			Headrick streamgage (07305000) on North Fork Red River			Snyder streamgage (07307010) on Otter Creek		
	Mean streamflow (ft^3/s)	Mean base flow		Mean streamflow (ft^3/s)	Mean base flow		Mean streamflow (ft^3/s)	Mean base flow	
		ft^3/s	% (BFI)		ft^3/s	% (BFI)		ft^3/s	% (BFI)
1980	59.9	4.5	7.5	208.3	42.7	20.5	--	--	--
1981	35.1	4.1	11.6	88.0	23.3	26.5	--	--	--
1982	146.0	20.6	14.1	311.1	66.4	21.3	--	--	--
1983	144.4	20.6	14.3	232.6	43.6	18.8	--	--	--
1984	21.3	11.0	51.7	53.8	32.3	60.0	--	--	--
1985	54.4	9.9	18.1	127.2	38.5	30.3	--	--	--
1986	323.8	59.7	18.4	895.4	246.7	27.6	--	--	--
1987	230.6	74.4	32.3	909.8	401.7	44.1	--	--	--
1988	134.0	55.2	41.2	398.7	164.9	41.4	--	--	--
1989	141.8	45.9	32.4	471.6	90.0	19.1	--	--	--
1990	89.9	29.4	32.6	446.5	122.5	27.4	--	--	--
1991	88.1	19.1	21.7	356.9	96.5	27.0	--	--	--
1992	151.4	57.7	38.1	388.8	141.0	36.3	--	--	--
1993	--	--	--	815.0	294.5	36.1	--	--	--
1994	--	--	--	105.2	58.9	56.0	--	--	--
1995	--	--	--	874.4	179.8	20.6	--	--	--
1996	--	--	--	450.3	189.5	42.1	--	--	--
1997	--	--	--	1,274.0	491.9	38.6	--	--	--
1998	--	--	--	561.5	248.1	44.2	--	--	--
1999	--	--	--	303.1	94.6	31.2	--	--	--
2000	--	--	--	210.4	74.5	35.4	--	--	--
2001	--	--	--	327.3	119.0	36.4	35.8	10.1	28.2
2002	--	--	--	84.2	35.9	42.6	4.8	1.1	22.7
2003	--	--	--	83.0	29.8	35.9	7.1	0.3	3.9
2004	--	--	--	233.2	53.3	22.8	10.4	0.4	4.0
2005	--	--	--	158.1	68.2	43.2	4.3	0.2	5.5
2006	--	--	--	72.5	22.4	30.8	4.7	0.9	20.0
2007	--	--	--	460.9	173.1	37.6	89.1	21.4	24.0
2008	--	--	--	157.1	53.0	33.7	--	--	--
2009	--	--	--	70.6	32.1	45.4	--	--	--
2010	--	--	--	164.3	35.1	21.3	--	--	--
2011	--	--	--	51.6	13.1	25.3	--	--	--
2012	--	--	--	45.2	12.2	26.9	--	--	--
2013	--	--	--	17.2	6.4	37.1	--	--	--
Mean	124.7	31.7	25.7	335.5	111.6	33.6	22.3	4.8	15.5
Mean, in acre-ft/yr	90,318	22,964		243,074	80,860		16,166	3,477	

The 2012 Oklahoma Comprehensive Water Plan prioritized 12 water-management planning basins where water-supply shortages were most likely to occur by 2060 based on available hydrologic data and projected demands; 3 of the 12 prioritized water-management planning basins (34, which includes Elk Creek; 36, which includes Lake Altus; and 42, which includes part of the Elm Fork Red River; fig. 2) are in the North Fork Red River watershed. Surface-water resources are fully allocated in water-management planning basins 34, 36, and 42, and physical and chemical resource limitations in these basins were projected to cause surface-water shortages by 2020, 2050, and 2050, respectively (OWRB, 2012b, p. 116–118). Water-management planning basin 36, which encompasses a portion of the North Fork Red River aquifer upgradient from Lake Altus, was identified as the Oklahoma water-management planning basin most susceptible to shortages in alluvium and terrace groundwater by 2060. Water-management planning basin 42, which encompasses a portion of the North Fork Red River aquifer along the Elm Fork Red River, was identified as the second most susceptible to shortages in alluvium and terrace groundwater by 2060.

Climate Characteristics and Trends

The climate of the North Fork Red River aquifer study area is classified as humid subtropical (Kottek and others, 2006). Daily maximum temperatures usually exceed 100 degrees Fahrenheit (°F) for 20 to 35 days in summer, and the maximum recorded temperature was 120 °F at Altus in 1936 (Oklahoma Climatological Survey, 2015a). The period of greatest monthly precipitation usually occurs in May and June, and a secondary period of greater precipitation often occurs in September and October. Monthly precipitation usually is least in the winter months when snow totals of 1 to 10 inches (in.) are common (Oklahoma Climatological Survey, 2015a). Winds average about 10 miles per hour annually and are prevailingly from the south and southeast (Oklahoma Climatological Survey, 2015a).

Historical data from selected climate stations in southwest Oklahoma (climate division 7) have been quality assured, bias-corrected, and summarized monthly as part of the U.S. Historical Climatology Network (National Climatic Data Center, 2015; fig. 3, table 3). The monthly summarized data were used to calculate and graph annual and monthly temperature and precipitation statistics for the study area, and the data from some individual climate stations (National Climatic Data Center, 2015; Oklahoma Climatological Survey, 2015a) were summarized to show the variability of these statistics within the study area. A lowess smooth line (Cleveland, 1979) was used to delineate periods of below- and above-average precipitation.

The mean annual precipitation in the study area for the period of record 1895–2015 was about 27.6 inches per year (in/yr) (fig. 3*A*, table 3). A relatively long dry period occurred in 1930–80 with 33 of 51 years (65 percent) recording below-average precipitation. Within this dry period, years were grouped into four 5- to 12-year spans of below-average precipitation punctuated by 3- to 5-year spans of above-average precipitation. The period 1981–2000 was a historically unprecedented wet period in which 16 of 20 years (80 percent) had above-average precipitation (fig. 3*A*). The period 2010–14 was noteworthy as an exceptionally dry period.

The mean annual temperature in the study area for the period of record 1895–2015 was about 61.2 °F (fig. 3*B*, table 3). Mean annual temperatures increase to the southeast from about 60 °F at the Erick climate station in Beckham County to about 62 °F at the Altus Dam climate station in Kiowa County.

The mean annual temperature was about 0.4 °F greater and the mean annual precipitation was about 1.6 in/yr greater for the study period 1980–2013 compared to the period of record (table 3). Over the study period, the annual mean precipitation was greater than the mean for the period of record in 20 of 34 years. The 20-year wet period 1981–2000 and the 17-year (and continuing) warm period 1996–2013 were unprecedented in the period of record (fig. 3). The mean monthly precipitation for the study period 1980–2013 was greatest (4.2 in.) in May and least (1.1 in.) in January (fig. 4*A*). The mean monthly temperature for the study period 1980–2013 was greatest (84 °F) in July and least (39 °F) in January (fig. 4*B*).

Multi-year to decadal droughts are not uncommon for the study area. The 1929–41 (“Dust Bowl”), 1952–56, and 1961–72 drought periods were among the most severe in the 20th century; a shorter and less severe 1976–81 drought period also occurred in the late 20th century. The 21st century began with the drought periods 2002–06 and 2010–14 (Tortorelli, 2008; Shivers and Andrews, 2013) (fig. 3*A*). The most severe of these droughts developed from extended periods of below-average precipitation paired with above-average temperature. The precipitation and temperature characteristics of the 1952–56 drought period were similar to those of the 2010–14 drought period, and the effects of these drought periods on aquifer water levels also were comparable (fig. 3).

Climate models used by the Climate Model Intercomparison Program predict about a 5-°F increase in annual minimum and maximum temperatures in the study area between the historical period 1950–2005 and the future period 2050–74 (Alder and Hostetler, 2013). These climate models also predict a slight decrease in mean annual precipitation between the historical period 1950–2005 and the future period 2050–74 (Alder and Hostetler, 2013). If these predictions come to pass, they are likely to cause increased water demand, especially for irrigation; more water would be required to grow the same crops under the predicted warmer and drier climate conditions.

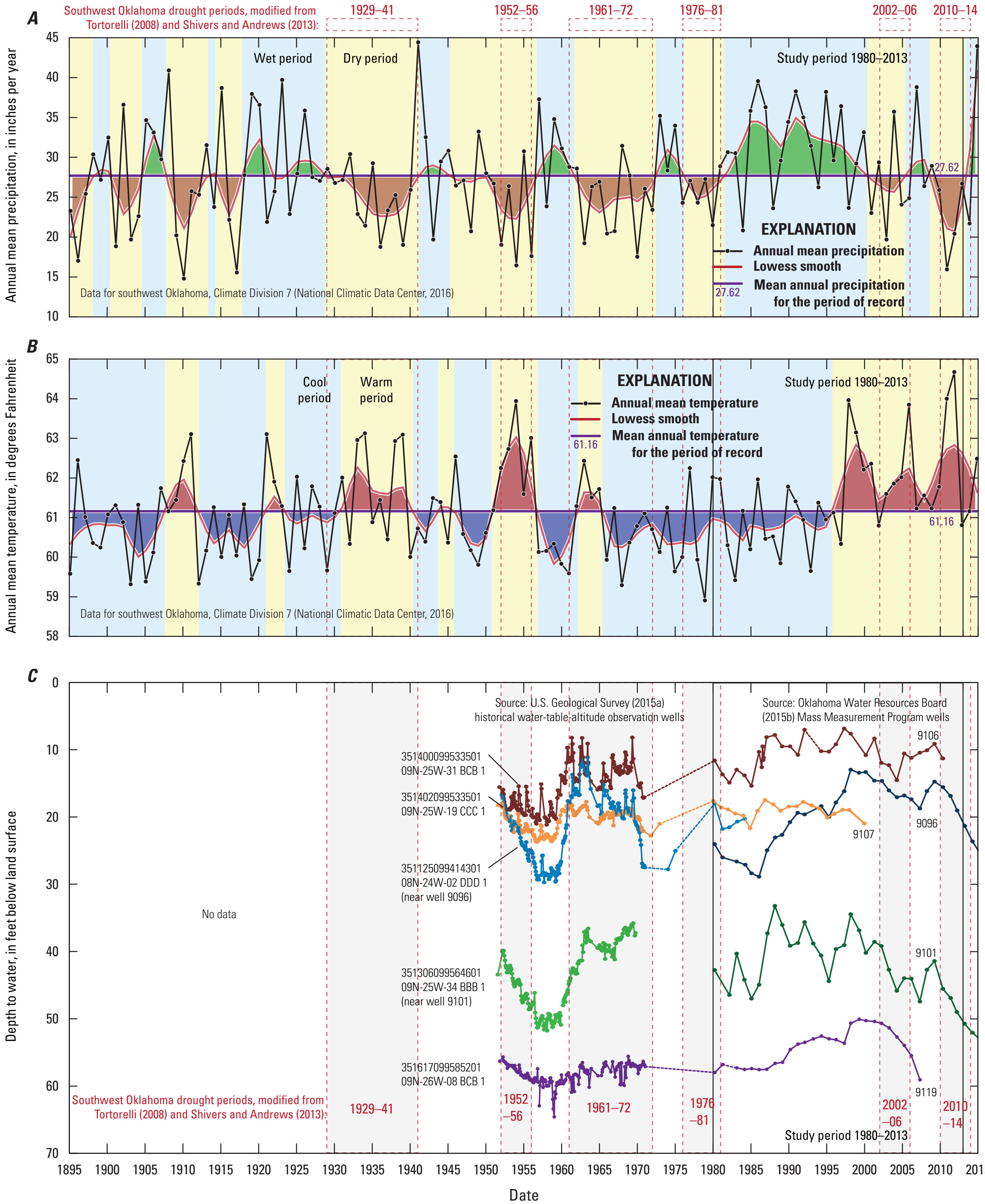


Figure 3. *A*, Annual mean precipitation; *B*, annual mean temperature; and *C*, depth to water in selected wells, southwest Oklahoma, 1895–2015.

Table 3. Mean annual precipitation and mean annual temperature data summaries from selected regions and stations in and near the North Fork Red River aquifer study area, southwest Oklahoma.

[°F, degrees Fahrenheit; --, data not available or not used]

Region or station number	Region or station name	Period of record[1]	Number of years	Mean annual precipitation (inches per year)			Mean annual temperature (°F)		
				1947–79	1980–2013	Period of record	1947–79	1980–2013	Period of record
Climate region summary (National Climatic Data Center, 2015)									
Climate Division 7	Southwest Oklahoma	1895–2015	121	26.39	29.20	27.62	60.86	61.56	61.16
Climate station summary (Oklahoma Climatological Survey, 2015a)									
340184	Altus Dam	1945–2013	62	22.42	28.74	26.84	62.55	62.04	62.31
342944	Erick	1904–2013	96	22.40	25.29	24.40	60.10	60.80	60.16
346035	Moravia	1941–2013	68	22.63	26.38	25.53	--	--	--
347952	Sayre[2]	1936–2013	77	21.35	25.59	23.98	61.60	--	61.14
348299	Snyder	1906–2011	77	22.73	25.76	26.84	--	--	--
349668	Willow	1980–2013	34	--	27.30	27.30	--	--	--

[1]Period of record may not be continuous.

[2]Station not in aquifer boundary, used for temperature data only.

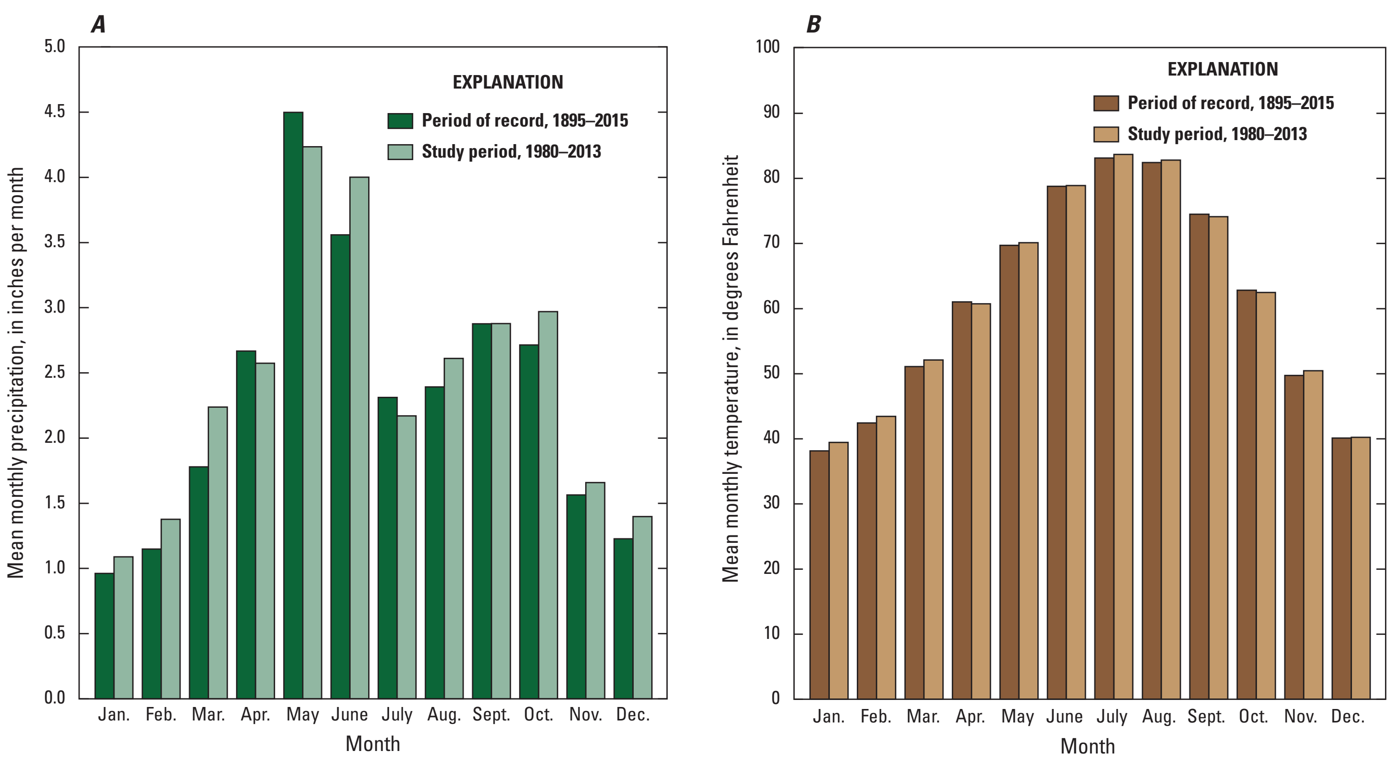


Figure 4. *A*, Mean monthly precipitation and *B*, mean monthly temperature, southwest Oklahoma, 1895–2015 and 1980–2013. Data for southwest Oklahoma, Climate Division 7 (National Climatic Data Center, 2015).

Land Cover

During the period 2010–15, shrubs/range and crops each covered about a third of the land overlying the North Fork Red River aquifer (Fry and others, 2011; National Agricultural Statistics Service, 2016; fig. 5). Grass/pasture composed most of the remaining third (fig. 5), though scattered wooded (forest) areas and towns (developed areas) including Texola, Erick, Carter, Willow, Snyder, and Mangum also overlie the aquifer. Other towns, including Elk City, Sayre, Lone Wolf, and Granite, which mostly do not overlie the aquifer, draw water from the North Fork Red River aquifer for public supply.

Winter wheat (72.9 percent of cropland by area) was the dominant crop type overlying the North Fork Red River aquifer during the period 2010–15. Cotton (7.7 percent), rye (5.6 percent), alfalfa (3.3 percent), and sorghum (1.7 percent) accounted for at least 1 percent of cropland by area, and other crops, including peanuts (1.1 percent) and barley (1.0 percent), accounted for 4.6 percent of cropland by area (fig. 5). About 4 percent of cropland by area was fallow or idle. Though crop types may change with economic and hydrologic factors, the areal percentages of total crop land cover and individual crop types did not change much over the period 2010–15 (National Agricultural Statistics Service, 2016).

The frost-free growing season is about 200 days and lasts from mid-April to late October (National Agricultural Statistics Service, 2015; Oklahoma Climatological Survey, 2015b). Most crops including corn, cotton, peanuts, sorghum, soybeans, sunflowers, and canola are grown in this season, but winter wheat is planted in the early fall and harvested in June. The length of the growing season and the water requirement for crops in a given year vary with the climate characteristics of that year (Masoner and others, 2003).

Groundwater-Use Characteristics and Trends

The OWRB permits and regulates groundwater use, with the exception of groundwater use of less than 5 acre-ft/yr for domestic and agricultural purposes and groundwater use for irrigation of less than 3 acres of land. Groundwater-use data for Oklahoma are self-reported annually to the OWRB by permitted users, and the OWRB staff reviewed groundwater-use data described in this report to ensure the quality and completeness of the data. In 2013, 412 long-term temporary and prior-right groundwater-use permits were active for the North Fork Red River aquifer (OWRB, 2015b) (fig. 6). Each permit may include multiple wells that share the allocated groundwater use. Most groundwater-use permits were allocated for irrigation and public supply (fig. 7, table 4). Groundwater-use permits for irrigation were tied to wells and land areas that were relatively evenly distributed across the aquifer; most groundwater-use permits for public supply, in contrast, were tied to wells and land areas concentrated south of Sayre in Beckham County and northeast of Willow in Greer County (fig. 6).

The mean annual reported groundwater use was 15,279 acre-ft/yr for the period of record 1967–2013 and 15,859 acre-ft/yr for the study period 1980–2013 (table 4; Christopher Neel, OWRB, written commun., 2015). The year with the greatest reported groundwater use (26,714 acre-feet [acre-ft]) was 2011. Below-average precipitation and above-average temperatures in that year likely contributed to the increased groundwater use. The year with the least reported groundwater use (9,875 acre-ft) was 1975, and the year with the least reported groundwater use per permit (about 77 acre-ft) was 1997; both 1975 and 1997 were years with above-average precipitation (fig. 3). The groundwater-use period of record 1967–2013 was separated into three smaller periods (1967–85, 1986–97, and 1998–2013) to illustrate trends in the reported groundwater use. The mean annual reported groundwater use decreased from 13,503 to 12,246 acre-ft/yr from the period 1967–85 to the period 1986–97, and then increased from 12,246 to 19,429 acre-ft/yr from the period 1986–97 to the period 1998–2013 (table 4, fig. 7).

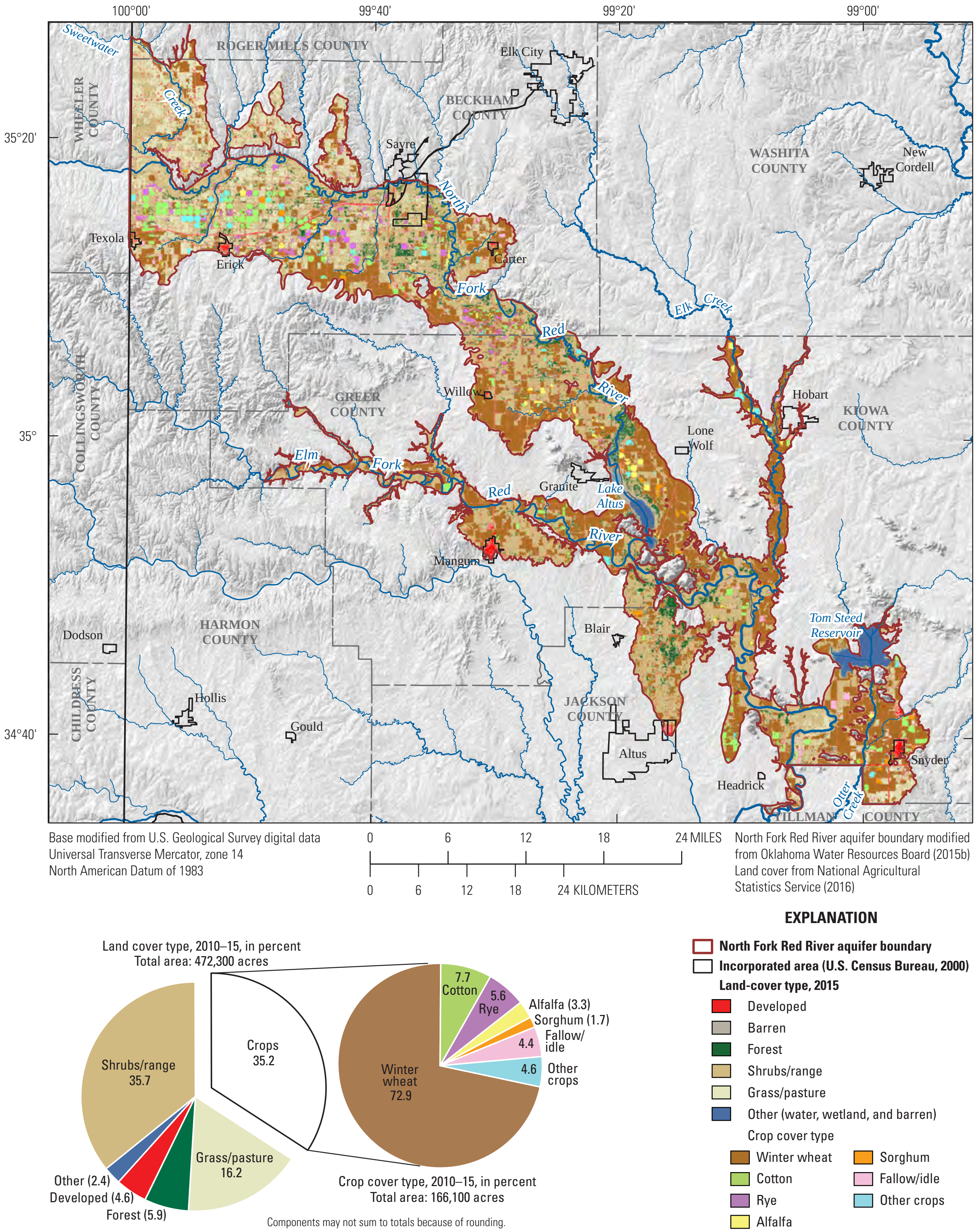


Figure 5. Land and crop cover over the North Fork Red River aquifer, southwest Oklahoma, 2010–15.

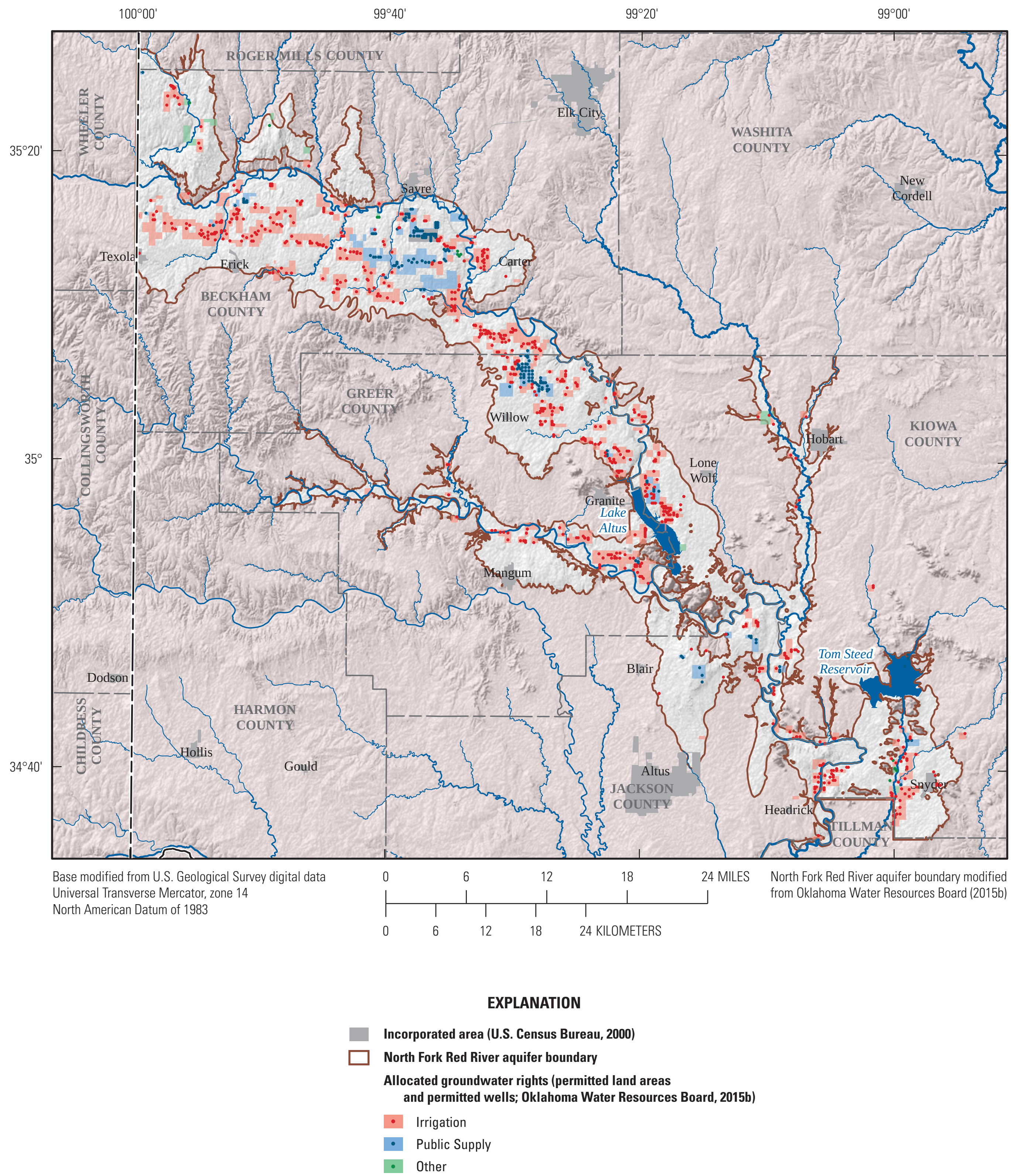


Figure 6. Land areas and wells permitted for groundwater use from the North Fork Red River aquifer, southwest Oklahoma, 2015.

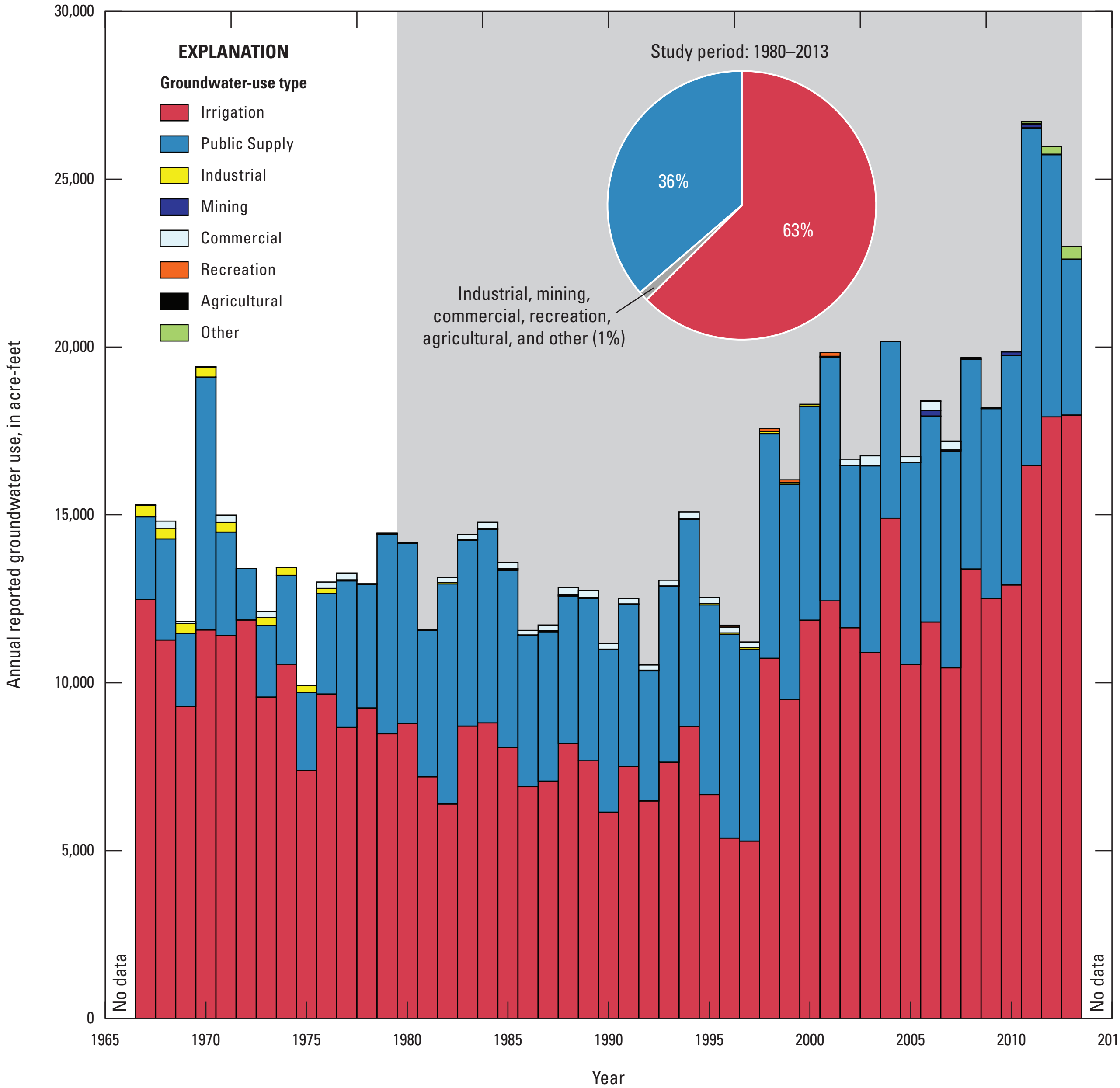


Figure 7. Annual reported groundwater use by type from the North Fork Red River aquifer, 1967–2013. Data from the Oklahoma Water Resources Board water-use database (Christopher Neel, Oklahoma Water Resources Board, written commun., 2015).

Table 4. Mean annual reported groundwater use by type for the North Fork Red River aquifer, 1967–2013.

[Data from Oklahoma Water Resources Board water-use database (Christopher Neel, Oklahoma Water Resources Board, written commun., 2015); PWS, public water supply; values in parentheses are percentage of total groundwater use]

Period	Mean annual reported groundwater use, in acre-feet per year (and percentage), by type[1]								
	Irrigation	PWS	Industrial	Mining	Commercial	Recreation	Agriculture	Other	Total
1967–85	9,446	3,828	139	0	93	0	0	0	13,503
	(70.0)	(28.3)	(1.0)	(0.0)	(0.7)	(0.0)	(0.0)	(0.0)	(100)
1986–97	6,993	5,046	30	0	172	5	0	0	12,246
	(57.1)	(41.2)	(0.2)	(0.0)	(1.4)	(0.0)	(0.0)	(0.0)	(100)
1998–2013	12,872	6,389	16	30	74	17	4	41	19,429
	(66.3)	(32.9)	(0.1)	(0.2)	(0.4)	(0.1)	(0.0)	(0.2)	(100)
Study period, 1980–2013	9,928	5,754	24	14	115	10	2	20	15,859
	(62.6)	(36.3)	(0.2)	(0.1)	(0.7)	(0.1)	(0.0)	(0.1)	(100)
Period of record, 1967–2013	9,980	5,096	69	10	107	7	1	14	15,279
	(65.3)	(33.4)	(0.5)	(0.1)	(0.7)	(0.0)	(0.0)	(0.1)	(100)

[1]Excludes water use of less than 5 acre-feet per year for domestic and agricultural purposes and water use for irrigation of less than 3 acres of land.

Though three of the four greatest individual users of groundwater were municipalities (Elk City, Mangum, and Sayre), irrigation was the major groundwater-use type for the period of record 1967–2013. Irrigation accounted for about 70 percent of reported groundwater use for the period 1967–85, about 57 percent of reported groundwater use for the period 1986–97, and about 66 percent of reported groundwater use for the period 1998–2013 (fig. 7, table 4). Annual irrigation use averaged 9,446 acre-ft/yr for the period 1967–85, 6,993 acre-ft/yr for the period 1986–97, and 12,872 acre-ft/yr for the period 1998–2013 (table 4). Reported groundwater use for irrigation notably increased in 1998 and generally continued to increase through 2013 (fig. 7). The number of reporting permits also notably increased in 1998 and continued to increase during the period 1998–2013. These increases in reported groundwater use and the number of reporting permits likely resulted from decreased precipitation in 1998 as compared to the 3 previous years. Sustained increases in reported groundwater use for the period 1998–2013 also coincided with and may be related to a period of above-average annual mean temperature (1996–2015, fig. 3*B*). Most of the increase in reported groundwater use for the period 1998–2013 was for irrigation in Beckham County which increased from about 30 to 50 percent of reported groundwater use in that period (fig. 8).

Yields of wells completed in the North Fork Red River aquifer vary with location and depth. Well yields reported for irrigation, public-supply, and domestic plus non-irrigation agricultural use were mostly 100–450, 150–250, and 10–25 gallons per minute (gal/min), respectively (OWRB, 2015b; USGS, 2015a; table 5, fig. 9). Irrigation and public-supply wells with the greatest reported yields (greater than or equal to 800 gal/min) generally were located in west-central Beckham County north of Erick, Okla., and near Lake Altus east of Granite, Okla. Wells with the greatest reported yields generally were greater than 150 feet (ft) in depth.

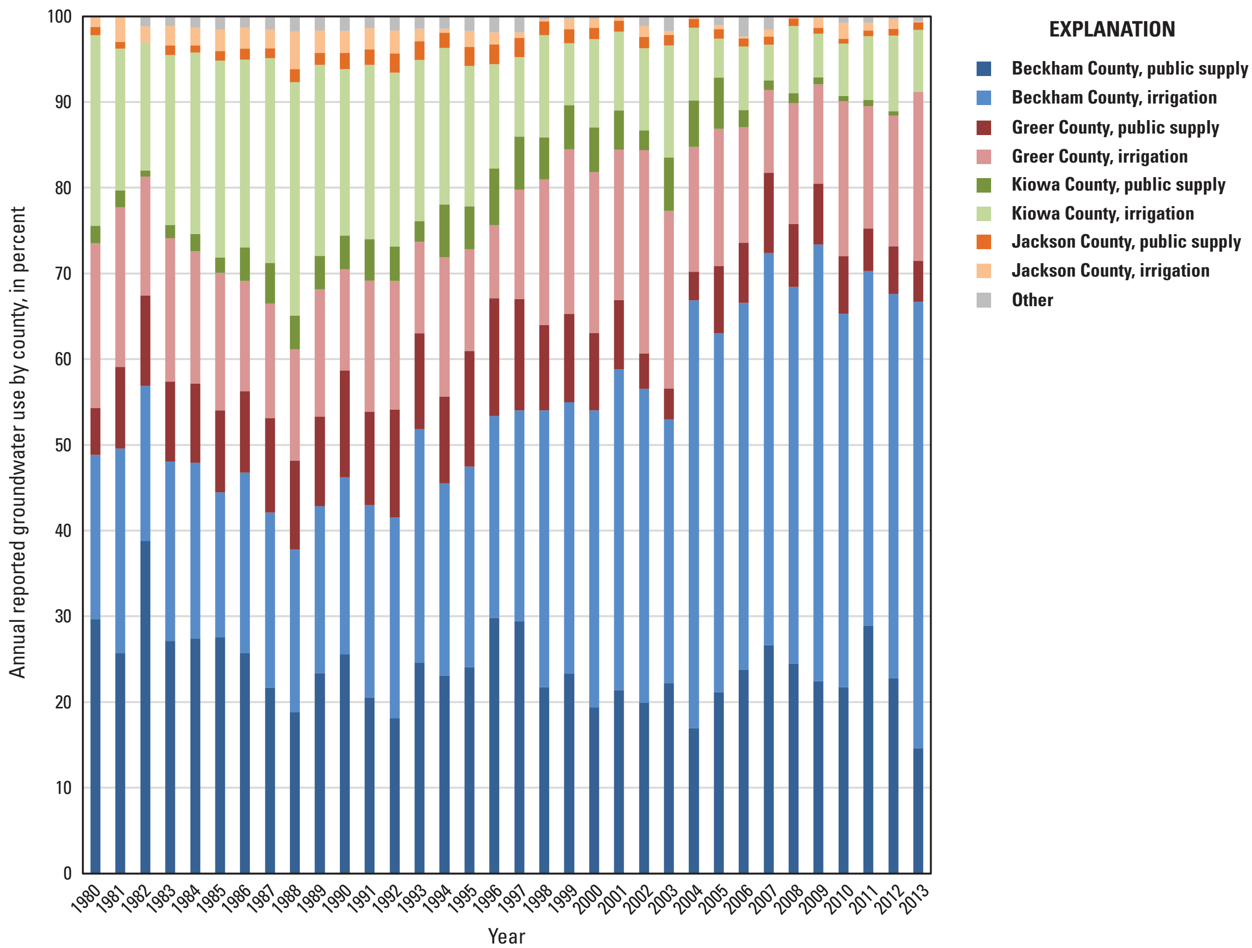


Figure 8. Annual reported groundwater use by county from the North Fork Red River aquifer, 1980–2013. Data from the Oklahoma Water Resources Board water-use database (Christopher Neel, Oklahoma Water Resources Board, written commun., 2015).

Table 5. Statistical summary of reported yields of wells completed in the North Fork Red River aquifer, 1936–2015.

[Data compiled from the Oklahoma Water Resources Board (2015b) and U.S. Geological Survey (2015a)]

Water-use type	Number of wells with reported yield values	Statistics for reported well-yield values, in gallons per minute[1]					
		Minimum	25th percentile	Median	75th percentile	Maximum	Mean
Irrigation	500	15	100	250	450	1,500	333
Public supply	126	15	150	198	250	900	215
Industrial and mining	55	5	35	60	70	1,200	94
Domestic and agriculture (non-irrigation)	682	1	10	15	25	300	25

[1]Well-yield values less than 1 gallon per minute were excluded.

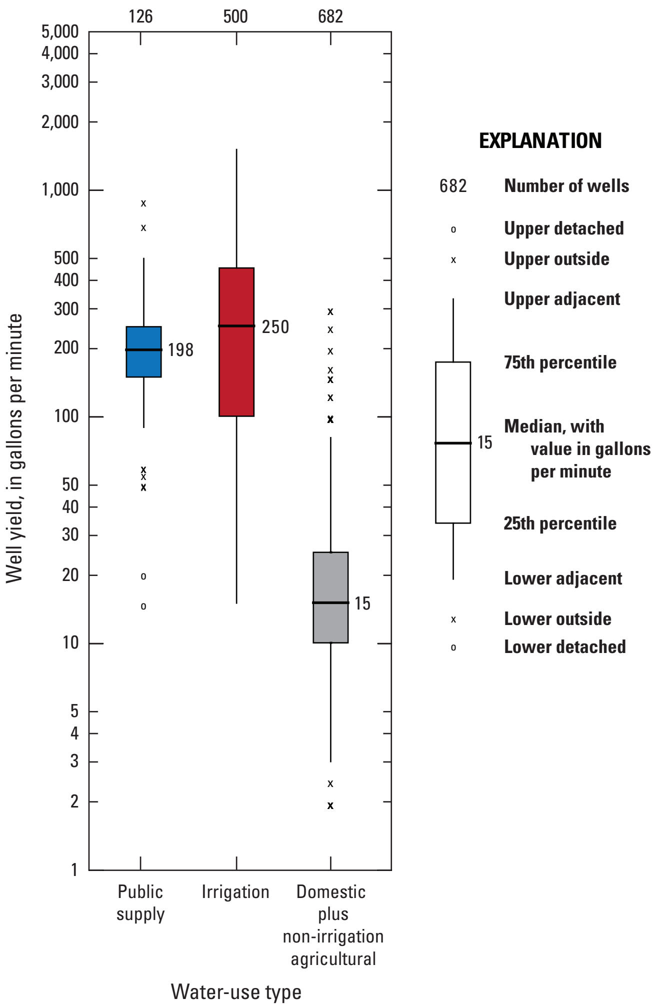


Figure 9. Statistics for reported yields of wells completed in the North Fork Red River aquifer. Data compiled from the Oklahoma Water Resources Board (2015b) and the U.S. Geological Survey (2015a).

Streamflow Characteristics and Trends

According to data collected at the Carter streamgage (07301500), the North Fork Red River upstream from Lake Altus has become increasingly dependent on base flow since the beginning of the period of record in the late 1930s (Smith and Wahl, 2003; Esralew and Lewis, 2010). Though annual precipitation in west central Oklahoma (climate division 4; National Climatic Data Center, 2015) significantly increased over the streamgage period of record, no trends in annual streamflow were apparent at the Carter streamgage (07301500). Annual peak streamflow and annual number of zero-flow days at this streamgage significantly decreased over the period of record while annual base flow and annual base-flow index significantly increased over the period of record (Esralew and Lewis, 2010). The causes of these trends in annual streamflow statistics are not clear. Increasing trends in base flow could be related to changes in irrigation practices that may promote artificial recharge of applied water and contribute additional base flow to streams. Another possible cause of these trends in streamflow statistics is the construction of impoundments (Kennon, 1966) in the North Fork Red River watershed. Though no large impoundments overlie the North Fork Red River aquifer upstream from the Carter streamgage (07301500), several floodwater-retarding structures were constructed on the North Fork Red River tributaries Timber Creek (in the early 1960s) and McClellan Creek (in the 1980s) (U.S. Army Corps of Engineers, 2015a) (fig. 2). Floodwater-retarding structures were designed to impound runoff and slowly release it downstream; therefore, these structures could contribute to the decreasing trends in annual peak streamflow and annual number of zero-flow days as well as the increasing trends in annual base flow and annual base-flow index. Whatever the cause, these trends in annual streamflow statistics are important considerations for water resources planning for irrigation and public-supply surface-water use at Lake Altus.

Groundwater Quality

The groundwater quality in some parts of the North Fork Red River aquifer may limit groundwater use for some purposes. Groundwater-quality data for the North Fork Red River aquifer were collected between July 28, 2014, and August 13, 2014, as part of the OWRB Groundwater Monitoring and Assessment Program (OWRB, 2015c). Groundwater was sampled from 20 wells; 14 were in Beckham County, 5 were in Greer County, and 1 was in Kiowa County (fig. 10). The groundwater samples were analyzed for selected parameters including physical properties (specific conductance, temperature, and pH), major ions, nutrients, and trace metals (table 6). Total dissolved solids (TDS) concentrations of groundwater ranged from 295 to 3,520 milligrams per liter (mg/L) with a mean concentration of 895 mg/L and a median concentration of 543 mg/L (table 6). The U.S. Environmental Protection Agency (2017) has established a secondary drinking-water standard of 500 mg/L for TDS, but the State of Oklahoma designates a domestic beneficial use for groundwater with TDS concentrations below 3,000 mg/L (OWRB, 2015c). Specific conductance values ranged from 508 to 4,830 microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C) with a mean value of 1,340 µS/cm and a median value of 862 µS/cm. All groundwater samples from the North Fork Red River aquifer were classified as hard (hardness concentration exceeded 180 mg/L). Nitrate plus nitrite was the only parameter with measured concentrations exceeding a U.S. Environmental Protection Agency (2017) primary drinking-water standard (10 mg/L). Nitrate plus nitrite concentrations exceeded this standard in six samples; the maximum measured nitrate plus nitrite concentration was 19.4 mg/L, the median was 7.95 mg/L, and the 75th percentile was 10.73 mg/L.

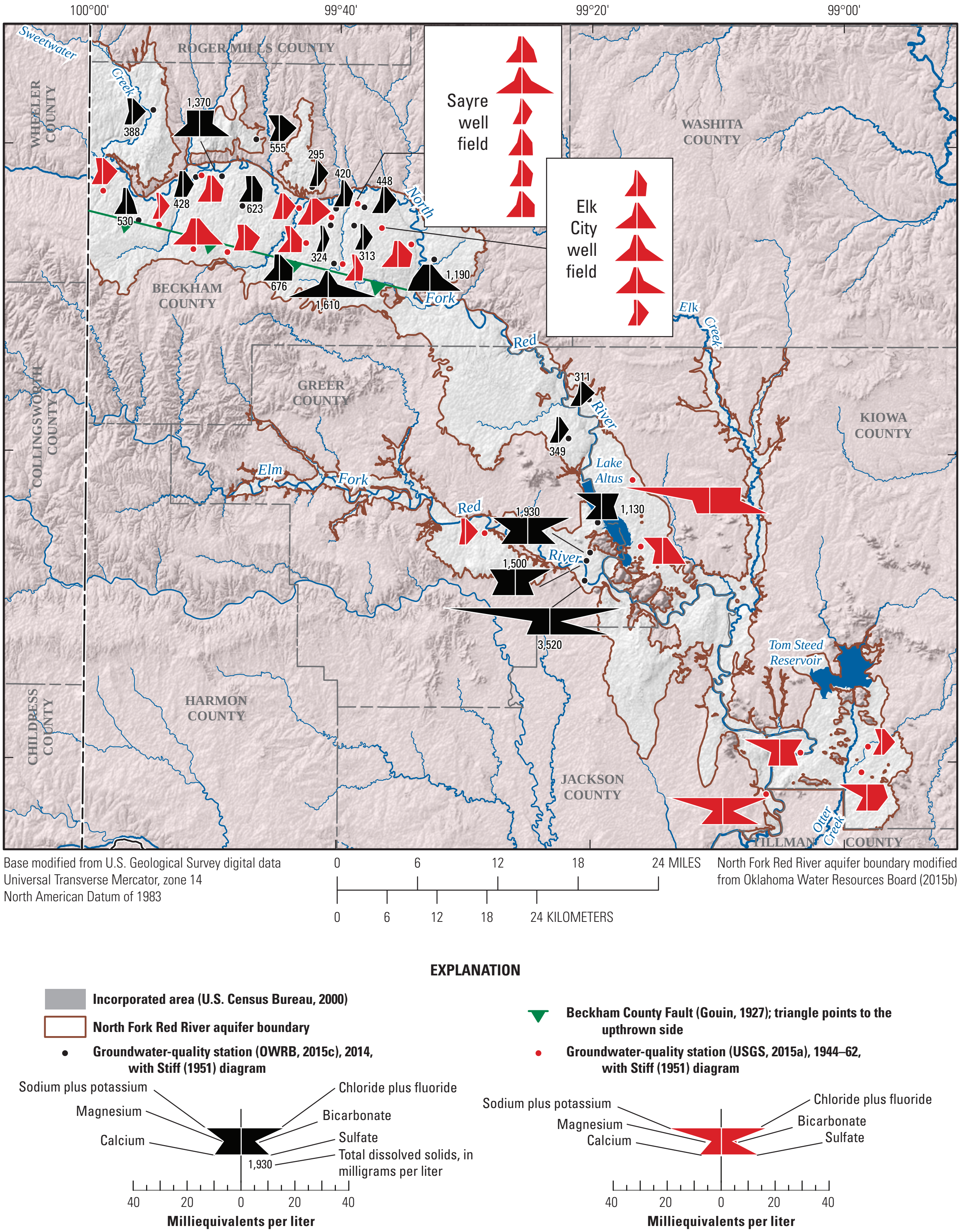


Figure 10. Groundwater-quality stations in the North Fork Red River aquifer, southwest Oklahoma, 1944–62 and July–August 2014.

Table 6. Statistical summary of groundwater-quality data from 20 wells completed in the North Fork Red River aquifer, July–August 2014.

[All data are from OWRB (2015c). µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; <, less than analytical detection limit; µg/L, micrograms per liter; --, not calculated because more than 10 analyses were below analytical detection limit; +, includes samples with different analytical detection limits]

Water-quality constituent	Units of measurement	Number of samples less than detection limit	Mean of detections	Minimum	Percentile			Maximum
					25	50	75	
Specific conductance	µS/cm at 25 °C	0	1,340	508	631	862	1,840	4,830
Temperature	°C	0	21.5	18.9	20.1	21.1	22.2	30.6
pH	standard units	0	7.06	6.85	6.99	7.06	7.16	7.26
Alkalinity (as $CaCO_3$)	mg/L	0	225	134	199	232	252	331
Total dissolved solids	mg/L	0	895	295	379	543	1,230	3,520
Hardness	mg/L	0	487	187	265	342	794	1,180
Calcium	mg/L	1	121	53.2	71.8	94.9	172	312
Magnesium	mg/L	1	34.6	10.3	17	23	46.9	81.6
Sodium	mg/L	1	114	4.4	23.9	37.4	102	905
Potassium	mg/L	2	2.56	<0.5	1.5	2.1	3.2	9.3
Bicarbonate	mg/L	0	277	165	244	286	310	408
Sulfate	mg/L	2	268	<10	38.4	142	383	1,090
Chloride	mg/L	5	138	<10	11.6	24.8	79.8	981
Fluoride	mg/L	8	0.295	<0.2	<0.2	0.28	0.42	0.74
Bromide	µg/L	1	593	<100	265	329	613	1,960
Silica	mg/L	0	23.2	9.95	13.9	24.9	27.4	43.7
Nitrate plus nitrate (as nitrogen)	mg/L	0	8.29	0.83	5.58	7.95	10.73	19.4
Phosphorous	µg/L	5	0.029	<0.005	0.015	0.023	0.042	0.103
Aluminum+	µg/L	20	--	<50	<50	<50	<50	<50
Arsenic+	µg/L	7	1.92	<1.0	--	1.6	2.6	7.6
Barium+	µg/L	0	131	10.8	38.6	89	173	577
Boron+	µg/L	1	193	<20	57.2	97.6	178	1,460
Cadmium	µg/L	20	--	<5	<5	<5	<5	<5
Chromium	µg/L	20	--	<5	<5	<5	<5	<5
Copper	µg/L	17	--	<5	<5	<5	<5	51.7
Iron+	µg/L	19	--	<50	<50	<50	<50	32.9
Lead+	µg/L	20	--	<10	<10	<10	<10	<10
Manganese+	µg/L	15	--	<5.0	<5.0	<5.0	5.5	7.6
Molybdenum+	µg/L	19	--	<5.0	<5.0	<5.0	<5.0	12.8
Uranium	µg/L	5	4.1	<1	1.6	3.4	5.1	12.9
Vanadium+	µg/L	6	9.8	<5.0	<5.0	7.9	14.2	29.3
Zinc+	µg/L	12	--	<5.0	<5.0	4.3	16.2	91.7

The 2014 OWRB major-ion groundwater-quality data for each site were graphed on Stiff (1951) diagrams and mapped on figure 10. Historical (1944–62) Stiff diagrams showing available groundwater-quality data from the USGS National Water Information System (NWIS) database (USGS, 2015a) were added to figure 10 for visual comparison. The 2014 samples from Beckham County mostly were below the mean and median TDS values, indicating relatively fresh groundwater in those areas that may have lower groundwater residence times, possibly near zones of greater recharge. Stiff diagram distribution for these sites displayed low sodium, potassium, magnesium, chloride, and sulfate levels, with small spikes in calcium and bicarbonate, possibly derived from the dissolution of calcium-carbonate caliche. Three samples from Beckham County had greater TDS, calcium, and sulfate signatures, likely caused by dissolution of gypsum from the Cloud Chief or Blaine Formations (fig. 11). Of the six 2014 samples from Greer and Kiowa Counties, four had greater than average TDS concentrations and had high concentrations of sodium, chloride, calcium, and sulfate. These four sites are near the confluence of the Elm Fork Red River and the North Fork Red River. These increased constituent concentrations likely were from dissolution of halite and gypsum beds of the Blaine Formation of Permian age, which is exposed in the headwaters of the Elm Fork Red River watershed (figs. 11–12).

Major-ion groundwater-quality data (OWRB, 2015c; USGS, 2015a) were graphed on a Piper (1944) diagram (fig. 13) for visualization of groundwater types and mixing trends between groundwater of the North Fork Red River aquifer and the adjacent Permian bedrock. Groundwater samples from Permian bedrock units showed a downgradient transition from calcium- and sulfate-dominated water (in the Rush Springs Sandstone and Dog Creek Shale) to sodium- and chloride-dominated water (in the Flowerpot Shale and Hennessey Group). Groundwater samples from the North Fork Red River aquifer showed a similar pattern when grouped by county (fig. 13). Calcium was the dominant cation and bicarbonate was the dominant anion in most of the groundwater samples from the North Fork Red River aquifer, especially those from Beckham County (fig. 13). In some samples from Beckham County, however, sulfate was the dominant anion, which may indicate influence from gypsum-rich units in the underlying Permian bedrock. In most downgradient samples from the North Fork Red River aquifer (in Greer, Kiowa, and Jackson Counties), sodium was the dominant cation, and chloride or sulfate was the dominant anion. These groundwater samples were characteristic of samples from the Flowerpot Shale and Hennessey Group of Permian age (figs. 11–13).

System	Geologic Unit		Hydrogeologic Unit	Thickness, in feet	Description
Quaternary	Alluvium and terrace deposits (with colluvium and dune deposits)		North Fork Red River aquifer	0–250	Silt, sand, and clay deposited by North Fork and tributaries often reworked by wind; occasionally containing quartzitic gravel and slightly cemented by calcium carbonate.
Tertiary	Ogallala Formation		High Plains (Ogallala) aquifer	0–600	Brown to light tan to salmon, mostly unconsolidated clay, silt, sand, and gravel with zones of caliche near the surface.
Permian	Quartermaster Formation	Elk City Sandstone	Elk City aquifer	0–400	Reddish-brown, fine-grained sandstone with silt and clay, weakly cemented by iron oxide, calcium carbonate, and gypsum.
		Doxey Shale			Reddish-brown, silty shale and siltstone.
	Cloud Chief Formation			0–400	Reddish-brown to orange-brown shale interbedded with siltstone and sandstone; some dolomite and much gypsum near base.
	Whitehorse Group	Rush Springs Formation	Western Oklahoma minor aquifer	0–390	Red to pink, massive, fine-grained, gypsiferous sandstone.
		Marlow Formation			Orange-brown, fine-grained sandstone and siltstone with some dolomite and gypsum.
	El Reno Group	Dog Creek Shale		0–80	Red, brown, and green gypsiferous shales with several beds of siltstone, sandstone, and dolomite.
		Blaine Formation		0–140	Beds of white massive gypsum and thin beds of gray medium-grained dolomite or dolomitic limestone separated by well-defined units of red and green shale.
		Flowerpot Shale		0–150	Red, brown, and maroon blocky shales with green and gray shales and thin beds of gypsum and dolomite; Satin-spar gypsum occurs throughout.
		Duncan (San Angelo) Sandstone		0–40	Grayish-brown to buff, indurated, highly cross-bedded, ripple-marked, nonfossiliferous, silty to very fine-grained dolomitic sandstone with interbedded shale.
	Hennessey Group			0–500	Yellowish gray to buff unfossiliferous shale with calcareous fine-grained siltstone.
Cambrian	Wichita Granite Group				Igneous rocks of Wichita Uplift.

Modified from Smith and Wahl, 2003

Figure 11. Stratigraphic chart showing surficial geologic and hydrogeologic units of the North Fork Red River aquifer study area, southwest Oklahoma.

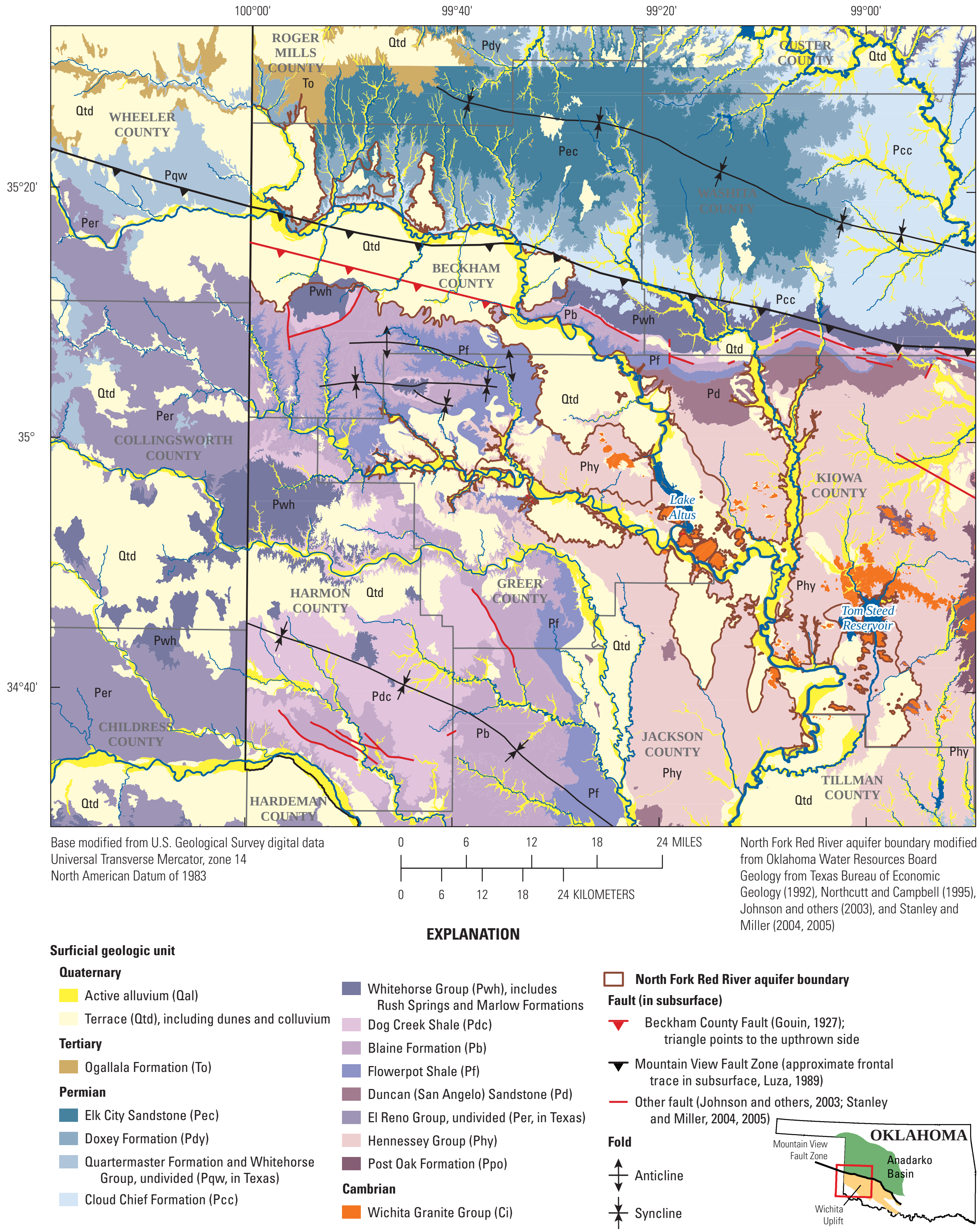


Figure 12. Surficial geologic units and major structural features of the North Fork Red River aquifer study area, southwest Oklahoma.

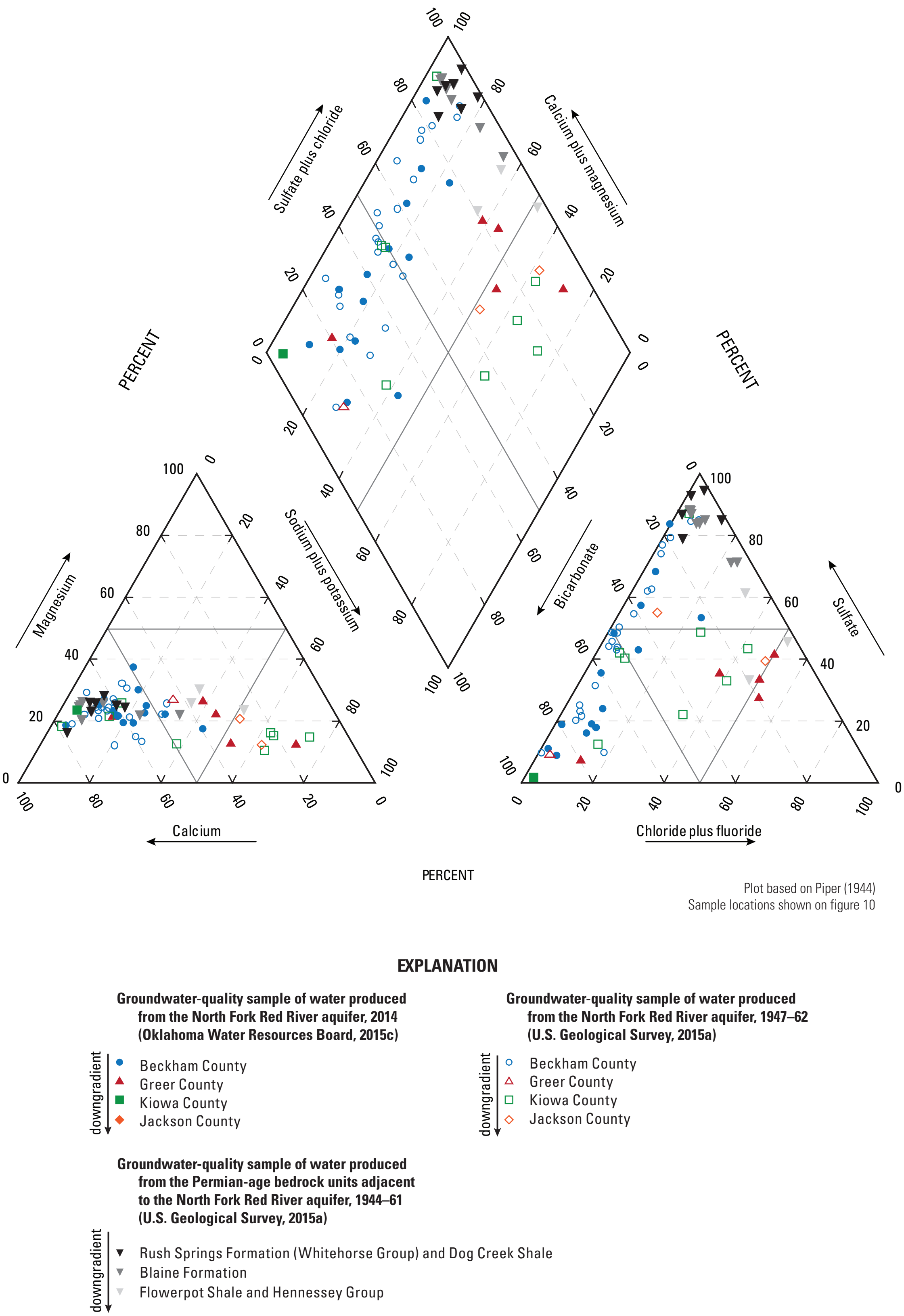


Figure 13. Piper diagram showing groundwater-quality samples of water produced from the North Fork Red River aquifer, 1944–62 and July–August 2014.

Hydrogeology of the North Fork Red River Aquifer

In northern Beckham County, the North Fork Red River parallels the Mountain View Fault Zone (fig. 12), which was most active in the late Paleozoic but has been relatively dormant in recent geologic time (Johnson, 1989). The Mountain View Fault Zone separates the Wichita Uplift and the southern limb of the Anadarko Basin, a broad syncline with an axis trending west-northwest to east-southeast (fig. 12). In southeastern Beckham County, the North Fork Red River turns south and then southwest as it traverses the Wichita Uplift (fig. 12). The Paleozoic sedimentary rocks of the Anadarko Basin can be tens of thousands of feet thick. The Paleozoic sedimentary rocks of the Wichita Uplift are only hundreds to thousands of feet thick and are not present where igneous rocks outcrop.

Quaternary Alluvium and Terrace

The Quaternary alluvium and terrace deposits (figs. 11–12) that compose the North Fork Red River aquifer were transported primarily by water and range from clay to gravel in size. The terrace material includes windblown deposits (Burton, 1965) that form dunes as high as 30 ft in the adjacent deposits of the Tillman Terrace aquifer (Barclay and Burton, 1953). Narrow rings of boulder-size gravel formed adjacent to the slopes of granitic mountains and coalesced with terrace deposits, but these colluvial (talus) deposits are a minor component of the aquifer in terms of geographic extent (Stanley and Miller, 2004). Discontinuous and poorly sorted layers of clay, silt, sand, and gravel generally become coarser with depth in the alluvium and terrace deposits, and quartzite gravels often occur near the contact with underlying bedrock (Barclay and Burton, 1953; Merritt, 1958; Burton, 1965; Hollowell, 1965a, b). Zones of calcium-carbonate caliche are common in the aquifer, especially near the land surface in Beckham County (Burton, 1965).

Bedrock Units

Tertiary Ogallala Formation

Strata of the Ogallala Formation outcrop in the far northwest part of the study area (figs. 11–12). The Ogallala Formation is composed of gravel, sand, silt, and clay sediments loosely held together by calcium carbonate cement which locally forms layers of caliche (Belden and Osborn, 2002). These sediments were eroded from the ancestral Rocky Mountains and were deposited in alluvial fans that coalesced to form a large piedmont (Gutentag and others, 1984). Strata of the Ogallala Formation may underlie the Quaternary alluvium and terrace deposits north of the North Fork Red River in the vicinity of Sweetwater Creek in northwest Beckham County. The extent of subcrop areas of the Ogallala Formation is not well defined because the loosely consolidated materials of the Ogallala Formation, especially as found in drill cuttings, resemble those of the overlying alluvium and terrace deposits.

Permian Bedrock Units

Mesozoic sedimentary rocks are absent, and Paleozoic (Permian) bedrock units underlie most of the Quaternary alluvium and terrace deposits in the study area (figs. 11–12). The Permian bedrock units (often referred to as red beds) generally are fine grained and are composed of red to orange-brown shale, siltstone, and fine sandstone interbedded with dolomite and gypsum (Stanley and Miller, 2004, 2005). The Permian bedrock units in Beckham County generally are coarser grained than Permian bedrock units in other parts of the study area and are dominated by the Elk City Sandstone and Doxey Shale (known as the Quartermaster Formation, undivided, in Texas), Cloud Chief Formation, and Whitehorse Group (Stanley and Miller, 2004, 2005) (figs. 11–12). Compared with the overlying Quaternary alluvium and terrace deposits, these Permian bedrock units generally act as barriers to groundwater flow, though some members of these units are minor aquifers in the study area. The most notable of these members is the youngest member of the Whitehorse Group, the Rush Springs Formation, which constitutes the Rush Springs aquifer to the east of the study area (fig. 11). Stratigraphically below the Whitehorse Group are the Dog Creek Shale, Blaine Formation, Flowerpot Shale, and Duncan (San Angelo) Sandstone, collectively known as the El Reno Group of Permian age (figs. 11–12). These mostly fine grained clastic and evaporite units underlie the Quaternary alluvium and terrace deposits in southern Beckham and northern Greer Counties (figs. 11–12) (Stanley and Miller, 2004, 2005). The shale-rich Flowerpot Shale and Hennessey Group, which generally act as barriers to groundwater flow, underlie the Quaternary alluvium and terrace deposits in the southern part of the study area south of Lake Creek (figs. 11–12) (Stanley and Miller, 2004, 2005).

Cambrian Wichita Granite Group

South and east of Lake Altus, the Quaternary alluvium and terrace deposits of the North Fork Red River aquifer are interrupted by igneous rocks of the Wichita Granite Group, the oldest unit exposed in the study area (figs. 11–12). These igneous rocks outcrop as isolated, steep-sided hills and mountains near Lake Altus and Tom Steed Reservoir. These igneous rocks are generally found at shallower depths in the Wichita Uplift than in surrounding geologic provinces (like the Anadarko Basin); however, detailed maps of depth to subsurface occurrences of igneous rocks have not been presented in publicly available literature. Igneous rocks of the Wichita Granite Group generally are assumed to be barriers to groundwater flow.

Hydrogeologic Framework

A hydrogeologic framework is a three-dimensional representation of the aquifer and the surrounding geologic units at a scale that captures the regional controls on groundwater flow. A hydrogeologic framework was developed for the North Fork Red River aquifer and included a definition of the aquifer extent and potentiometric surface, as well as a description of the textural and hydraulic properties of aquifer materials. The hydrogeologic framework was used in the construction of the numerical groundwater-flow model of the North Fork Red River aquifer described in this report.

Aquifer Extent

The geographic extent of the North Fork Red River aquifer was updated from the OWRB (2015b) by using geologic maps (Johnson and others, 2003; Miller and Stanley, 2004; Stanley and Miller, 2004, 2005) and available well (and test-hole) completion reports (OWRB, 2015b; USGS, 2015a). The aquifer extent was expanded to include (1) the mapped alluvium adjacent to Elk Creek and tributaries up to the Washita County border, (2) the mapped alluvium and selected terrace deposits adjacent to Elm Fork Red River and tributaries in Greer County, (3) the mapped alluvium and terrace deposits along Sweetwater Creek near the Roger Mills County border, and (4) relatively thin terrace deposits along the southwest margin of a large terrace lobe in northern Jackson County (fig. 12). The update of the aquifer extent also resulted in the removal of areas previously designated as North Fork Red River aquifer, most notably a lobe of elevated terrace deposits in northwest Beckham County that the geologic maps show as small discontinuous areas of terrace deposits surrounded by Permian bedrock. Some areas of the North Fork Red River aquifer, though designated as Permian bedrock on the geologic maps (fig. 12), were included in the aquifer extent because they contained permitted wells (fig. 6) thought to produce water from the North Fork Red River aquifer (based on lithologic log evidence); the most notable examples of these areas are (1) south of Tom Steed Reservoir in southern Kiowa County and (2) west of Lake Altus in eastern Greer County.

Where present, the top of the North Fork Red River aquifer was defined for this report as the land-surface altitude obtained from a 10-meter (horizontal resolution) digital elevation model (DEM) (USGS, 2015b). The base of the North Fork Red River aquifer was mapped previously by Kent (1980) from a limited number of well logs and seismic data points. The Kent (1980) map of the aquifer base was verified for this report by using test-hole completion reports from Burton (1965), Hollowell (1965a, b), and Steele and Barclay (1965). The Kent (1980) map of the aquifer base also was modified for this report to incorporate additional data collected since 1980; these additional data included well (and test hole) completion reports from the USGS (2015a) and the OWRB (2015b). Well completion reports that included drillers' lithologic logs were analyzed for the presence of terms representing consolidated Permian bedrock units (such as "redbed," "gypsum," "mudrock," and "bedrock"). The altitude associated with the first occurrence of these terms in the logs was used as the altitude of the aquifer base. The lowest altitude listed on the lithologic log was considered to be the maximum possible altitude of the aquifer base at that location for logs that did not fully penetrate the North Fork Red River aquifer. Well completion reports and lithologic logs were available for most of the aquifer extent; however, few well completion reports and lithologic logs were available near the major streams of the study area. To provide bedrock-altitude control in areas near major streams, synthetic logs were placed about every mile along the major streams overlying the aquifer and given an aquifer base altitude that was 35 ft below land surface; this 35-ft estimate was the approximate mean depth of near-stream test-hole and cross-section data reported in literature from the study area (Barclay and Burton, 1953; Burton, 1965; Hollowell, 1965a, b). As part of this investigation, four Geoprobe hydraulic profiling tool (HPT) test holes (fig. 1) were drilled along the North Fork Red River in Beckham County; these test holes reached a mean depth of about 28 ft in the aquifer, but some of those holes may have stopped at impenetrable caliche zones before reaching the full depth to bedrock.

Several faults are known to dissect the Permian bedrock units in parts of Beckham County (fig. 12); these faults were not evident in logs of the unconsolidated aquifer materials and, therefore, are not expected to affect groundwater flow. Gouin (1927) identified the Beckham County Fault (fig. 12) primarily from the thickness of North Fork Red River aquifer deposits; wells on the southern (upthrown) side of the fault penetrated about 50 ft of aquifer thickness, and wells on the northern (downthrown) side of the fault penetrated up to 200 ft of aquifer thickness. Some areas of the aquifer, usually those with few well completion reports, had less than 30 ft of aquifer thickness, and these areas were assigned a minimum aquifer thickness of 30 ft for this report. The aquifer thickness, as used in this report, is the difference between the land-surface (aquifer-top) altitude and the bedrock (aquifer-base) altitude; the aquifer saturated thickness, as used in this report, is the difference between the water-table altitude and the bedrock (aquifer-base) altitude.

Potentiometric Surface

A potentiometric surface shows the altitude at which the water level would have stood in tightly cased wells at a specified time; the potentiometric surface is usually contoured or spatially interpolated from synoptic water-table-altitude measurements in many wells across the aquifer extent. A 1979 potentiometric map from Kent (1980) was used to define the potentiometric surface around 1980. A 2013 potentiometric surface was contoured from water-level altitudes measured between December 2012 and

January 2013 in about 100 selected wells (fig. 14) by using measurement methods described in Cunningham and Schalk (2011). Those water-table-altitude measurements also were used as calibration data for the numerical groundwater-flow model described in this report (table 1; USGS 2015a). The 1979 and 2013 potentiometric surface maps did not include enough colocated water-level measurements to allow direct comparisons of water-level altitudes, but those maps are useful for showing the general directions of groundwater flow in the aquifer; groundwater flows perpendicular to potentiometric contours in the direction of decreasing contour altitudes (fig. 14). The general patterns and directions of groundwater flow were the same for the 1979 and 2013 potentiometric surface maps.

Textural and Hydraulic Properties of Aquifer Materials

The distribution and variability of textural and hydraulic properties of aquifer materials were assumed to be the primary controls on groundwater flow in the North Fork Red River aquifer. Drillers' lithologic log data were used to determine the textural properties of aquifer materials. Textural terms in each lithologic log (OWRB, 2015b) were standardized, categorized, and converted to percentage-coarse-material values by using the methods of Mashburn and others (2013). The percentage-coarse-material value for each lithologic log then was used to estimate and spatially interpolate the hydraulic properties of the North Fork Red River aquifer materials.

Lithologic Log Standardization and Calculation of Percentage-Coarse-Material Values

Lithologic logs included terms such as "redbed," "shale," "mudrock," and "gypsum" to describe Permian bedrock units and terms such as "gravel," "sand," "silt," and "clay" to describe the texture of unconsolidated alluvium and terrace deposits of the North Fork Red River aquifer. However, terms used for lithologic descriptions varied between drillers. To simplify and standardize the lithologic logs, lithologic descriptions of unconsolidated deposits were reclassified into four lithologic categories (clay, silt, sand, and gravel) that were assumed to have quartile ranges of percentage-coarse material (0–25, 25–50, 50–75, and 75–100 percent coarse material, respectively). The midpoint of the respective quartile range (12.5, 37.5, 62.5, or 87.5 percent coarse material, respectively) was, thus, assigned to each lithologic depth interval by using the same method as Mashburn and others (2013). The percentage-coarse-material value for each lithologic log was computed as the thickness-weighted mean of percentage-coarse-material values assigned to the unconsolidated lithologic categories in the log. The maximum percentage-coarse-material value for any lithologic log was 87.5 percent (all gravel), and the minimum percentage-coarse-material value for any lithologic log was 12.5 percent (all clay).

More than 1,500 lithologic logs were used for the percentage-coarse-material analysis, and at least 500 of those logs fully penetrated the aquifer. Limitations of using lithologic logs include errors in spatial location, depths of intervals, and detail of lithologic descriptions. Logs with obvious errors were corrected to extract as much useful information as possible; logs with inscrutable errors were discarded. The bedrock contact was interpolated by using professional judgment and geologic information from previous publications; the bedrock contact was approximated in areas where few lithologic logs were available.

Spatial Distribution of Percentage-Coarse-Material Values

The percentage-coarse-material values for each lithologic log were spatially interpolated across the aquifer by using the inverse-distance-weighted (IDW) interpolation method (Esri, Inc., 2017), where values nearest the interpolated location have the greatest influence on the interpolated value at that location. The IDW interpolation used a power of 3 and a neighborhood of 300. The power is the exponent to which the inverse of the distance between the interpolated location and nearby values is raised, and the neighborhood is the maximum number of nearby values used in the interpolation.

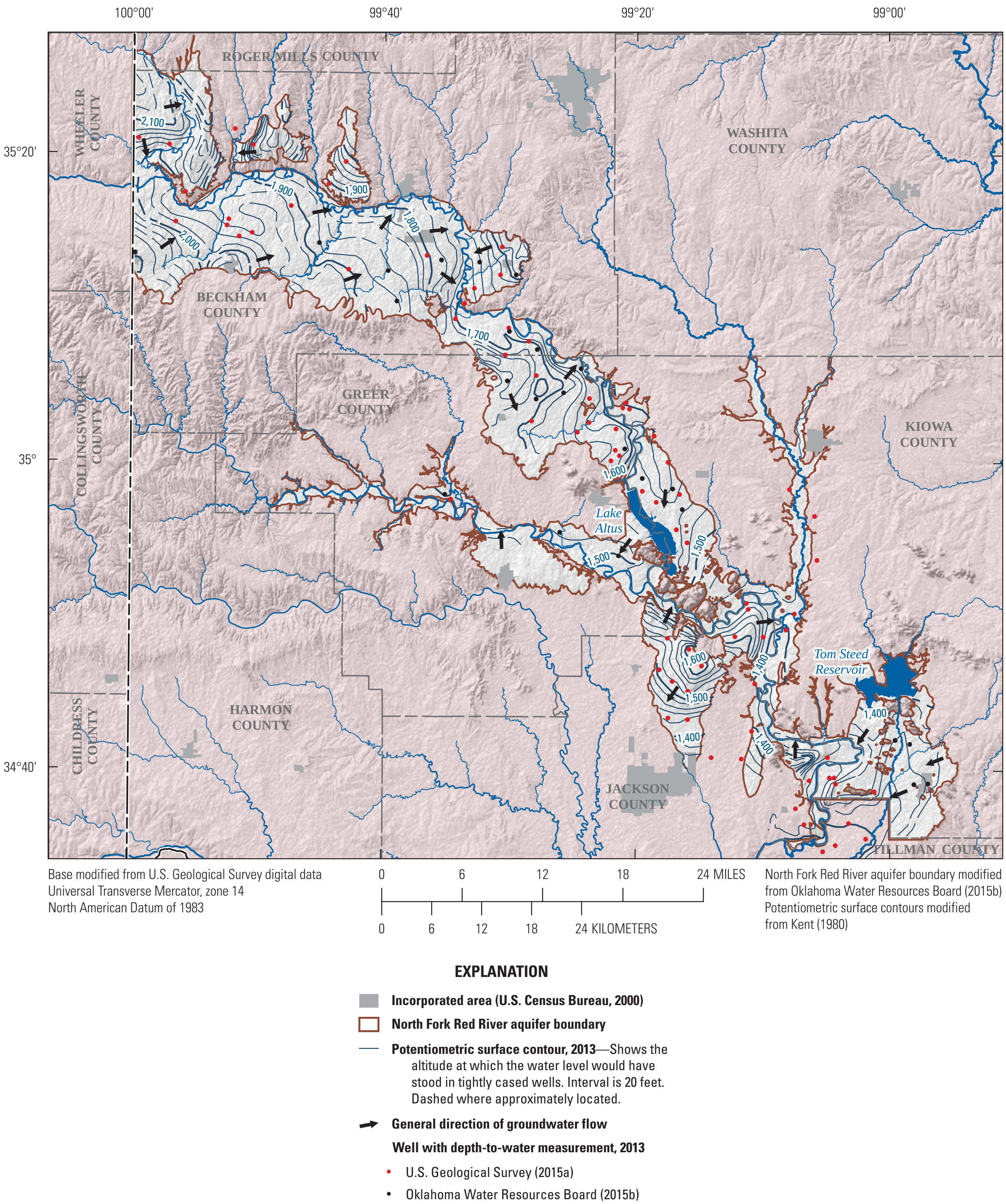


Figure 14. Potentiometric surface contours and general direction of groundwater flow in the North Fork Red River aquifer, 2013.

Hydraulic Properties

Ellis and others (2017) developed a linear mathematical relation between percentage-coarse-material values and horizontal hydraulic conductivity (Kh) determined from core material. The core material was obtained from alluvium and terrace deposits of the Canadian River in western Oklahoma that were similar to the North Fork Red River alluvium and terrace deposits in terms of geologic setting and provenance. The estimated mean Kh for each lithologic log location in the North Fork Red River aquifer was calculated by using the Ellis and others (2017) relation:

$$Kh = (1.25 \times Pcm) - 12.4 \tag{1}$$

where

Kh is the horizontal hydraulic conductivity in feet per day; and

Pcm is the percentage-coarse-material value.

Using the Ellis and others (2017) relation, the estimated Kh determined for lithologic logs in the North Fork Red River aquifer must be within the range of 3 to 97 feet per day (ft/d; 12.5 to 87.5 percent coarse material). The mean and median estimated Kh determined from lithologic logs were 52 ft/d and 57 ft/d, respectively. The range and distribution of Kh estimated from lithologic logs were similar to the range and distribution of Kh measured with depth in four Geoprobe HPT logs (McCall, 2010; Geoprobe Systems, 2015; figs. 1 and 15). Kh measured in the HPT logs ranged from 1 to 97 ft/d with a median of 64 ft/d (fig. 15) and a mean of 61 ft/d (table 7). The Kh measured from the HPT logs generally was greater than the Kh estimated from the lithologic logs; however, these Kh values are difficult to compare because they were determined by using different methods. The Kh values measured from the HPT logs represent point measurements of Kh at every 0.6 in. of depth at only four locations (all near the present channel of the North Fork Red River, fig. 1), and the Kh values estimated from the lithologic logs were averaged from generalized descriptions of drill cuttings.

The relation between percentage-coarse-material (or Kh) values and specific yield (Sy) is nonlinear and depends on the sorting and dominant size of aquifer materials (Johnson, 1967). In general, Sy is maximized for medium to coarse sand, which tends to be well sorted; Sy decreases as the aquifer materials become finer (and a greater percentage of pore water is retained by surface tension) or coarser (and sorting becomes poorer) (Johnson, 1967). Dominant grain size and sorting cannot be derived from lithologic logs, and Sy is usually estimated by using long-duration multi-well aquifer tests (Neuman, 1987).

Three multi-well aquifer tests (AT1, AT2, and AT3, fig. 1, table 7) were performed in the alluvium and terrace deposits of the North Fork Red River aquifer in Beckham County in November–December 1954 by the USGS and the OWRB (then known as the Oklahoma Planning and Resource Board) (USGS, 2015a). The aquifer tests were performed on pumping (irrigation) wells, each with three observation wells 170–360 ft away. The irrigation wells were pumped for up to 66 hours at a constant rate while drawdown was measured in the observation wells. The aquifer test data (observation-well water-level changes over time) were analyzed by using the modified Theis (1935) nonequilibrium methods of Cooper and Jacob (1946). Mean transmissivities resulting from these aquifer tests (AT1, AT2, and AT3) were 7,500, 5,900, and 7,900 feet squared per day (ft^2/d), respectively, and mean hydraulic conductivities were 90.4, 40.7, and 95.2 ft/d, respectively. Sy values calculated from these aquifer tests were 0.064, 0.051, and 0.152 respectively (table 7).

Another multi-well aquifer test (AT4, fig. 1, table 7) was performed near Lake Altus by Kent (1980) and Paukstaitis (1981). A well was pumped at a rate of 100 gal/min for 50 hours while measurements of drawdown were recorded at an observation well 75 ft away. The aquifer-test data were analyzed for this report by using the modified Theis (1935) nonequilibrium method of Cooper and Jacob (1946). The transmissivity calculated from this aquifer test by using the Prickett (1965) late match method was 4,480 ft^2/d, and the hydraulic conductivity was 124 ft/d (Kent, 1980). An Sy value of 0.057 was calculated from the Kent (1980) and Paukstaitis (1981) aquifer test data by using the Cooper and Jacob (1946) method with the Prickett (1965) late-match transmissivity (table 7); however, the numerical groundwater-flow model of Kent (1980) used a mean Sy value of 0.246. A set of multi-well aquifer tests from the nearby and contiguous Tillman Terrace aquifer (fig. 1) also produced Sy values lower than those used in the Kent (1980) model for the North Fork Red River aquifer; these Sy values ranged from 0.010 to 0.087, with a mean of 0.036 (Barclay and Burton, 1953). However, Barclay and Burton (1953) stated that the maximum estimated Sy value (0.087) was most representative of the aquifer because the other Sy values were estimated from multi-well aquifer tests of short duration.

Based on available multi-well aquifer test data (table 7) and published studies (Ryter and Correll, 2016; Ellis and others, 2017), a mean Sy value of 0.12 was estimated for the North Fork Red River aquifer. Values for selected other hydraulic properties were assumed because they were too difficult or expensive to measure and because they were not available in published reports about the study area. The ratio of horizontal to vertical hydraulic conductivity (anisotropy) of the Quaternary alluvium and terrace deposits was assumed to be 3, which matched the anisotropy used for a numerical groundwater-flow model of the Canadian River alluvial aquifer of western Oklahoma (Ellis and others, 2017). The hydraulic conductivity for the Permian bedrock units was assumed to be constant at 0.003 ft/d and was comparable to hydraulic conductivity estimates for Permian shale units in southwest Oklahoma reported by Sullivan (1998). The specific storage and anisotropy values for the Permian bedrock units were assumed to be constant at 0.00001 and 10, respectively; these values were comparable to those used by Ryter and Correll (2016) and Ellis and others (2017) for Permian bedrock units in northwest Oklahoma.

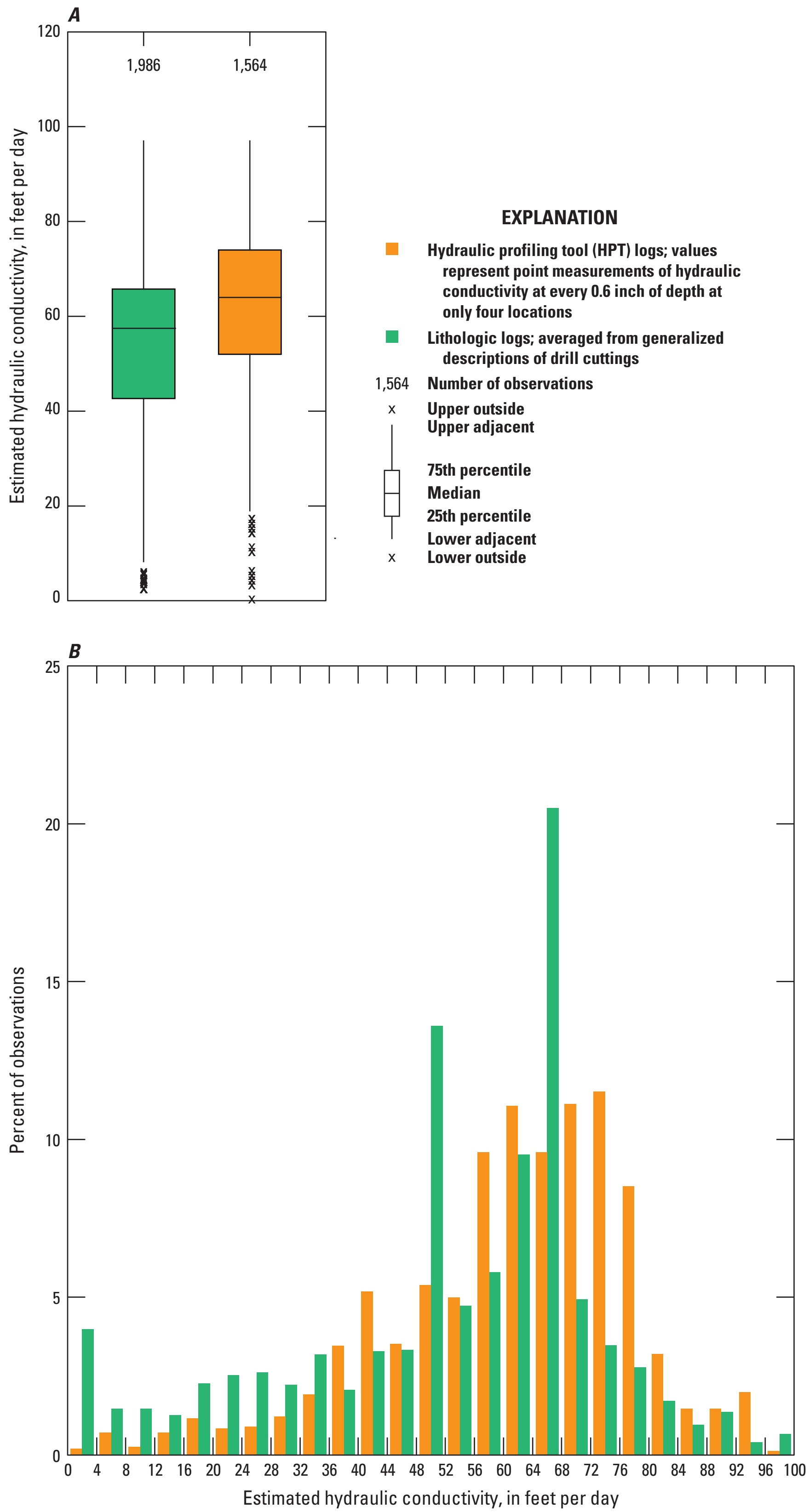


Figure 15. Distributions of estimated hydraulic conductivity observations in the North Fork Red River aquifer.

Table 7. Hydraulic properties calculated from hydraulic profiling tool test holes and multi-well aquifer tests in the North Fork Red River aquifer.

[NAD 83, North American Datum of 1983; Sy, specific yield; ft^2/d, foot squared per day; Kh, hydraulic conductivity; ft/d, foot per day; --, data not available]

Station name (fig. 1)	Data source	Date	County	Analysis methods	Test hole or pumping well			Hydraulic properties		
					Station number	Latitude (NAD 83 degrees)	Longitude (NAD 83 degrees)	Mean Sy	Transmissivity (ft^2/d)	Mean Kh (ft/d)
					Hydraulic profiling tool test holes					
HPT1	U.S. Geological Survey (2015a)	4/1/2014	Beckham	McCall (2010)	351800099524801	35.300113	-99.879995	--	--	55.4
HPT2	U.S. Geological Survey (2015a)	4/1/2014	Beckham	McCall (2010)	351759099492401	35.299716	-99.82335	--	--	64.0
HPT4	U.S. Geological Survey (2015a)	4/2/2014	Beckham	McCall (2010)	351552099414001	35.264451	-99.694512	--	--	62.7
HPT5	U.S. Geological Survey (2015a)	4/2/2014	Beckham	McCall (2010)	350949099302701	35.163637	-99.507607	--	--	62.1
Mean:								--	--	61.1
Range:								--	--	55.4–64.0
					Multi-well aquifer tests					
AT1	U.S. Geological Survey (2015a)	December 7–9, 1954	Beckham	Cooper and Jacob (1946)	351657099584701	35.282552	-99.980108	0.064	7,500	90.4
AT2	U.S. Geological Survey (2015a)	November 15–19, 1954	Beckham	Cooper and Jacob (1946)	351339099424001	35.227551	-99.711487	0.051	5,900	40.7
AT3	U.S. Geological Survey (2015a)	November 12–17, 1954	Beckham	Cooper and Jacob (1946)	351438099370801	35.24394	-99.619262	0.152	7,900	95.2
AT4	Paukstaitis (1981) and Kent (1980)	March 15–18, 1979	Kiowa	Cooper and Jacob (1946)	--	34.969	-99.321	--	3,540	98.9
				Prickett (1965), early match	--	34.969	-99.321	--	4,680	130
				Prickett (1965), late match with Cooper and Jacob (1946) analysis of Sy	--	34.969	-99.321	[1]0.057	4,480	124
Mean[2]:								0.081	5,780	78.3
Range[2]:								0.057–0.152	3,540–7,900	40.7–98.9

[1]Calculated using data from Paukstaitis (1981, fig. 21) and Kent (1980, p. 19). Paukstaitis (1981) and Kent (1980) did not calculate specific yield, but presented the information needed to calculate specific yield.

[2]Except for Sy, mean and range do not include Prickett (1965) analysis for AT4.

Conceptual Groundwater-Flow Model

A conceptual groundwater-flow model (hereafter referred to as the conceptual model) is a simplified description of the major inflow and outflow sources (hydrologic boundaries) of a groundwater-flow system as well as an accounting of the estimated mean flows from those sources (water budget, table 8) for a specified period of time. A conceptual model was developed for the North Fork Red River aquifer to constrain the construction and calibration of a numerical groundwater-flow model (hereafter referred to as the numerical model) that reasonably represented the groundwater-flow system. The conceptual-model water budget (table 8) estimated mean annual inflows to and outflows from the North Fork Red River aquifer for the period 1980–2013 and included a sub-accounting of mean annual inflows and outflows for the portions of the aquifer that were upgradient and downgradient from Lake Altus, which were determined by using the 11120302 subwatershed boundary (figs. 2 and 16).

Hydrologic Boundaries

Hydrologic boundaries in the conceptual model represent real-world sources (inflows) and sinks (outflows) of water to the aquifer. Boundaries that act as both inflows and outflows, depending on which flow component dominates, may be referred to as net inflows or outflows.

Recharge

Recharge is the predominant inflow to the North Fork Red River aquifer. Recharge, as defined in this report, is the amount of precipitation (over a given time) that reaches the saturated zone through the process of infiltration through the unsaturated zone. Factors that affect recharge rates are precipitation rates, ET rates, permeability and moisture capacity of the unsaturated zone, and slope of the land surface. Recharge rates are difficult to measure directly because they vary over short spatial and temporal scales; therefore, recharge

Table 8. Conceptual groundwater-flow model mean annual water budget for the North Fork Red River aquifer, 1980–2013.

[All units in acre-feet per year; --, not quantified; ET, evapotranspiration; %, percent]

Water-budget category	Conceptual model: Upgradient from Lake Altus	Conceptual model: Downgradient from Lake Altus	Conceptual model: Total	Percentage of water budget	Notes
Aquifer area (percent)	54.6%	45.4%	100.0%		
Inflow					
Recharge	62,790	52,210	115,000	95%	9.5 percent of mean annual precipitation, 1980–2013
Net change in groundwater storage[1]	3,358	2,792	6,150	5%	Computed from changes in aquifer water levels
Net lakebed seepage[2]	--	--	--	--	Assumed to be negligible inflow (less than 1 percent of budget)
Total inflow	66,148	55,002	121,150	100%	
Outflow					
Net streambed seepage[2]	27,824	44,010	71,835	59%	Calculated from base-flow data at streamgages (table 2)
Saturated-zone ET	10,720	16,080	26,800	22%	About 60 percent of saturated zone ET assumed to be downgradient from Lake Altus
Well withdrawals	13,322	2,537	15,859	13%	Known to be increasing over the period 1980–2013
Net lateral groundwater flow, springs, and seeps[2]	2,782	4,401	7,183	6%	Springs and seeps were estimated to be no greater than 10 percent of net streambed seepage
Total outflow	54,648	67,029	121,677	100%	

[1]Positive values indicate loss of groundwater storage from the aquifer. Loss of groundwater storage is reported as an aquifer inflow for comparison with the numerical groundwater-flow model in which storage loss is represented as a positive value for mass balance purposes (fig. 16, table 14).

[2]Net lakebed seepage, net streambed seepage, and net lateral groundwater flow represent the net effect of aquifer inflows and outflows.

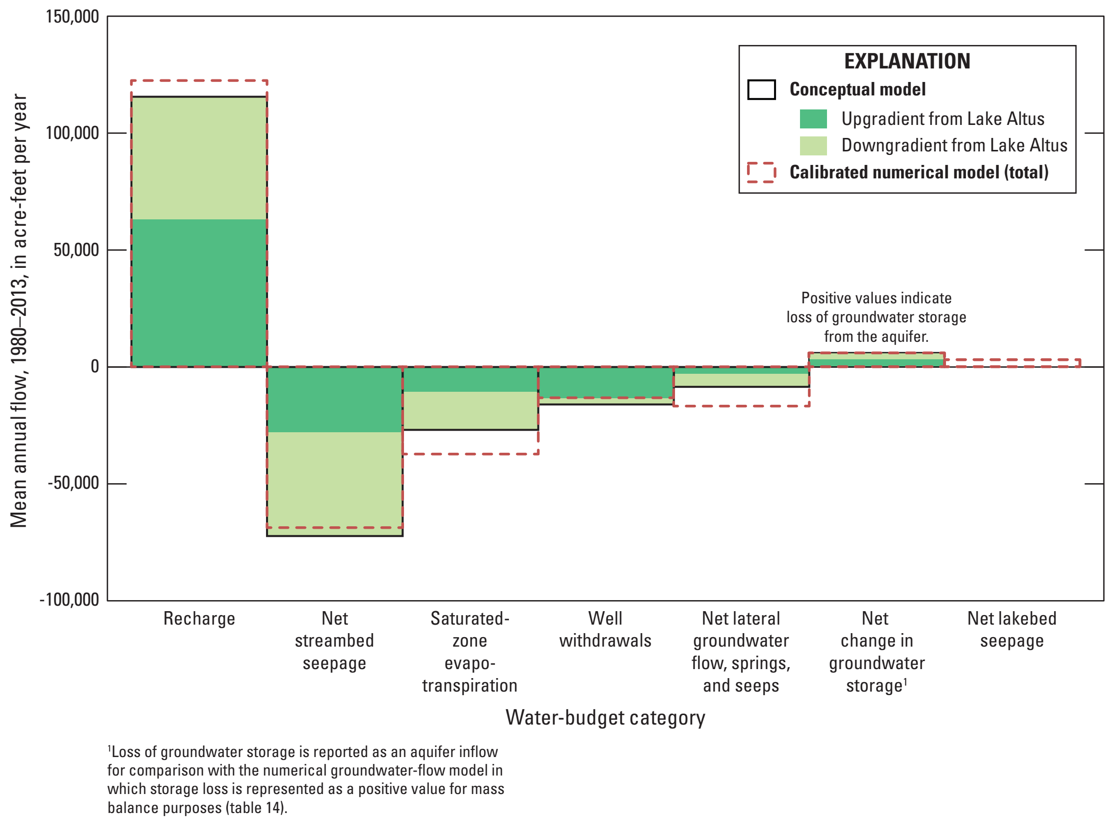


Figure 16. Mean annual flow by water-budget category for the conceptual model and the calibrated numerical model of the North Fork Red River aquifer, 1980–2013.

rates are often estimated by using multiple methods. Some methods estimate recharge at specified points, and some methods estimate recharge at the basin or regional scale. The basin-scale RORA and PART (Rorabaugh, 1964; Rutledge, 1998) methods, which are based on streamgage data, were most appropriate for the scale of this study; however, most streams in the study area violated the assumptions of these methods because (1) they were losing streams during part of the year, (2) they were regulated by large reservoirs, or (3) they exceeded the recommended drainage-basin area limit of 500 mi^2.

The RORA method uses a recession-curve displacement technique to estimate groundwater recharge from each storm period based on a one-dimensional analytical model of groundwater discharge to a fully penetrating stream (the streambed altitude is the aquifer-base altitude) in an idealized aquifer with uniform spatial recharge (Rorabaugh, 1964; Rutledge, 1998). This method approximates recharge at times when ET and groundwater use are minimal, during which base flow is assumed to be groundwater discharge that is approximately equal to recharge. The RORA method was used to estimate annual recharge at the Sweetwater streamgage (07301420) on Sweetwater Creek, which has a drainage-basin area of 437 mi^2. This streamgage was the only streamgage in the study area that did not violate the suggested drainage-area limitation for application of the RORA method. Annual recharge at the Sweetwater streamgage (07301420) for the period of record 1986–2013 ranged from 0.10 in/yr in 2012 to 1.45 in/yr in 1997; the RORA-estimated mean annual recharge for that period was 0.60 in/yr or about 2.4 percent of the mean annual precipitation (25.29 in/yr) for the 1980–2013 period at the Erick (342944) climate station. The RORA-estimated mean annual recharge (0.60 in/yr) was about 31 percent of the mean annual recharge (1.91 in/yr) computed by using the Soil-Water-Balance (SWB) code (Westenbroek and others, 2010); the application of the SWB code is described in detail in the Recharge and the Soil-Water-Balance Code section of this report. The RORA-estimated mean annual recharge could be biased low, however, if recharge flowed across the drainage-basin boundary without discharging to Sweetwater Creek.

The water-table fluctuation (WTF) method (Healy and Cook, 2002) also was used to estimate recharge to the North Fork Red River aquifer. The WTF method is based on the premise that short-term (hours to a few days) rises in continuously recorded groundwater levels in unconfined aquifers are caused by recharge arriving at the saturated zone following a period of precipitation. The method is best applied to aquifers with shallow water tables that display rapid water-level rises and declines in response to precipitation. The method cannot distinguish between recharge from precipitation and recharge from other sources such as irrigation return flow or streambed seepage. Using the WTF method, recharge (R) was calculated as the sum of individual water-level rises in response to precipitation:

$$R = Sy\,\Delta h/\Delta t \qquad (2)$$

where

- Sy is the specific yield (dimensionless),
- Δh is the change in water level, in inches, and
- Δt is the change in time, in months.

Continuous water-level recorder wells CR1 and CR2 (fig. 1), which were downgradient from many permitted production wells, were not ideal for estimating recharge by using the WTF method because few water-level rises in response to precipitation were observed. Monthly recharge during 2014 was estimated at continuous water-level recorder well CR3 (fig. 1), which was upgradient from permitted production wells. The barometric-pressure-corrected water-level hydrograph from CR3 (fig. 17, table 1) showed some water-level rises in response to precipitation, which totaled 22.4 in. at the Hobart climate station (HOBA, fig. 1) in 2014 (Oklahoma Mesonet, 2015). The minimum estimated monthly recharge at CR3 was 0.0 in. for the month of January because no precipitation was observed in that month. When using an Sy of 0.12, the maximum estimated monthly recharge at CR3 was 0.5 in. during May, and estimated annual recharge at CR3 was 2.4 in. (about 11 percent of precipitation) during 2014.

Estimates of mean annual recharge rates for other Quaternary alluvium and terrace deposits with similar climate in western Oklahoma include 2.3 in/yr (Adams and Bergman, 1996), about 8 percent of mean annual precipitation for that study; 3.15 in/yr (Barclay and Burton, 1953), about 11 percent of mean annual precipitation for that study; and 1.74 in/yr

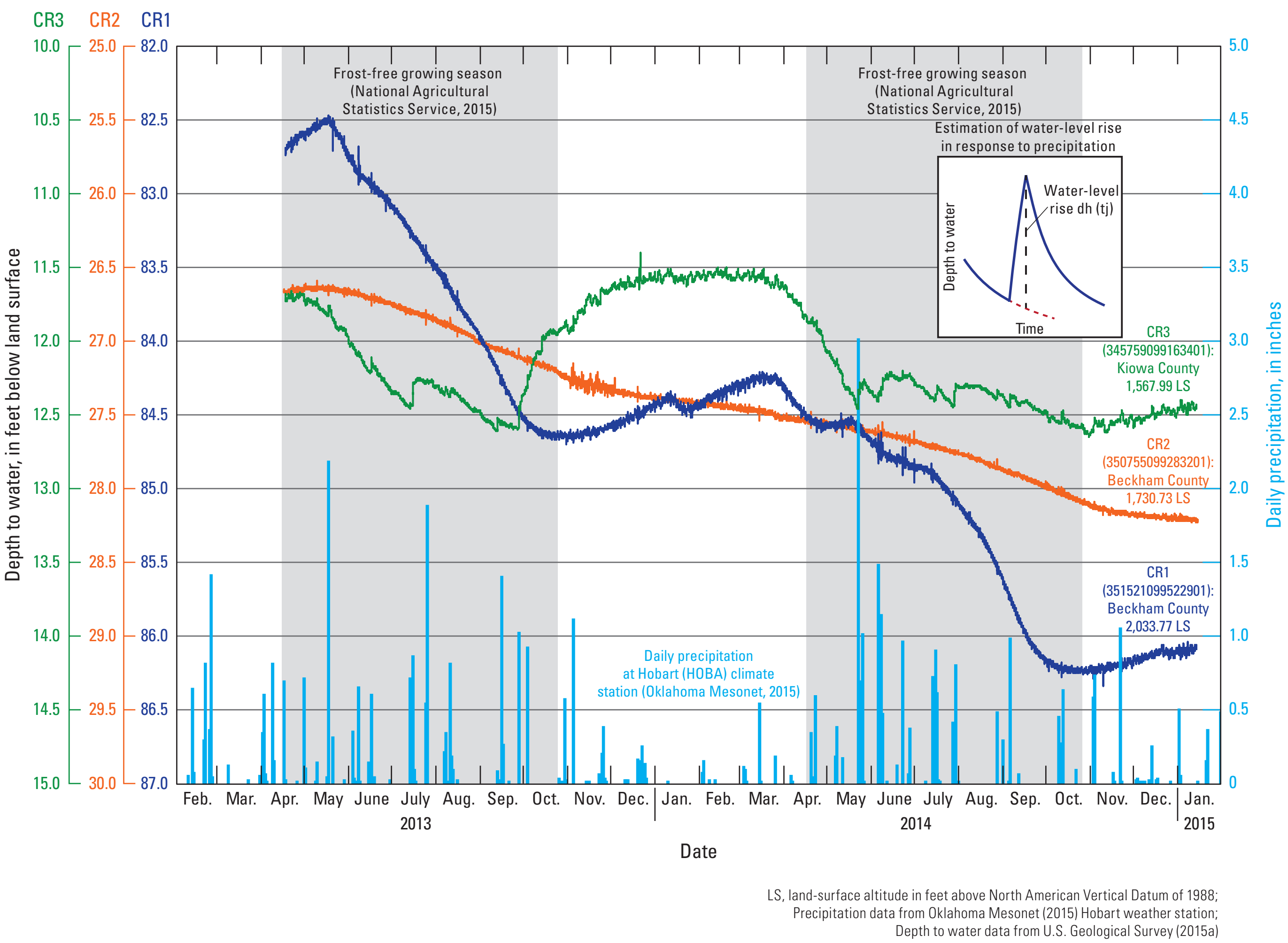


Figure 17. Daily precipitation and depth to water in continuous water-level recorder wells completed in the North Fork Red River aquifer, February 2013 through January 2015.

(Steele and Barclay, 1965), about 7 percent of mean annual precipitation for that study. Based on estimated annual recharge percentages from these studies and the WTF method, the mean annual recharge rate to the North Fork Red River aquifer for the period 1980–2013 was estimated to be about 2.77 in/yr or 9.5 percent of the mean annual precipitation (29.2 in/yr, table 3) for the same period. This 1980–2013 mean annual recharge rate of 2.77 in/yr (0.231 feet per year [ft/yr]), multiplied by the aquifer area of 497,582 acres, is equivalent to a mean annual recharge volume of about 115,000 acre-ft/yr (table 8). The mean annual recharge volumes upgradient and downgradient from Lake Altus, apportioned by percentage of aquifer area (54.6 and 45.4 percent, respectively), were about 62,800 and 52,200 acre-ft/yr, respectively (table 8).

Lateral Groundwater Flows

Upgradient from Lake Altus, the alluvium and terrace deposits of Wheeler County, Texas (fig. 12), which are adjacent to the deposits of the North Fork Red River aquifer, were assumed to exchange lateral groundwater flow with the aquifer. The rate and direction of lateral groundwater flow across the Texas border may vary, however, during seasonally and decadally alternating wet and dry periods. During a severe drought in 2013 (fig. 3), the Texas border was roughly perpendicular to most of the mapped potentiometric surface contours (fig. 14) and, therefore, was roughly parallel to the direction of most groundwater flow (generally toward the North Fork Red River). Based on the configuration of the 2013 potentiometric surface (fig. 14), the net lateral groundwater flow across the Texas border may have accounted for a small inflow to the aquifer in 2013. The potentiometric surfaces for 1951 and 1979 (Kent, 1980), also mapped during dry periods (fig. 3*A*), show a configuration similar to that of fig. 14. No water-table-altitude data were available from west of the Texas border; therefore, rates of lateral groundwater flow across the Texas border could not be quantified.

Downgradient from Lake Altus, lateral groundwater flows across the Tillman County border were expected to be outflows based on the potentiometric surfaces of the North Fork Red River aquifer (fig. 14) and the Tillman Terrace aquifer (Barclay and Burton, 1953; Osborn, 2002). Based on estimates of the mean hydraulic gradient, hydraulic conductivity, and saturated thickness in the area, net lateral groundwater flows across the Tillman County border were estimated to be small outflows of about 1,100 acre-ft/yr.

Net lateral groundwater flows exchanged with the surrounding Permian bedrock units (predominantly shale and siltstone with relatively low hydraulic conductivity) were assumed to be a negligible part of the conceptual-model water budget of the North Fork Red River aquifer. No estimates of the flow between the Permian bedrock and the aquifer were available in published reports.

Streambed Seepage

Synoptic streamflow measurements (also known as seepage-run measurements) were collected by using the methods of Rantz and others (1982) during a period of minimal runoff on March 11–13, 2013 (USGS, 2015a). These measurements were intended to capture tributary-inflow and base-flow conditions across the aquifer at one point in time. The synoptic streamflow measurements were used to calculate net streambed seepage and classify stream reaches as gaining (having a downstream increase in base flow) or losing (having a downstream decrease in base flow). These March 2013 streambed-seepage data (fig. 18) show that (1) most small tributaries that originate away from the aquifer carried negligible (less than 1 ft^3/s) base flows to the North Fork Red River, (2) stream reaches upstream from the Texas border generally were gaining, (3) stream reaches between the Texas border and Lake Altus generally were losing, and (4) stream reaches downstream from Lake Altus generally were gaining. However, the March 2013 streambed-seepage data were collected during a severe drought period (fig. 3) and therefore may be more representative of less-frequent drought conditions than typical late-winter base-flow conditions. Other synoptic streamflow measurements were reported by Smith and others (2003) and Stephens (2003) for reaches upstream from Lake Altus, but most of these measurements captured some streamflow runoff component and were not ideal for base-flow comparisons. A set of synoptic streamflow measurements from July 2003 (Stephens, 2003), another dry year, reinforced that reaches of the North Fork Red River upstream from Lake Altus can be losing or dry in the summer months when ET, irrigation, and public-supply water demands are greatest.

Annual and monthly base flows (fig. 19; table 2, only mean annual base flows shown) were computed at streamgages for the period 1980–2013 by using the Base-Flow Index (BFI) code (Wahl and Wahl, 1995) in the USGS Groundwater Toolbox (Barlow and others, 2015) and streamflow data from USGS (2015a). The BFI code uses the minimum streamflow in a moving n-day window as a basis for hydrograph separation, and a window of 5 days was used for all streamgages. Base-flow computation at regulated streamgages can be complicated by releases from large reservoirs and floodwater-retarding structures because these releases (and the subsequent bank storage releases associated with these releases) are usually indistinguishable from natural base flows. For this reason, hydrograph separation methods may overestimate base flows at regulated streamgages; the base flows computed for those regulated streamgages are useful, however, as a maximum limit on estimated base flow.

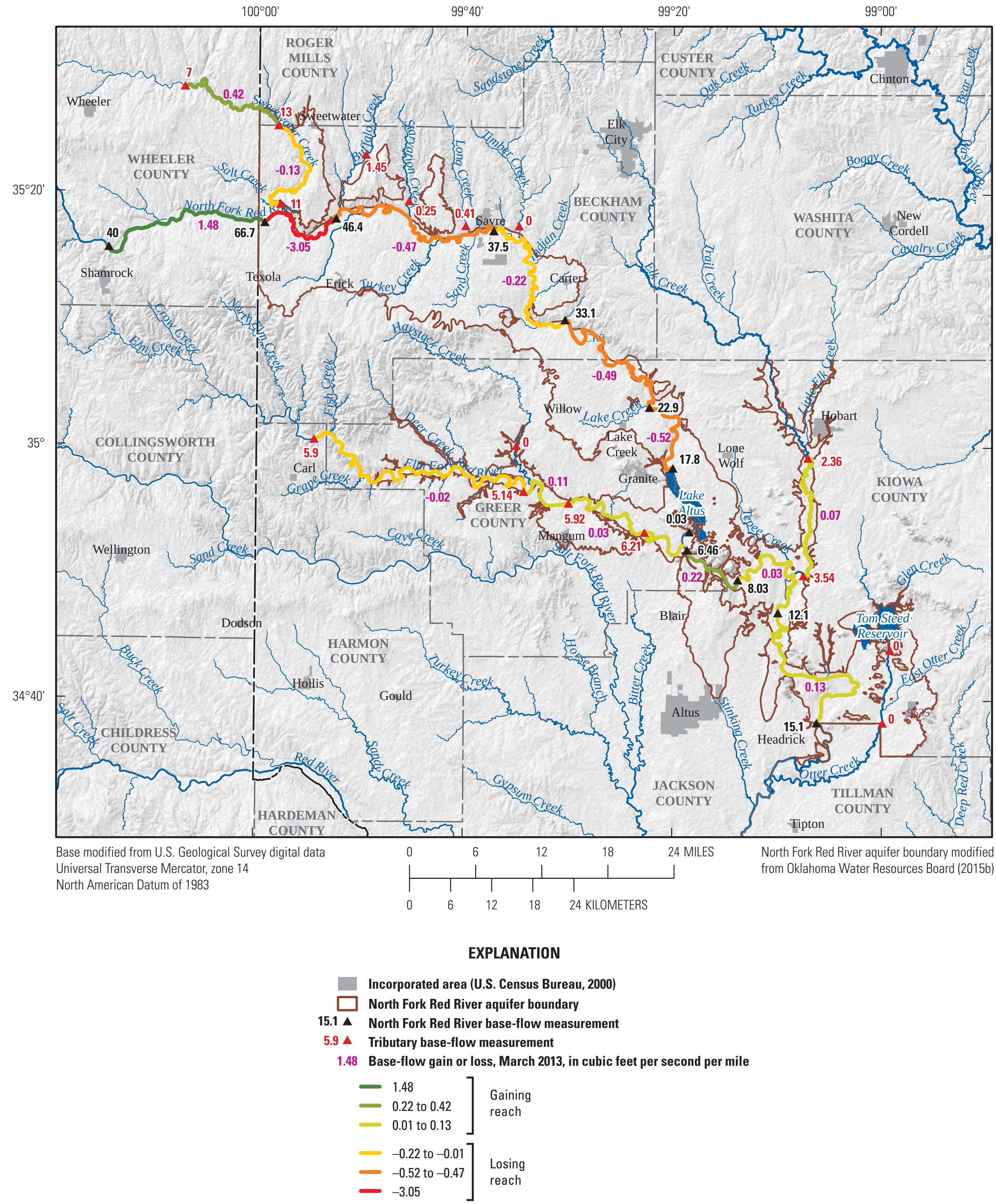


Figure 18. Base-flow measurements with gaining and losing reaches of the North Fork Red River and tributaries, March 2013.

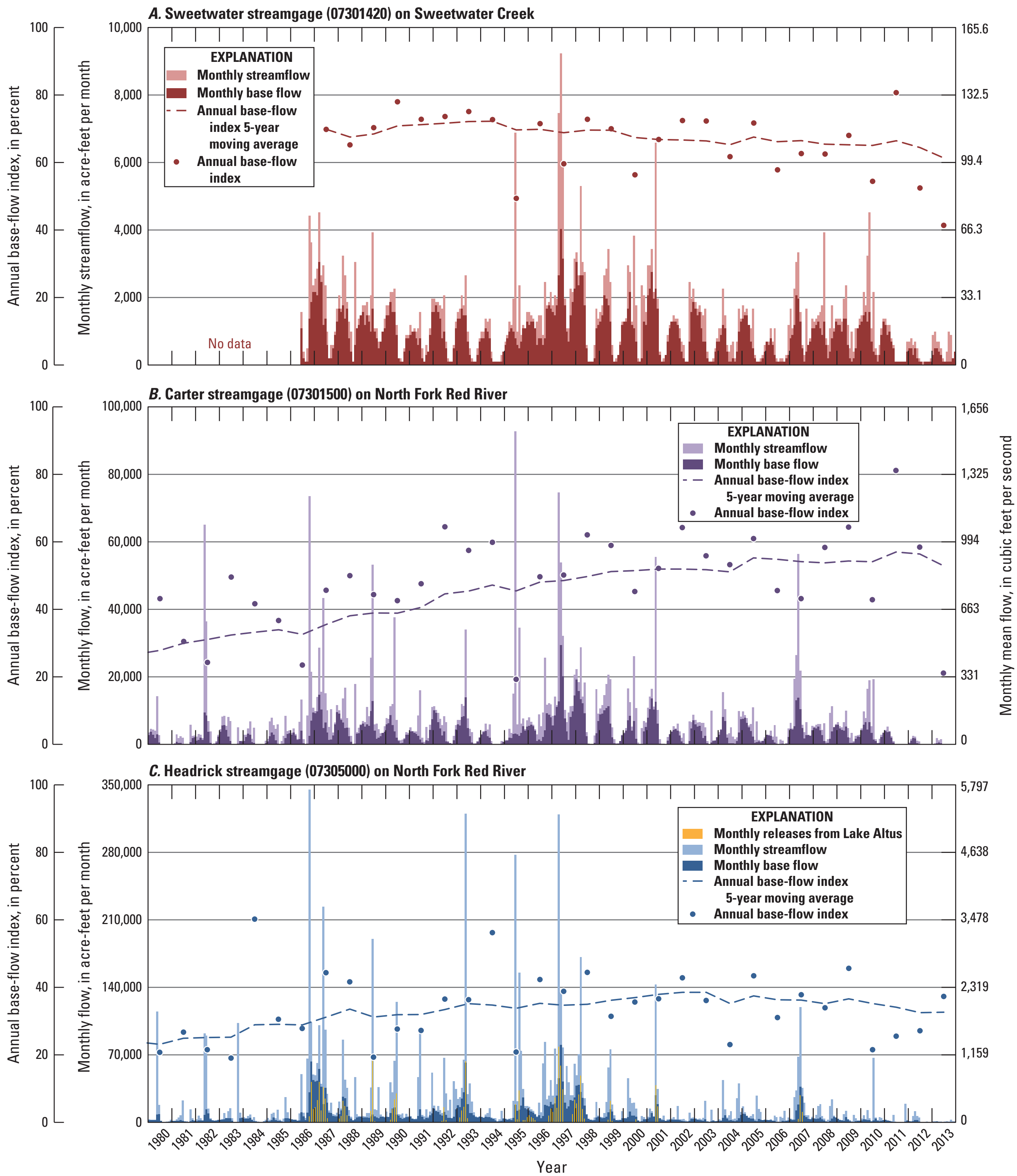


Figure 19. Monthly streamflow, monthly base flow, and annual base-flow index for *A*, Sweetwater streamgage (07301420) on Sweetwater Creek; *B*, Carter streamgage (07301500) on North Fork Red River; and *C*, Headrick streamgage (07305000) on North Fork Red River, 1980–2013.

Streambed seepage is the predominant outflow from the North Fork Red River aquifer. The annual net streambed seepage upgradient from Lake Altus was estimated to be 27,824 acre-ft/yr (table 8) and was calculated as the mean annual base flow at the Carter streamgage (07301500) minus the mean annual base flows at the Shamrock (07301300) and Kelton (07301410) streamgages (table 2). Because no streamgages are located between the Carter streamgage (07301500) and Lake Altus (a distance of about 27 river miles), additional streambed seepage may occur in this reach that was not represented in the calculation. The annual net streambed seepage downgradient from Lake Altus was estimated to be 44,010 acre-ft/yr (table 8) and was calculated as the mean annual base flows at the Headrick (07305000) and Snyder (07307010) streamgages minus the mean annual base flows at the Carl (07303400) and Hobart (07304500) streamgages plus 50 percent of the mean annual releases from Lake Altus (table 2). This 50-percent figure was assumed to represent the unknown portion of annual releases that flowed to the North Fork Red River aquifer as bank storage and streambed seepage and was later discharged to the North Fork Red River as base flow. Mean annual releases from Lake Altus for the period 1980–2013 were about 35,100 acre-ft/yr (U.S. Bureau of Reclamation, 2015b).

Lakebed Seepage

Net lakebed seepage between the North Fork Red River aquifer and Lake Altus or Tom Steed Reservoir was not measured but probably was a small component of the water budget of the aquifer. Lakebed seepage flows were expected to vary seasonally with changes in lake stage, which generally was highest in the late spring months and lowest in the fall months. Annual lakebed seepage flows probably alternate between being aquifer inflows and outflows. The annual lakebed seepage of Lake Altus, for example, probably is an aquifer outflow during drought years when the lake stage is relatively low and an aquifer inflow when the lake is full. The annual lakebed seepage of Tom Steed Reservoir, however, probably is an aquifer inflow in most years because the lake stage is typically at a higher altitude than the surrounding aquifer materials. The net lakebed seepage of Lake Altus and Tom Steed Reservoir (combined) was assumed to be a negligible aquifer inflow (less than 1 percent of the conceptual-model water budget for the period 1980–2013).

Springs and Seeps

Few springs in alluvium and terrace deposits of the study area have been documented in published reports. Some reports, however, contain brief references to small springs, seeps, or perennial streams that are assumed to be spring-fed in the Quaternary alluvium and terrace deposits near the contact with underlying Permian bedrock. Steele and Barclay (1965) mentioned the presence of abundant small springs in the terrace deposits along the Elm Fork Red River northeast of Mangum, Okla. (figs. 1 and 12). Burton (1965), in describing the alluvium and terrace deposits of Beckham County, mentioned that Spring Creek was the only perennial stream in that area. Barclay and Burton (1953) mentioned small springs along the eastern edge of the terrace deposits of Otter Creek just outside of the North Fork Red River aquifer study area. According to the available literature for the study area, small distributed springs and seeps and not large point discharges are most typical in the alluvium and terrace deposits of the North Fork Red River aquifer. Published flow rates for springs and seeps discharging from the North Fork Red River aquifer were not available, but they were expected to be a small part of the conceptual-model water budget; flows to springs and seeps were assumed to be proportional to base flow and were estimated to be no more than 10 percent of net streambed seepage for the study period.

Saturated-Zone Evapotranspiration

ET is the process by which water is transferred to the atmosphere directly through evaporation (or sublimation in the case of snow and ice) and indirectly through plant transpiration. Much of this process, however, occurs at or near the land surface as precipitation pools as surface water or infiltrates the soil unsaturated zone and becomes available to the plant root zone. These surface-water and unsaturated-zone components of ET were not considered to be a part of the conceptual model for the North Fork Red River aquifer because they occur before infiltrating precipitation has become groundwater recharge (reached the saturated zone). A supplementary component of ET, however, occurs in areas of the aquifer where the saturated zone intersects the plant root zone, most commonly in lower lying areas near streams; this component of ET (saturated-zone ET) was an important part of the conceptual-model water budget.

Rates of saturated-zone ET are difficult to estimate over a large area but should be roughly proportional to (1) the area where the saturated zone intersects the plant root zone, (2) the mean depth to groundwater in that area during the growing season, and (3) the mean rate of transpiration associated with the assemblage of plants in that area. The area where the saturated zone intersects the plant root zone probably is small (compared to the entire North Fork Red River aquifer area) and confined to the 107,200-acre area of active alluvium (Qal, fig. 12; Johnson and others, 2003; Stanley and Miller, 2004) along perennial or near-perennial streams. About 21 percent (22,300 acres) of the active alluvium area was classified as wetland (land area with frequently saturated or flooded soils) by the National Wetlands Inventory (U.S. Fish and Wildlife Service, 2015). The area where the saturated zone intersects the plant root zone probably is slightly larger than the area classified as wetland, however, because land areas do not have to be flooded to contribute to saturated-zone ET. About 25 percent (26,800 acres) of the active alluvium area (107,200 acres), therefore, was assumed to contribute to saturated-zone ET. Saturated-zone ET also was assumed to be proportional to and no greater than the potential ET minus the actual ET computed by using the Hargreaves and Samani (1985) method as described by Westenbroek and others (2010). This assumption resulted in the summed components of ET not exceeding the potential ET. The saturated-zone component of ET was assumed to be active for about half the year (182.5 days), greatest annually in wet and hot years, and greatest monthly in early summer (Scholl and others, 2005) when precipitation and temperature are above average (fig. 4).

By using the assumptions previously listed, groundwater outflow by saturated-zone ET could be estimated from daily water-level fluctuation data at wells with shallow depths to water according to methods of White (1932). Wells with these data were not available in the study area, but gage height data from selected streamgages (07301500, 07303400, 07304500, and 07305000; USGS, 2015a) showed daily declines in stream stage during summer low-flow conditions. These daily declines in stream stage (with rebounds at night) indicated that saturated-zone ET was an active process throughout the North Fork Red River aquifer, but the declines were too small to be accurately measured from the gage height data.

White (1932) estimated annual saturated-zone ET rates of 0.75–1.9 ft/yr for undisturbed salt grass cover in southwest Utah with a mean depth to water of 1–2 ft. Because ET rates in the high desert of Utah are likely to be greater than those in Oklahoma, an annual saturated-zone ET rate of about 1.0 ft/yr was assumed to be appropriate for the North Fork Red River. If about 25 percent (26,800 acres) of the active alluvium area (107,200 acres) had similar cover and depths to water, this assumed rate would correspond to an annual saturated-zone ET outflow of 26,800 acre-ft/yr (table 8). Annual saturated-zone ET was expected to be greater downgradient than upgradient from Lake Altus because the water table of the active alluvium tends to be shallower downgradient from Lake Altus (where gaining streams are more common, fig. 18). About 60 percent of the annual saturated-zone ET for the aquifer was allocated to the smaller downgradient portion of the aquifer (table 8), because that portion had mostly gaining reaches (and presumably more area with near-surface water table) according to the streambed-seepage data (fig. 18).

Well Withdrawals, Water-Level Response, and Storage Change

Mean annual well withdrawals were assumed to equal the mean annual reported groundwater use for the period 1980–2013, or 15,859 acre-ft/yr (table 4). About 84 percent of the annual well withdrawals for that period were from permitted wells upgradient from Lake Altus (mostly in Beckham and Greer Counties, fig. 8, table 8). Well withdrawals were greatest in dry and hot years because more water was required in those years to grow healthy crops. The water table generally falls during dry and hot years (especially during extended droughts) and rises during wet and cool years (fig. 3). The degree to which the water table fluctuates annually at a location is related in part to the volume of nearby ET and well withdrawals. For the study period 1980–2013, the OWRB (2015b) Mass Measurement Program recorded annual water-level measurements (usually in winter) from wells in the North Fork Red River aquifer. Those measurements show a general rise in water-level altitudes over the cooler and wetter early period (1980–2000) and a general decline in water-level altitudes over the hotter and drier late period (2001–2013) (figs. 20 and 3). Mean water levels for the period 1980–2013 fell 4.95 ft in Beckham County, fell 5.85 ft in Greer County, and rose 0.27 ft in Kiowa County (fig. 20). Assuming an Sy of 0.12 and a mean water-level decline of about 3.5 ft (the mean water-level change), the North Fork Red River aquifer lost about 209,000 acre-ft (6,150 acre-ft/yr) of storage during the period 1980–2013 (table 8).

Conceptual Groundwater-Flow Model Water Budget

The conceptual-model water budget (table 8) summarized mean water flows (fluxes) between each hydrologic boundary and the North Fork Red River aquifer for the period 1980–2013. Recharge accounts for most (95 percent) of the inflows to the North Fork Red River aquifer, and net streambed seepage accounts for most (59 percent) of the outflows from the North Fork Red River aquifer (fig. 16, table 8). The expected mean annual net change in groundwater storage (6,150 acre-ft/yr) was reported as an aquifer inflow for later comparison with the calibrated numerical model water budget (fig. 16, table 8). Estimated inflows exceeded outflows upgradient from Lake Altus, and estimated outflows exceeded inflows downgradient from Lake Altus; therefore, inflows upgradient and outflows downgradient from Lake Altus may have been overestimated in the conceptual-model water budget.

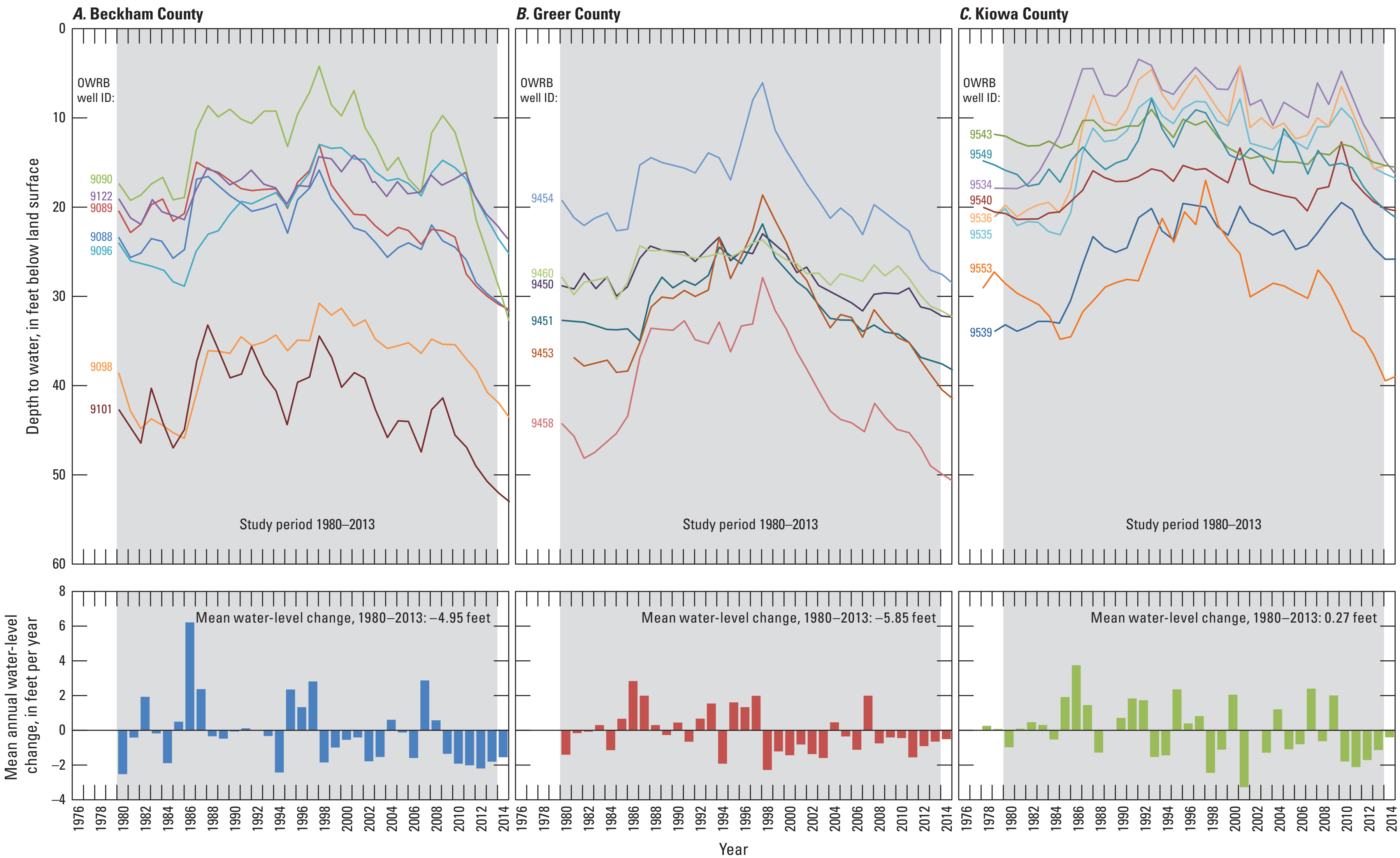


Figure 20. Annual water-level measurements and mean annual water-level change by county for Oklahoma Water Resources Board Mass Measurement Program wells completed in the North Fork Red River aquifer, 1978–2014. [OWRB well ID, Oklahoma Water Resources Board well identifier; data from Oklahoma Water Resources Board (2015b)]

Numerical Groundwater-Flow Model

A finite-difference numerical model of the North Fork Red River aquifer was constructed by using MODFLOW-2005 (Harbaugh, 2005) with the Newton formulation solver (MODFLOW-NWT; Niswonger and others, 2011) for improved solution of problems involving drying and rewetting. In the modular design of MODFLOW, each hydrologic boundary of the conceptual model, such as streambed seepage, recharge, or well withdrawal, is included as a package that, when activated, adds new inflow and outflow terms to the groundwater-flow equation being solved. Data inputs for each package are specified in machine-readable text files. Model space is discretized into cells, and the cell size is the finest resolution at which spatially varying properties (such as land-surface altitude or hydraulic conductivity) may be represented and varied. Model time is discretized into time steps within stress periods. The stress period length is the finest resolution at which temporally varying inflows and outflows may be represented and varied, and the time step length is the finest length of time for which model outputs may be written. The numerical model represents hydraulic properties that appear reasonable on the basis of water-table-altitude, base-flow, and lake-stage observations, but may not be unique. Different combinations of model input parameters may result in an equally reasonable fit to the observations. The calibrated numerical groundwater-flow model inputs and outputs are available in Smith and others (2017).

Spatial and Temporal Discretization

The numerical model of the North Fork Red River aquifer had 385 rows, 460 columns, about 27,600 active cells of 886 by 886 ft (270 by 270 meters), and 2 convertible layers. The cell size was chosen to minimize model-processing time while reasonably representing the variability of properties being modeled. The top layer (layer 1) represented the undifferentiated Quaternary alluvium and terrace deposits with variable thickness determined from the hydrogeologic framework, and the bottom layer (layer 2) represented the Permian bedrock with a nominal thickness of about 100 ft. The aquifer top altitude was multiplied by 1.001 in the numerical model to prevent confined aquifer conditions that occur when the simulated water-table altitude exceeds the aquifer top altitude.

The model active area (fig. 21) was created from the North Fork Red River aquifer extent (modified from the OWRB [2015b]), and expanded in some areas to ensure that each active cell was in connection with at least one other active cell. One terrace lobe in northern Beckham County was not included in the model active area because it was almost separated spatially and hydraulically from the rest of the North Fork Red River aquifer (fig. 21). Though the conceptual model divided the aquifer into areas upgradient and downgradient from Lake Altus, the numerical model described in this report combined both areas.

The numerical model was temporally discretized into 408 monthly transient stress periods (each with 2 time steps to improve model stability) representing the period 1980–2013. An initial steady-state stress period, in which the groundwater-flow equation had no storage component, represented mean annual inflows to and outflows from the aquifer and produced a solution that was used as the initial condition for subsequent transient stress periods. Though other units for length and time are used in this report, the numerical model was constructed by using units of meters and days.

Simulation of Hydrologic Boundaries

Hydrologic boundaries in the numerical model define where and how water may enter or leave the model (fig. 21) and include specified-head, specified-flux, and head-dependent boundaries. A specified-head boundary was used to simulate lakebed seepage at Tom Steed Reservoir. Specified-flux boundaries were used to simulate recharge and well withdrawals. Head-dependent boundaries were used to simulate saturated-zone ET, lateral groundwater flow between adjacent alluvium and terrace deposits, springs and seeps, streambed seepage, and lakebed seepage at Lake Altus.

Recharge and the Soil-Water-Balance Code

Conceptual-model recharge to the North Fork Red River aquifer was spatially and temporally distributed for each month of the study period 1980–2013 by using the SWB code (Westenbroek and others, 2010). The SWB code uses a modified Thornthwaite and Mather (1957) soil-water-balance method on a gridded data structure to compute the daily amount of precipitation infiltration that exceeds the storage capacity of the plant root zone and the demand from plants for ET. The Hargreaves and Samani (1985) method for a reference latitude range of 34.5–35.5 degrees was used to compute ET. Land-cover and soil properties were used to estimate the amount of daily precipitation that entered the soil profile and the amount of daily precipitation runoff. Land-cover types (Multi-Resolution Land Characteristics Consortium, 2011) were used to assign runoff curve numbers and plant root-zone depths. The default SWB plant root-zone depths for shrubs/range, grass/pasture, and crops (the dominant land-cover types overlying the aquifer, fig. 5) varied with soil texture and ranged from 2.0 to 3.6 ft (Dripps, 2003; Westenbroek and others, 2010). Soil properties (available water capacity and hydrologic soil group) were derived from the Soil Survey Geographic database (SSURGO; Natural Resources Conservation Service, 2015). Digital elevation models (USGS, 2015b) were used to determine the surface-water-flow direction for each grid cell as described in Westenbroek and others (2010). The grid cell size used for the SWB code was 886 by 886 ft (270 by 270 meters). The land-cover, soil, and altitude inputs were assumed to remain constant during the study period, but climate data inputs varied daily. Climate data inputs included interpolated grids of daily precipitation,

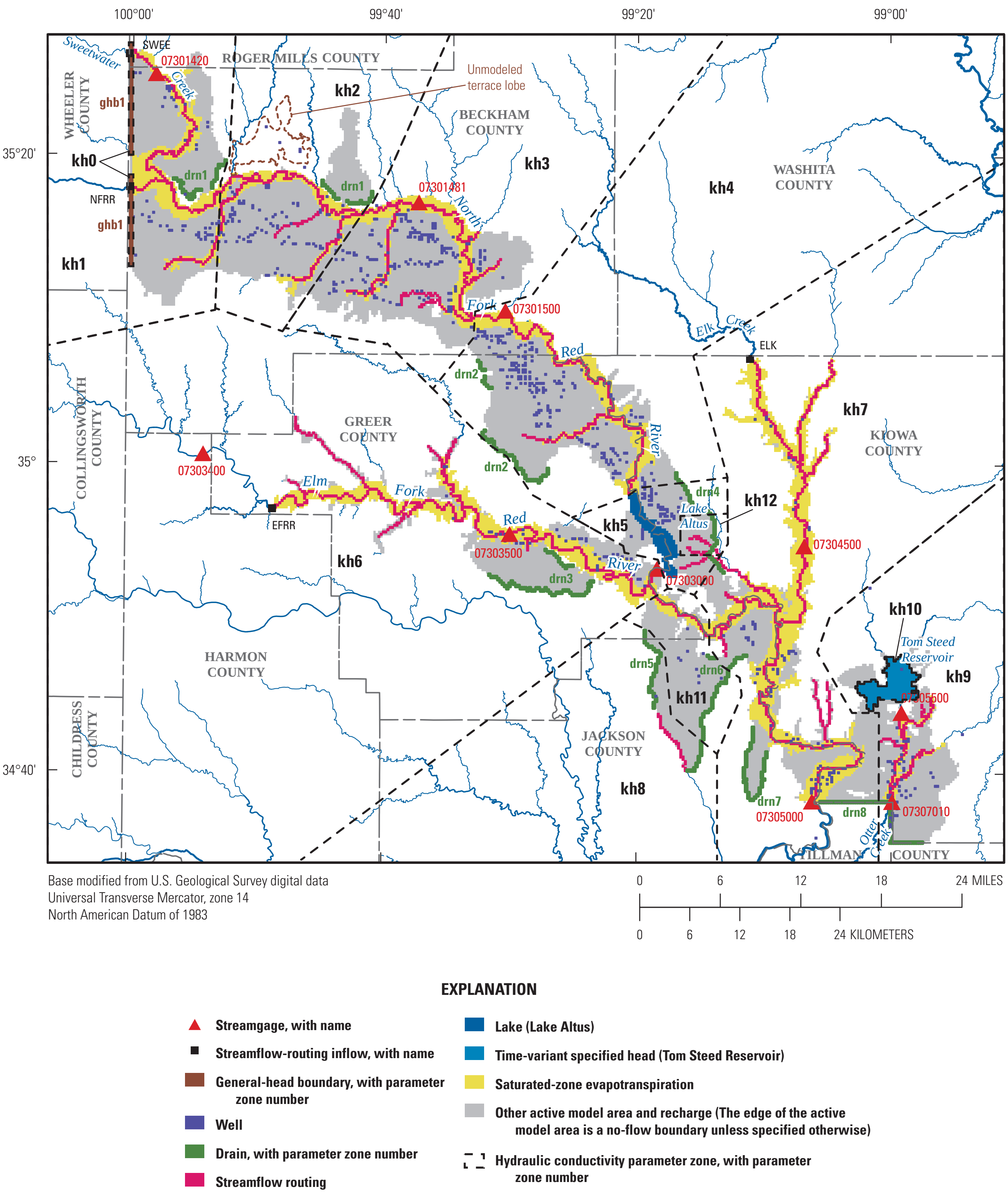


Figure 21. Active area, boundary conditions, and parameter zones for the numerical groundwater-flow model of the North Fork Red River aquifer, southwest Oklahoma.

maximum temperature, and minimum temperature data from selected climate stations (National Climatic Data Center, 2015; Oklahoma Mesonet, 2015; table 1) in and near the study area (fig. 1).

The initial SWB-estimated mean annual recharge for the North Fork Red River aquifer study area for the period 1980–2013 was 1.38 in/yr (fig. 22) or 50 percent of the mean annual recharge (2.77 in/yr) estimated for the conceptual model. The initial SWB code used default plant root-zone depths that were developed for use in northern Wisconsin where crops are grown in soils overlying thick, loosely consolidated deposits of glacial till (Dripps, 2003). Plant root-zone depths in western Oklahoma were assumed to be less than those of Wisconsin, and the default plant root-zone depths were scaled to 70 percent to reduce the simulated interception of soil moisture and increase estimated recharge to the aquifer. With the scaled plant root-zone depths (1.4 to 2.5 ft), the SWB-estimated mean annual recharge was 2.08 in/yr (fig. 22) or 75 percent of the mean annual recharge (2.77 in/yr) estimated for the conceptual model. The plant root-zone depths were not decreased further to avoid unreasonable values. The SWB-output monthly recharge grids were converted to mean daily recharge grids by dividing by the number of days per month; the mean daily recharge grids were used as precalibration numerical model inputs. The remaining difference (0.69 in/yr) between the SWB-estimated mean annual recharge (2.08 in/yr) and the conceptual-model-estimated mean annual recharge (2.77 in/yr) was gained by scaling the SWB monthly recharge grids with multipliers during the numerical model calibration.

The minimum and maximum SWB-estimated annual recharge amounts for the period 1980–2013 were about 0.2 in. (2012) and 4.7 in. (1986), respectively (fig. 22). Spatially, recharge was greatest in areas of active alluvium along the North Fork Red River and in selected areas of the terrace deposits (Qtd) where windblown sand (dune) deposits were abundant (figs. 12 and 23). Mean monthly recharge for the period 1980–2013 was greatest in May and June, when precipitation was greatest (fig. 4). Mean monthly recharge normalized by the mean monthly precipitation was greatest in the winter months, when ET was at a minimum.

Lateral Groundwater Flows

Lateral groundwater flows between the North Fork Red River aquifer and adjoining alluvium and terrace deposits in Texas were simulated by using the General-Head Boundary (GHB) package (Harbaugh and others, 2000) (fig. 21). The flow to or from a GHB cell is the product of the GHB conductance and the difference between the water-table altitude and the GHB altitude. The GHB conductance was roughly equivalent to the hydraulic conductivity of the aquifer multiplied by the numerical model cell size. Based on the potentiometric surfaces of the North Fork Red River aquifer (fig. 14) and the Tillman Terrace aquifer (Osborn, 2002; Barclay and Burton, 1953), lateral groundwater flows across the Tillman County border were expected to always be outflows. Therefore, lateral groundwater outflows from the North Fork Red River aquifer to the Tillman Terrace aquifer were simulated by using the Drain package (Harbaugh and others, 2000) (drn8, fig. 21). The drain conductance was roughly equivalent to the hydraulic conductivity of the aquifer multiplied by the numerical model cell size. Flow between the aquifer and drain cells functions the same way as the GHB package, except that there is no drain flow when the water-table altitude is less than the drain altitude.

Streams

Named streams (Horizon Systems Corporation, 2015) were simulated by using the Streamflow-Routing package, version 2 (SFR) (Niswonger and Prudic, 2005) (fig. 21). Only base flow was simulated in SFR streams. Inflows for SFR streams include base flows routed from upstream segments, specified inflows (base flows) from tributary streams, and streambed seepage from the water table; SFR outflows include base flows routed downstream and streambed seepage to the water table. The SFR package exchanges flow between the aquifer and the stream according to Darcy's Law (Darcy, 1856); the flow exchanged between the aquifer and the stream is the product of the streambed conductance and the difference between the water-table altitude and the stream stage. Simulated base flows are calculated for each part of the stream contained in a model cell, known as reaches, until the end of a segment, or group of cells with uniform or linear hydraulic properties, is reached during each time step. Computation of flows repeats in a downstream direction until flows are routed out of the numerical model active area.

All SFR stream segments were assigned an assumed streambed thickness of 6.6 ft and an estimated streambed conductivity of 16.4 ft/d. This streambed conductivity value was within the expected range of hydraulic conductivity determined from the aquifer hydrogeologic framework and was about 26 percent greater than the streambed conductivity used for a numerical model of the Beaver-North Canadian River alluvial aquifer (Ryter and Correll, 2016). The channel widths of stream segments were estimated from 2013 aerial photographs (Natural Resources Conservation Service, 2015) and ranged from 6.6 to 197 ft, gradually increasing downstream. The streambed altitude of each stream segment was derived from 10-meter DEMs (USGS, 2015b). Monthly base-flow inflows at the boundary of the numerical model active area were specified for Sweetwater Creek (SWEE), North Fork Red River (NFRR), Elk Creek (ELK), and Elm Fork Red River (EFRR) (fig. 21). These specified inflows were assigned based on distance-weighted flow between the nearest upstream and downstream streamgages. For periods when streamgage data were not available, mean monthly base-flow values averaged over the available period of record were used as specified inflows. All other streams were assumed to have no specified inflows at the boundary of the numerical

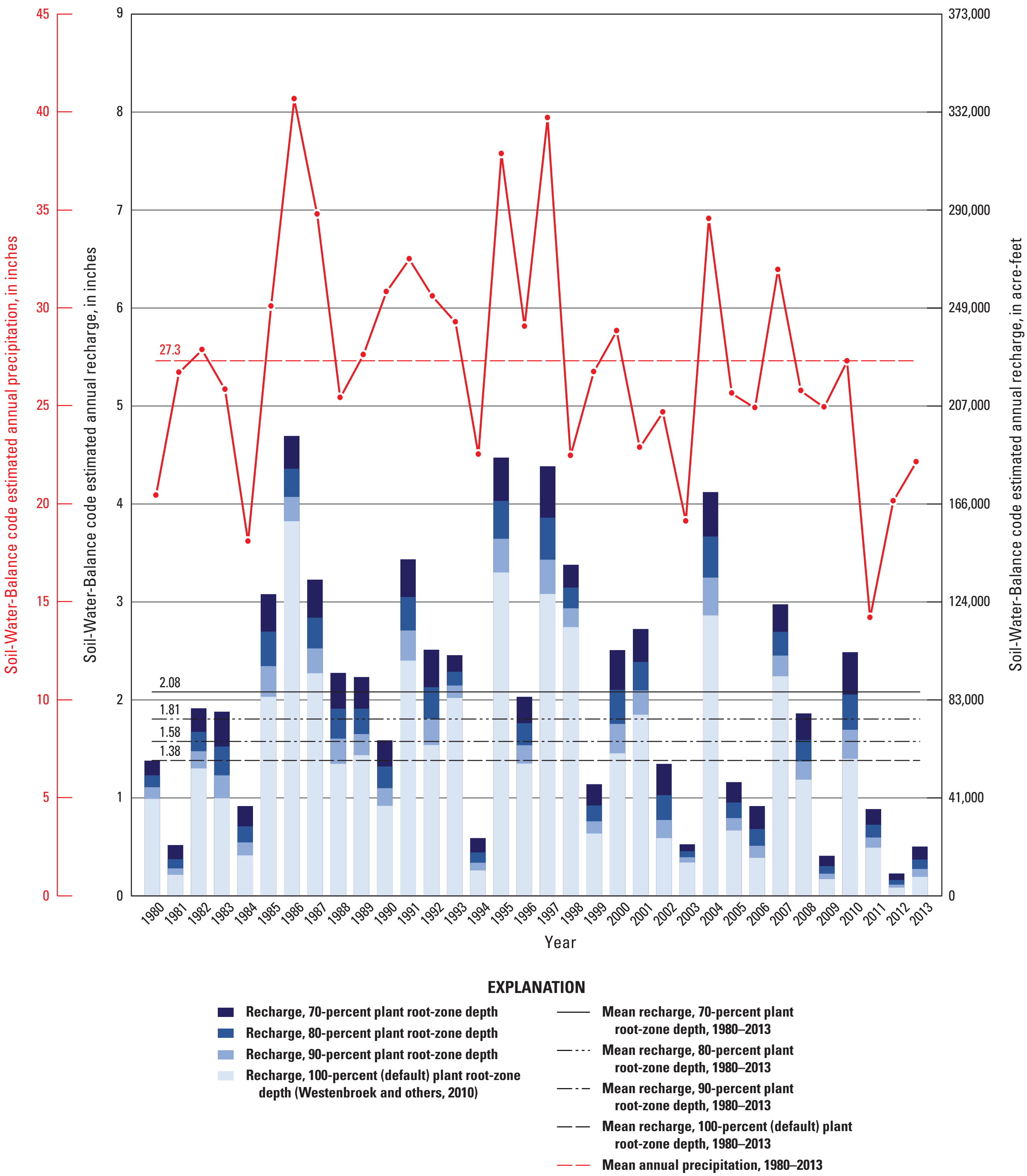


Figure 22. Annual precipitation and annual groundwater recharge computed by using the Soil-Water-Balance code (Westenbroek and others, 2010) for the North Fork Red River aquifer, 1980–2013.

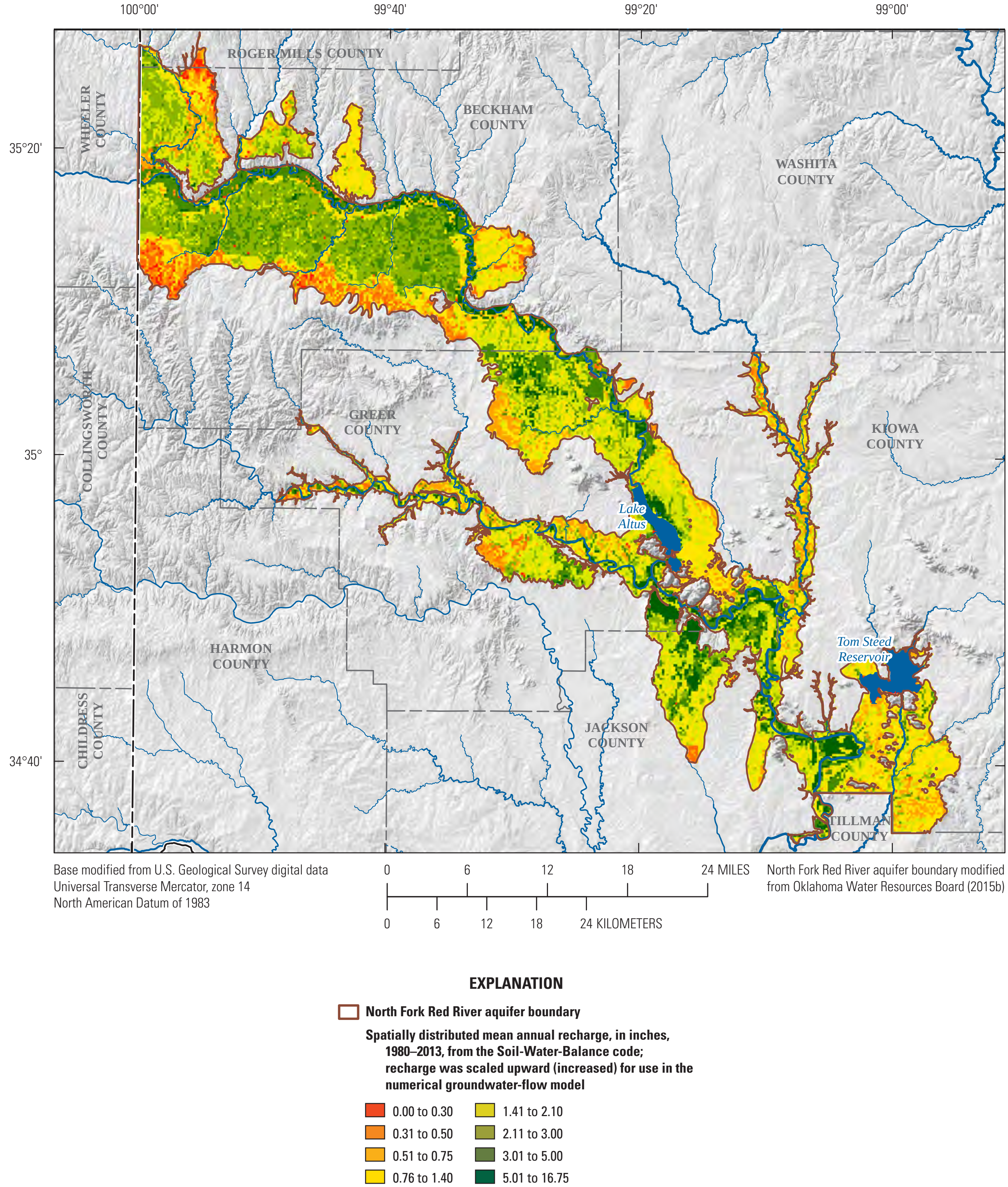


Figure 23. Mean annual groundwater recharge computed by using the Soil-Water-Balance code (Westenbroek and others, 2010) for the North Fork Red River aquifer, 1980–2013.

model active area. Withdrawals from Lake Altus for irrigation (LAID, permit 19390023) and public supply (city of Altus, permit 19260006) were simulated in the model. Permitted diversions from streams were not simulated; although these diversions were allocated about 5,000 acre-ft/yr by OWRB (2015b), the diversions were mostly on small intermittent streams (USGS, 2015b) with minimal to no base flow for much of the year and were considered a minor component in the overall water budget for the study area.

Lakes

Tom Steed Reservoir was simulated as a specified-head boundary by using the Time-Variant Specified-Head package (fig. 21). Simulated lake stage was varied monthly according to historical lake-stage records (U.S. Bureau of Reclamation, 2015c). Monthly lakebed seepage for Tom Steed Reservoir was governed by the hydraulic conductivity of the aquifer.

Lake Altus was simulated by using the Lake package (Merritt and Konikow, 2000; Niswonger and Prudic, 2005) (fig. 21). Lake Altus bathymetry and stage-storage relation data were obtained from a 2007 sedimentation survey (U.S. Bureau of Reclamation, 2014) and the relation was assumed to remain the same through all simulations. Lakebed seepage at Lake Altus was governed by a lakebed leakance factor of 1.3 feet per day per foot. Other data for components of the Lake Altus water budget varied monthly and were obtained from a variety of sources. Estimated lake-surface precipitation and evaporation data were supplied by the U.S. Army Corps of Engineers (2015b) and Andy Kmetz (U.S. Army Corps of Engineers, written commun., September 15, 2014). Lake-withdrawal volumes for irrigation and public-supply use were supplied by the U.S. Bureau of Reclamation (2015b). Flood-control releases were estimated by averaging release data from the U.S. Bureau of Reclamation (2015b) and North Fork Red River streamflows at the Lugert streamgage (07303000, fig. 1; USGS, 2015a). Flood-control releases from Lake Altus were not routed to the downstream SFR segments of the North Fork Red River. Surface-water inflows to Lake Altus were routed as SFR-simulated base flows from the North Fork Red River where it enters the lake (fig. 21). Runoff inflows to Lake Altus were assumed to equal the BFI-estimated runoff component of streamflow at the Carter streamgage (07301500). The Lake package simulation of Lake Altus is the only part of the numerical model that includes the runoff component of streamflow; inclusion of runoff was necessary to simulate the correct lake stage.

Springs and Seeps

Some groundwater was expected to leave the North Fork Red River aquifer through distributed spring and seep discharge areas where terrace deposits extend across major groundwater divides. These spring and seep discharge areas (drn1–drn7; fig. 21) were simulated by using the Drain package. The flow from the aquifer at a drain cell is the product of the drain conductance and the difference between the water-table altitude and the drain altitude. Flow between the aquifer and drain cells functions the same way as the GHB package, except that there is no drain flow when the water-table altitude is less than the drain altitude. The drain conductance varied by location but was roughly equivalent to the hydraulic conductivity of the aquifer multiplied by the numerical model cell size.

Saturated-Zone Evapotranspiration

Saturated-zone ET was simulated by using the Evapotranspiration package (Harbaugh and others, 2000) and was limited to the active alluvium areas near streams in the North Fork Red River aquifer (fig. 21). Maximum rates of saturated-zone ET were assumed to be proportional to and no greater than the potential minus actual ET as computed by the SWB code. The ET extinction depth, or the depth below land surface at which the saturated zone becomes inaccessible to plants, was set to 2.6 ft, which was about the area-weighted mean plant root-zone depth specified in the SWB code.

Well Withdrawals

Well withdrawals were simulated by using the Well package (Harbaugh and others, 2000). Annual reported groundwater use for each permit was distributed evenly to all of the wells attached to that permit (OWRB, 2015b). These annual well withdrawals then were distributed into monthly well withdrawals by using monthly demand distributions (fig. 24) for Oklahoma Comprehensive Water Plan water-management planning basin 36 (fig. 2) (OWRB, 2012a). Annual irrigation well withdrawals were multiplied by the monthly irrigation demand (as a percentage of annual groundwater withdrawals), and annual public-supply well withdrawals were multiplied by the monthly public-supply demand (as a percentage of annual groundwater withdrawals). Annual well withdrawals for other purposes were distributed evenly to all months of the year. Domestic withdrawals, which are not regulated or reported by the OWRB, were not simulated; these withdrawals were expected to be a minor component of total withdrawals because the rural population of the study area was small and most of the study area was served by rural or municipal public water-supply systems (OWRB, 1998).

Groups of wells attached to a single permit were not allowed to exceed (cumulatively) the annual permitted amount. Individual well withdrawals greater than 405 acre-ft/yr (equivalent to a continuous annual pumping rate of 250 gal/min) were considered unreasonable for this aquifer and were reduced to that threshold value to avoid instability in the numerical model. Steady-state well withdrawals were determined as the mean of withdrawals during the study period.

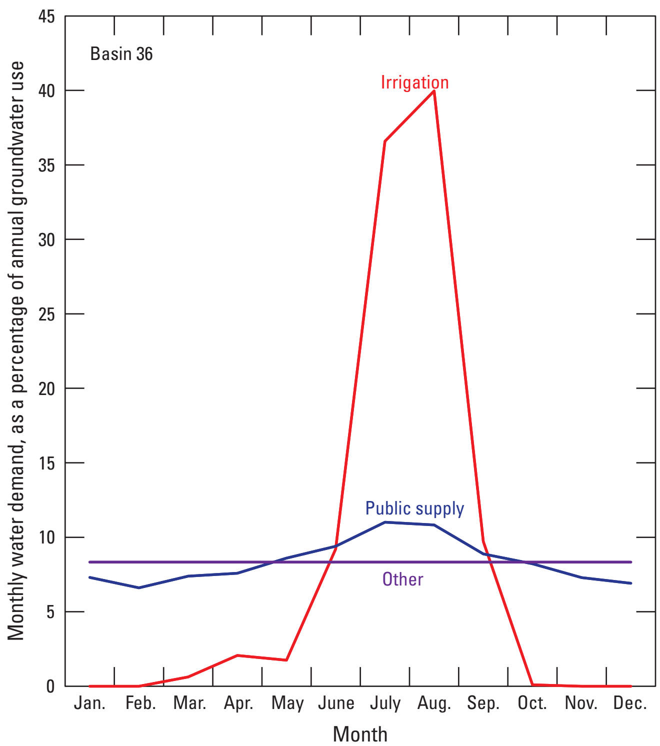


Figure 24. Monthly water demand by groundwater-use type from the North Fork Red River aquifer, 1980–2013. Modified from Oklahoma Water Resources Board (2012a).

Calibration

Model calibration is the process of systematically changing initial model input values (within reasonable limits) to improve the fit between model-simulated data and observed data (calibration targets). The preferred calibration results (1) minimize the differences between the simulated and observed data (residuals) and (2) conform to the conceptual model. The calibration process for the numerical model included manual adjustment of selected model inputs (parameters) followed by automated adjustment of parameters by using the parameter estimation code PEST (Doherty, 2010). The automated calibration approach used singular value decomposition-assist (Doherty, 2010) to reduce run times associated with the calibration of a large number of parameters.

For the North Fork Red River numerical model automated calibration, six parameter groups representing a total of 348 parameters were defined. These parameter groups included 323 parameters for recharge, 14 parameters for Kh (13 zone multipliers [kh0–kh12; fig. 21] and 1 array multiplier), 8 parameters for drain conductance, and 1 parameter each for GHB conductance, ET, and Sy. The locations of the Kh, drain conductance, and GHB conductance parameter zones are shown in figure 21. The recharge parameter group was composed of temporal recharge-rate multipliers for SWB-determined recharge in 323 of the 409 stress periods; the remaining 86 stress periods had negligible recharge. Kh values were grouped into 13 parameter zones (fig. 21), with each zone representing an area where Kh was thought to be relatively uniform. A rate multiplier was specified for each Kh zone and adjusted during calibration. The GHB and drain conductances were adjusted until the water table in the simulated alluvium and terrace locations approached the observed water table. An array multiplier was used to adjust the saturated-zone ET rates and was applied uniformly to all ET arrays for each stress period.

Calibration Targets

The numerical model was calibrated to water-table-altitude observations at selected wells, monthly base flow at selected streamgages, net streambed seepage as estimated for the conceptual model, and Lake Altus stage (table 9). Prior to the calibration process, weights were used to account for data quality. Weights were assigned as the inverse of the standard deviation, and the weighted calibration targets were placed into four observation groups on the basis of observation type (table 9). The objective function, or squared sum of the weighted residuals, provides a measure of the fit between observed and simulated data. The observation group contributions to the objective function (table 9) were adjusted prior to the start of the calibration process to ensure a balance between each group so that no single observation group dominated the calibration process. The base-flow observation group was assigned the greatest contribution to the objective function (37 percent) because those measurements were thought to have the greatest accuracy and temporal coverage during the model period 1980–2013. The water-table-altitude observation group was assigned the second greatest contribution to the objective function (30 percent) because those measurements were thought to have the greatest spatial coverage during the model period 1980–2013.

Table 9. Observation group contribution to the objective function for the automated calibration of the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.

[ft, feet; ft^3/s, cubic feet per second]

Observation group	Source	Number of observations	Group contribution (percent)	Objective function
Water-table altitude	Water-table-altitude observations (Oklahoma Water Resources Board, 2015b; U.S. Geological Survey, 2015a)	[1]1,695	30	29,122
Base flow	Sweetwater streamgage (07301420; U.S. Geological Survey, 2015a)	331	9	8,540
	Carter streamgage (07301500; U.S. Geological Survey, 2015a)	408	20	19,849
	Headrick streamgage (07305000; U.S. Geological Survey, 2015a)	408	8	8,332
Lake stage	Lake Altus stage (U.S. Bureau of Reclamation, 2015b)	408	22	21,556
Net streambed seepage	Conceptual groundwater-flow model (table 8)	1	11	10,818
		3,251	**100**	**98,217**

[1]Of the 2,079 water-table-altitude observations (table 11), 384 were removed from the automated calibration because they showed little sensitivity to any parameter changes.

Water-Table-Altitude Observations

The automated numerical model calibration used 1,695 water-table-altitude observations at 150 wells in the study area (table 1); 384 of the 2,079 water-table-altitude observations were removed from the automated calibration because they showed little sensitivity to any parameter changes. The majority of the water-table-altitude observations were annual measurements from OWRB (2015b) Mass Measurement Program wells, and those wells were distributed across most of the aquifer (some locations shown on fig. 1). Supplemental water-table-altitude observations were obtained from the USGS (2015a) (locations not shown on fig. 1). Most years in the study period 1980–2013 had greater than 60 total water-table-altitude observations (fig. 25*A*), but the number of water-table-altitude observations in each year generally decreased over time. Water-table-altitude observations during February–March 1980 were used as calibration targets for the steady-state stress period, and water-table-altitude observations during February–March 2014 were used as December 2013 calibration targets. All water-table-altitude observations were originally collected as depth-to-water measurements; water-table altitudes were calculated by subtracting the measured depth to water from the land-surface altitude specified by a 10-meter DEM (USGS, 2015b).

Weights were determined based on the location and altitude accuracy of each water-table-altitude observation well using methods of Clark and Hart (2009) and Hill and Tiedeman (2007). The location and altitude accuracy values recorded in the NWIS (USGS, 2015a) and OWRB (2015b) databases are based on the measurement methods, typically either a Global Positioning System or a topographic map. The recorded location accuracy was between 0.1 and 9.2 arc-seconds for water-table-altitude observation wells completed in the North Fork Red River aquifer. A radius equal to the location accuracy was created for each observation well, and the standard deviation of DEM land-surface altitudes in that radius was calculated. The standard deviation of the altitude accuracy was calculated by dividing half of the altitude accuracy code (in feet) by the critical value of a 95-percent confidence interval (Hill and Tiedeman, 2007). Standard deviations for the water-table-altitude observation wells ranged from 0.13 to 15.9 ft with a mean of 3.1 ft.

Base Flow and Net Streambed Seepage

The numerical model was manually calibrated to base-flow observations at six streamgages (fig. 25*B*), but the automated calibration only used base-flow observations from three streamgages that had long periods of record covering most of the model period (table 9). Monthly base-flow observations were available for each monthly stress period at the Carter (07301500) and Headrick (07305000) streamgages and for each monthly stress period since May 1986 at the Sweetwater streamgage (07301420) (fig. 25*B*, table 1). These 1,147 monthly base-flow observations were used as transient calibration targets. Monthly base-flow observations were available for shorter periods at other streamgages, but those observations were not used in the automated numerical model calibration. The base-flow observation uncertainty was determined by using the accuracy code for the streamflow data at each streamgage in NWIS. The majority of the field streamflow measurements during the transient period received a “fair” rating in NWIS, which corresponds to a 95-percent confidence interval of ±15 percent of true streamflow (USGS, 2015c). The standard deviation for the base-flow observations at each streamgage was then calculated as 15 percent of the base flow, divided by the critical value of a 95-percent confidence interval.

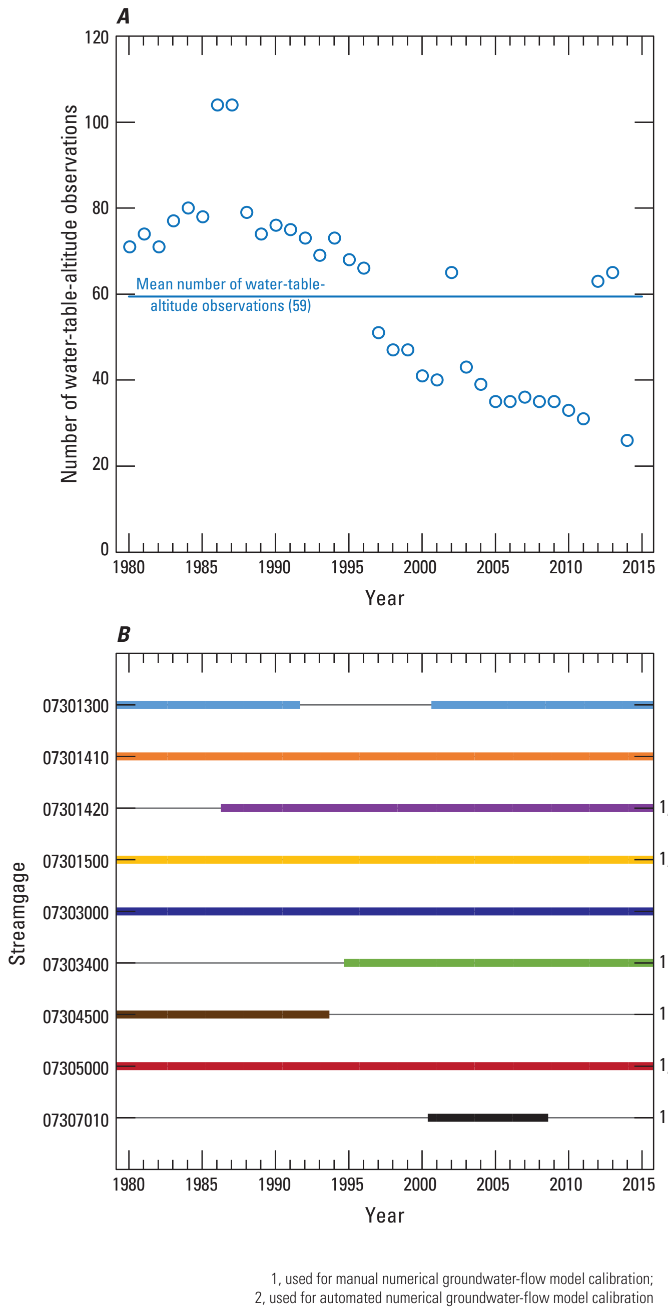


Figure 25. Temporal distribution of *A*, water-table-altitude observations and *B*, streamflow observations for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2015.

Net streambed seepage upgradient from Lake Altus (table 8) also was used as a calibration target. The simulated net streambed seepage upgradient from Lake Altus was determined as the sum of the "Flow to Aquifer" column in the SFR flow file divided by the 408 monthly stress periods for the transient simulation (Smith and others, 2017). Weights for the streambed seepage were assigned by using methods from Hill and Tiedeman (2007) and were given a 95-percent confidence interval of ±15 percent of actual flow. The standard deviations and variance of the base flow at each streamgage during the transient period were calculated, and the upstream and downstream streamgage variances were summed to produce a standard deviation for the streambed seepage.

Lake Altus Stage

Lake Altus stage observations from the U.S. Bureau of Reclamation (2015b) were referenced to the National Geodetic Vertical Datum of 1929; therefore, a conversion factor of 0.5 ft (National Oceanic and Atmospheric Administration, 2015) was added to reference these observations to the North American Vertical Datum of 1988 (NAVD 88). At normal-pool stage (1,559.5 ft above NAVD 88), Lake Altus storage was about 134,000 acre-ft; at inactive-pool stage (1,518.0 ft above NAVD 88), Lake Altus storage was about 1,600 acre-ft (U.S. Bureau of Reclamation, 2014). Because the inactive-pool storage was relatively small, it was not removed from estimates of Lake Altus storage used in this report.

Calibration Results

Calibration results were evaluated on the basis of the reduction of residuals and the fit of the calibrated numerical model water-budget components to those of the conceptual-model water budget. Residuals were calculated as observed minus simulated values; positive residuals indicate lower simulated than observed values, and negative residuals indicate higher simulated than observed values.

Simulated Aquifer Thickness and Saturated Thickness

The simulated mean aquifer thickness was 71 ft, and the simulated mean aquifer saturated thickness at the end of the simulation was 38 ft (table 10). The simulated maximum aquifer thickness was 326 ft and was located in cells adjacent to mountains downgradient from Lake Altus (table 10). These cells represent colluvium materials that were considered to be part of the aquifer, but probably have minimal saturated thickness. The large aquifer thickness in those cells was an artifact of the steep slope of the mountains downgradient from Lake Altus combined with the 886-by-886-ft model cell size, which resulted in overestimation of the aquifer top altitude. The simulated maximum aquifer thickness of 267 ft upgradient from Lake Altus (in central Beckham County) is more representative of the actual maximum aquifer thickness (table 10).

Table 10. Statistical summary of aquifer thickness, saturated thickness, and hydraulic properties for the calibrated numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.

[mi^2, square miles; ft, feet; ft/d, feet per day]

Aquifer part	Cell count	Area (mi^2)	Aquifer thickness (ft)			Aquifer saturated thickness (ft)			Hydraulic conductivity (ft/d)			Specific yield
			Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	
Upgradient from Lake Altus	15,075	424	31	79	267	0	41	183	8.4	36.5	114	0.12
Downgradient from Lake Altus	12,547	353	31	62	[1]326	0	35	82	16.1	57.8	119	0.12
Total (weighted)	27,622	777	31	71	[1]326	0	38	183	8.4	46.2	119	0.12

[1]The calibrated maximum aquifer thickness downgradient from Lake Altus is found in cells adjacent to mountains. The large aquifer thickness in those cells was an artifact of the steep slope of the mountains downgradient from Lake Altus combined with the 886-ft-by-886-ft model cell size, which resulted in overestimation of the aquifer-top altitude. The calibrated maximum aquifer thickness of 267 ft upgradient from Lake Altus (in cells of central Beckham County) is more representative of the actual maximum aquifer thickness.

Comparison of Simulated and Observed Values

Simulated and observed water levels were compared by using standard graphs (fig. 26) and statistical summaries (table 11). The combined mean residual for steady-state and transient simulations was –0.6 ft, indicating that, on average, simulated water levels were slightly higher than observed water levels. The combined water-table altitude root-mean-square error (RMSE) was 11.8 ft, and 75 percent of residuals were within ±13.9 ft of observed measurements (table 11). The simulated water-table relief was 799 ft (2,110–1,311 ft), and the combined RMSE as a percentage of this water-table relief was 1.5 percent. These error statistics were about double those for Reach I of the Canadian River alluvial aquifer (Ellis and others, 2017); however, the North Fork Red River aquifer had a more complex geologic setting and much greater well withdrawals than the Canadian River alluvial aquifer.

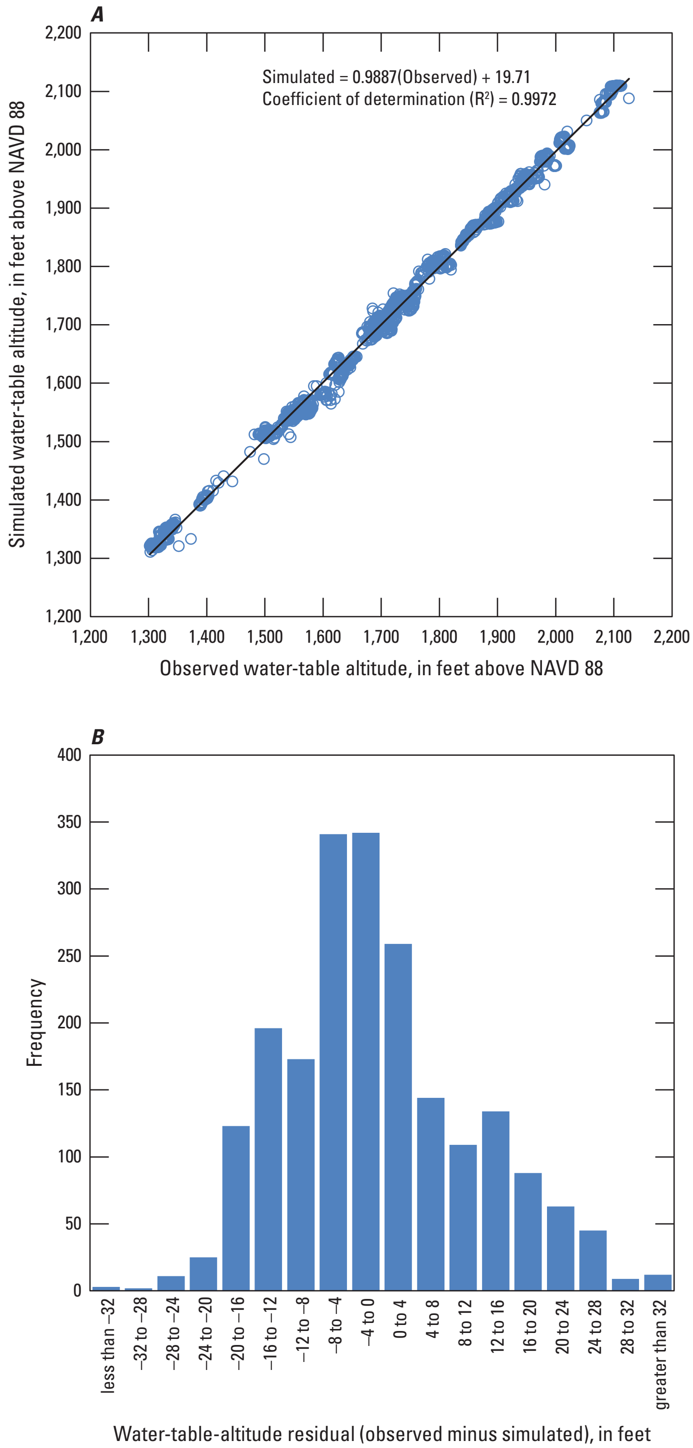


Figure 26. *A*, Observed and simulated water-table altitudes and *B*, water-table-altitude residual distributions for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013. [NAVD 88, North American Vertical Datum of 1988]

Table 11. Statistical summary of water-table-altitude residuals for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.

[±, plus or minus; RMSE, root-mean-square error]

Statistic	Steady-state	Transient	Combined
Observation count	67	2,012	2,079
Mean residual, in feet	–0.9	–0.6	–0.6
75th-percentile residual range, in feet	±16	±13.9	±13.9
RMSE, in feet	14.1	11.8	11.8
RMSE percentage of water-table relief (799 feet)	1.8	1.5	1.5

Water-table-altitude residuals were generally largest (observed greater than simulated) in the most upgradient (from local streams) terrace, where observed hydraulic gradients up to 60 feet per mile steeply slope towards the North Fork Red River and tributary streams (fig. 27). In contrast, simulated water levels near the active alluvium (base-flow discharge areas) were generally higher than observed water levels, particularly at altitudes between 1,700 and 1,800 ft in the central part of the study area (figs. 26–27). Simulated water levels that are less than observed in the upgradient terrace and greater than observed in the downgradient active alluvium (base-flow discharge areas) could both be explained by differences between the complexity (resolution) of the simulated and observed aquifer. Because of generalizations inherent in spatial discretization, modeled flow paths are likely to be simplified and shortened versions of actual flow paths (Mandelbrot, 1983). Simulated hydraulic gradients and recharge-to-discharge travel times, therefore, are likely to be smaller than observed. Simulated well hydrographs generally matched the trends of observed well hydrographs, but the magnitude of the simulated water-level change was typically less than the magnitude of the observed water-level change (fig. 28).

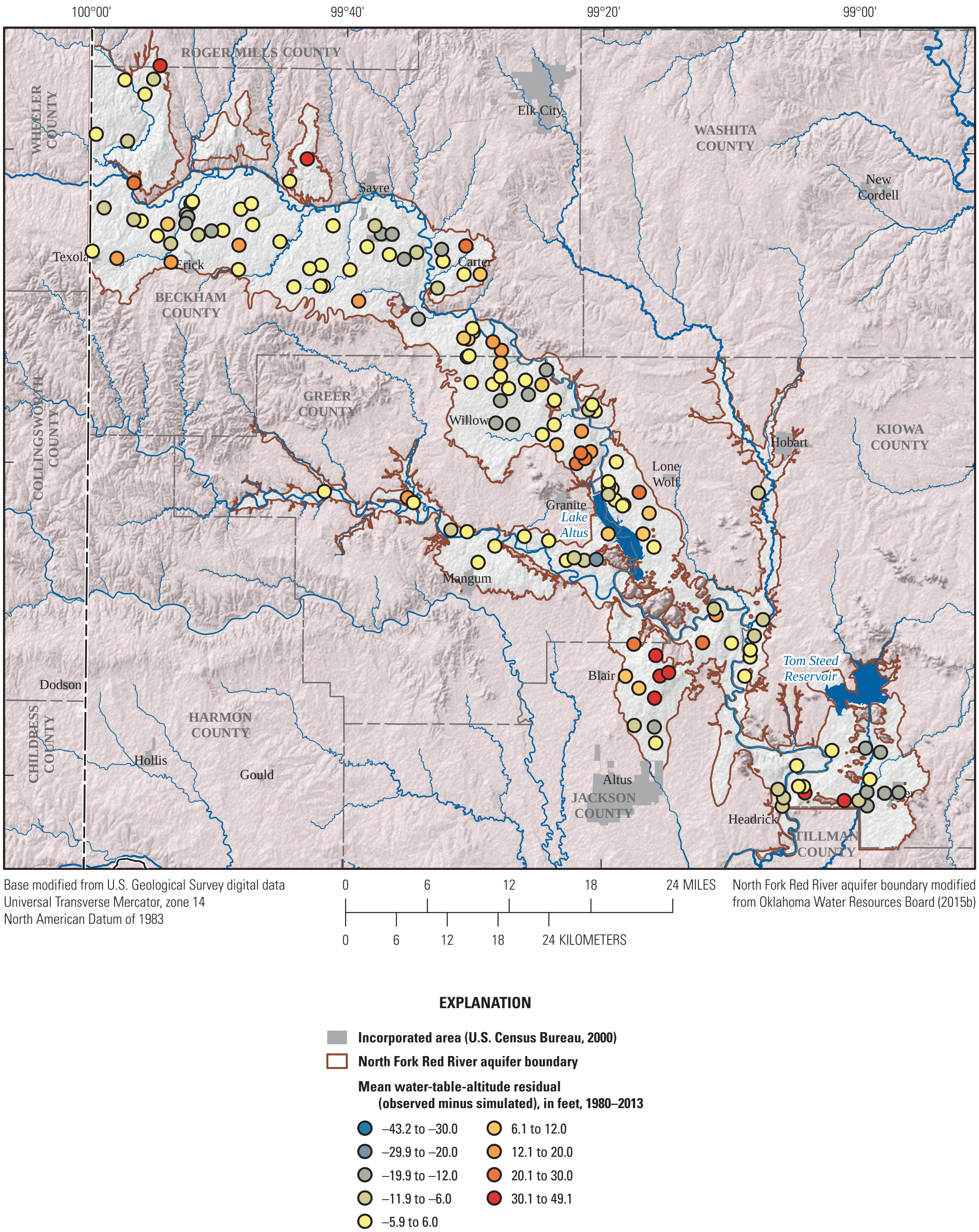


Figure 27. Spatial distribution of mean water-table-altitude residuals for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.

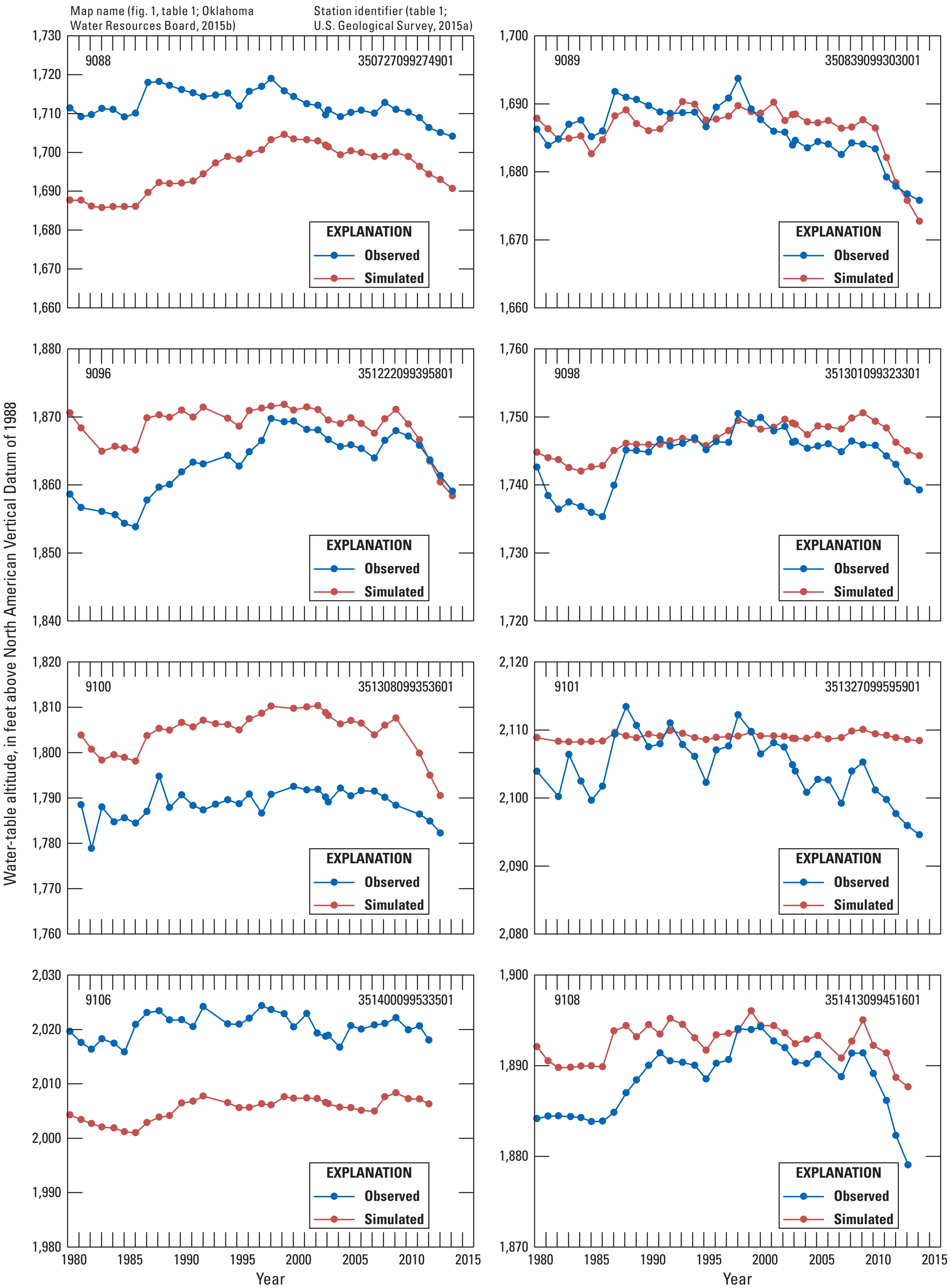


Figure 28. Observed and simulated water-table altitudes for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.

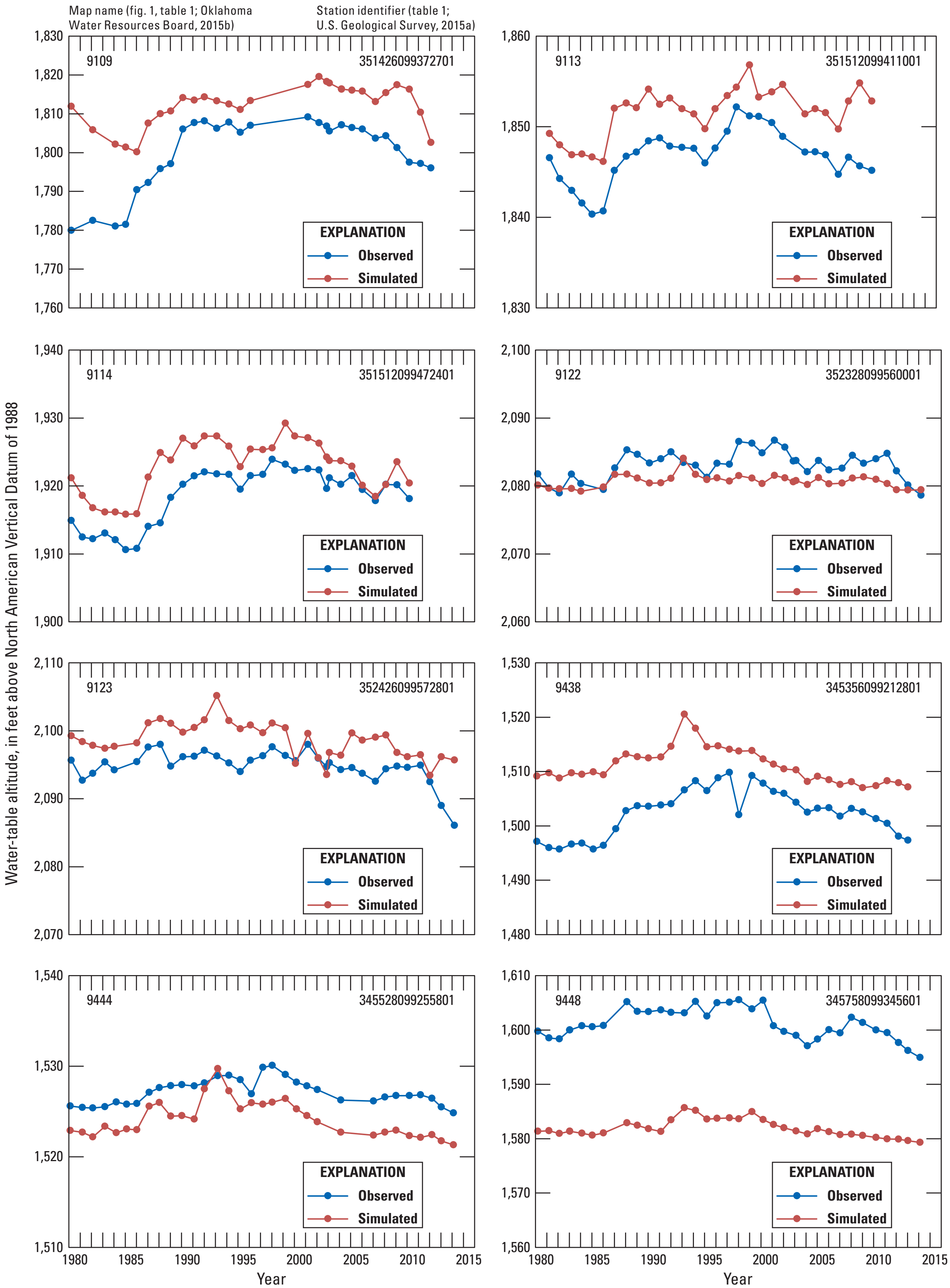


Figure 28. Observed and simulated water-table altitudes for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.—Continued

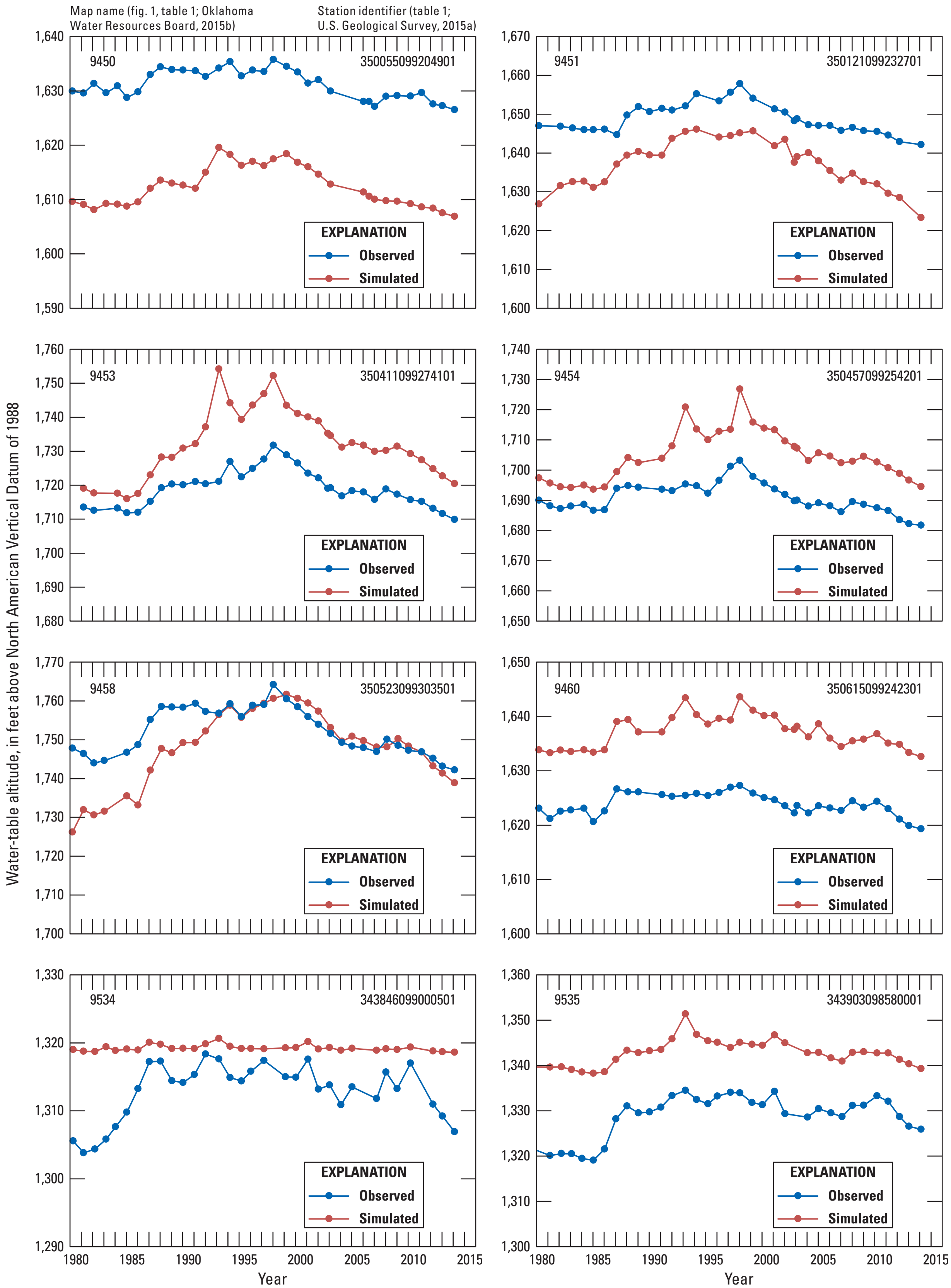


Figure 28. Observed and simulated water-table altitudes for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.—Continued

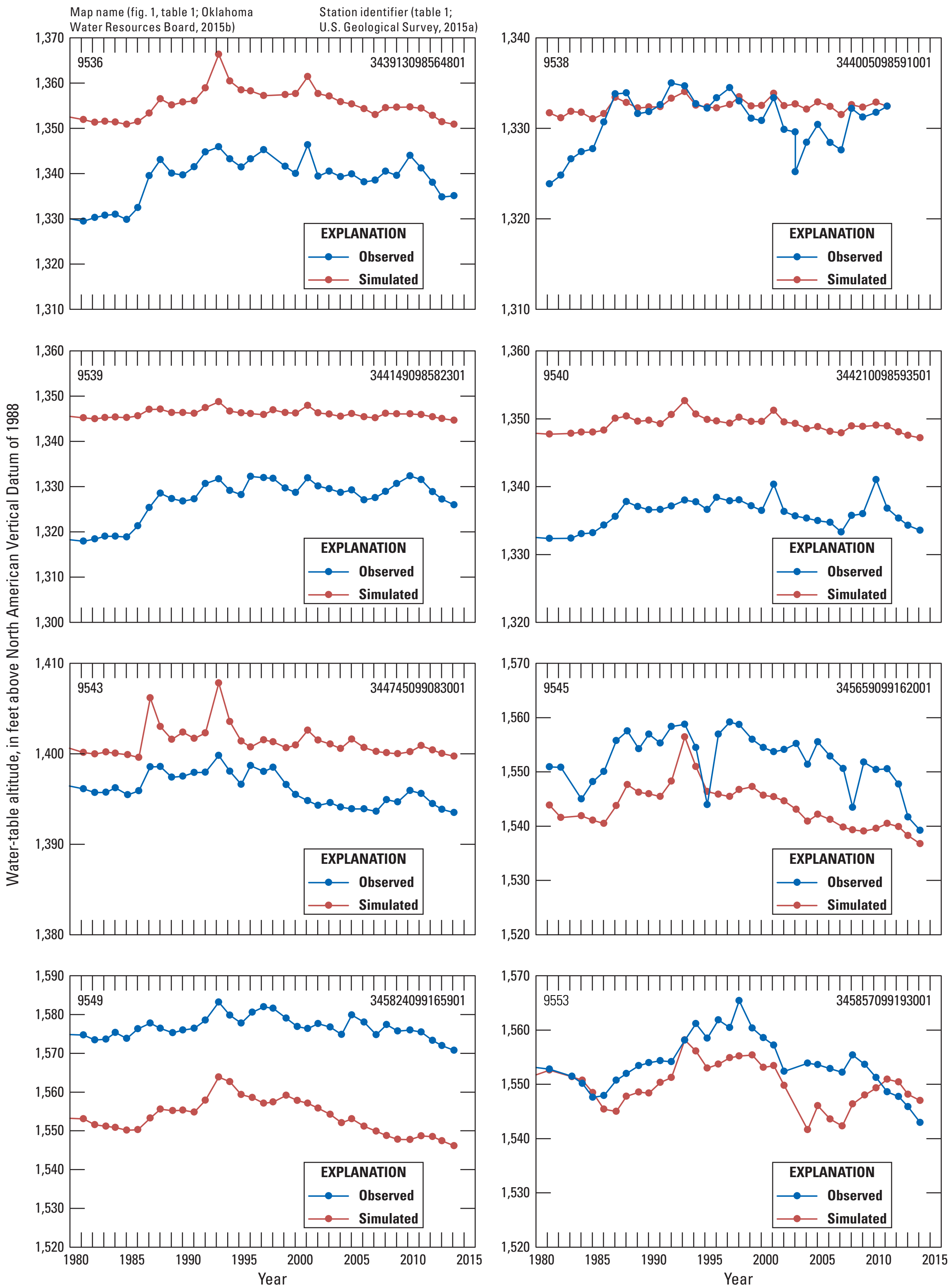


Figure 28. Observed and simulated water-table altitudes for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.—Continued

Automated calibration of the numerical model used base-flow data from the Sweetwater (07301420), Carter (07301500), and Headrick (07305000) streamgages, and manual calibration also incorporated base-flow data from the Carl (07303400), Hobart (07304500), and Snyder (07307010) streamgages (fig. 29, table 12). The mean simulated base flow was lower than the mean observed base flow for three of the six streamgages (table 12). For the two streamgages on North Fork Red River (Carter and Headrick), the RMSE was less than 10 percent of the range in observed base flow (table 12). For the four tributary streamgages, the RMSE was between about 2 and 15 percent of the range in observed base flow (table 12). The simulated base flows at the Carl (07303400) and Hobart (07304500) streamgages were mostly determined from specified inflows a short distance upstream and, therefore, are not shown in figure 29.

Periods of near zero flow occurring at most streamgages during summer months could not be completely reproduced (fig. 29, table 12). These overestimated summer low flows could be the result of underestimated saturated-zone ET, which is greatest in the summer months; however, saturated-zone ET could not be increased without also increasing recharge or negatively affecting residuals of other calibration targets. Base-flow residuals were generally larger during spring and fall high-flow periods than during summer low-flow periods (fig. 29), possibly indicating that observed base flows were overestimated by the BFI code (either because of reservoir releases or recharge processes such as bank storage flow or interflow that mostly operate on a submonthly time scale). The primary source of water to the aquifer is recharge, so large positive base-flow residuals (observed greater than simulated) also could be caused by underestimated or incorrectly distributed (spatially) recharge. Base-flow residuals were largest for the Headrick streamgage (07305000) (table 12). The observed base flow for the Headrick streamgage (07305000) is, to some degree, related to releases from Lake Altus that occurred during the study period, particularly during years 1986–88, 1993, 1997–98, and 2007 (fig. 29). No reliable or justifiable method was found for removing the effects of the Lake Altus and Tom Steed Reservoir releases on the observed base flows at the respective Headrick (07305000) and Snyder (07307010) streamgages.

The mean Lake Altus stage residual was 0.4 ft (table 13), indicating that the mean simulated stage was slightly lower than the mean observed stage (fig. 30). The RMSE was 3.7 ft, and 75 percent of the lake-stage residuals were within ±4.2 ft of observed stage. The maximum observed and simulated stage were both 1,561 ft, whereas the minimum simulated stage was 3 ft higher than the minimum observed stage. The largest Lake Altus stage residuals occurred in late 1981, late 1985, late 1994, and late 1998 when lake storage was relatively low; simulated Lake Altus stage also poorly matched observed stage during drought conditions in 2011–13 (fig. 30).

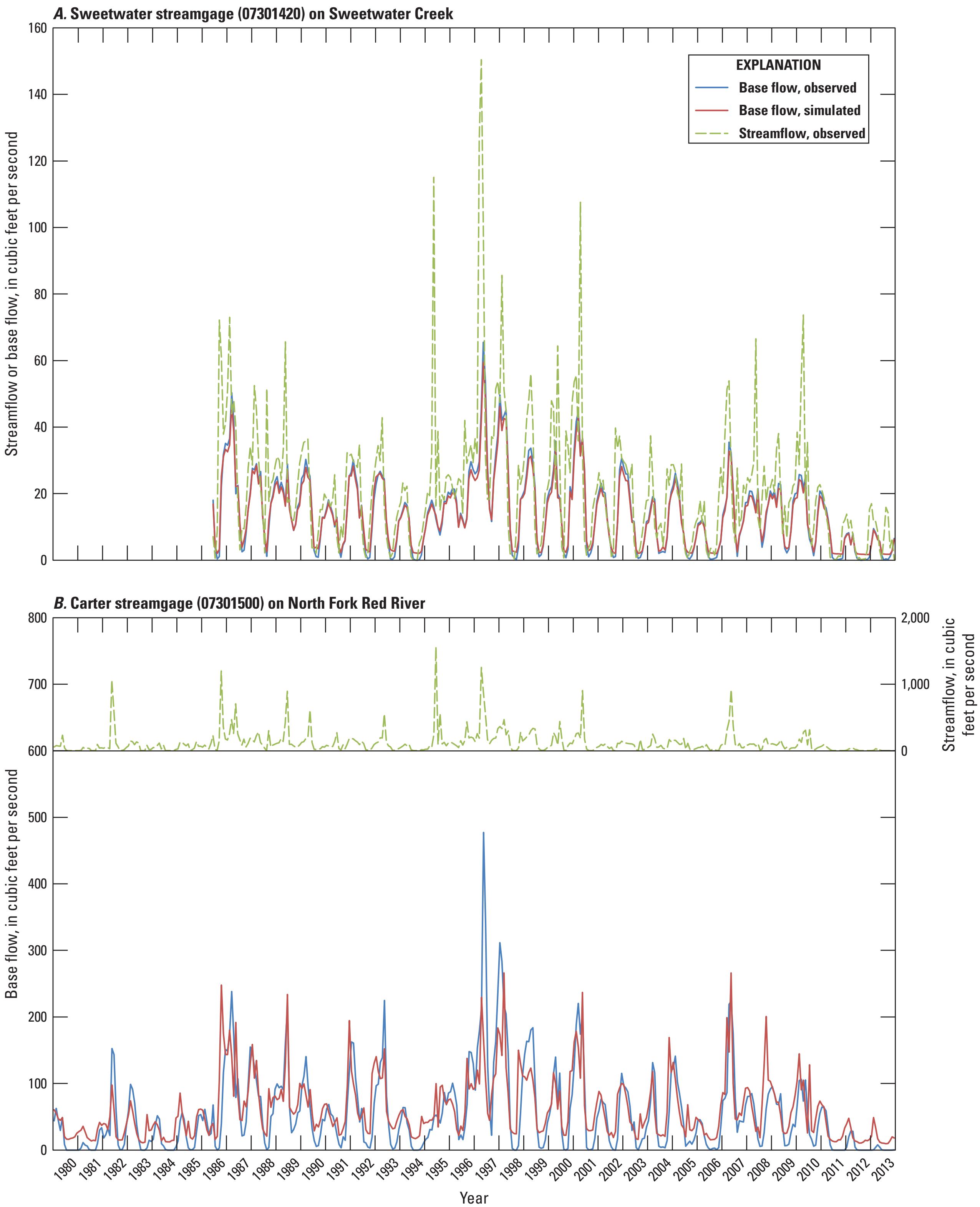


Figure 29. Observed streamflow, observed base flow, and simulated base flow at *A*, Sweetwater streamgage (07301420) on Sweetwater Creek; *B*, Carter streamgage (07301500) on North Fork Red River; *C*, Headrick streamgage (07305000) on North Fork Red River; and *D*, Snyder streamgage (07307010) on Otter Creek for the numerical groundwater-flow model of the North Fork Red River aquifer, southwest Oklahoma, 1980–2013.

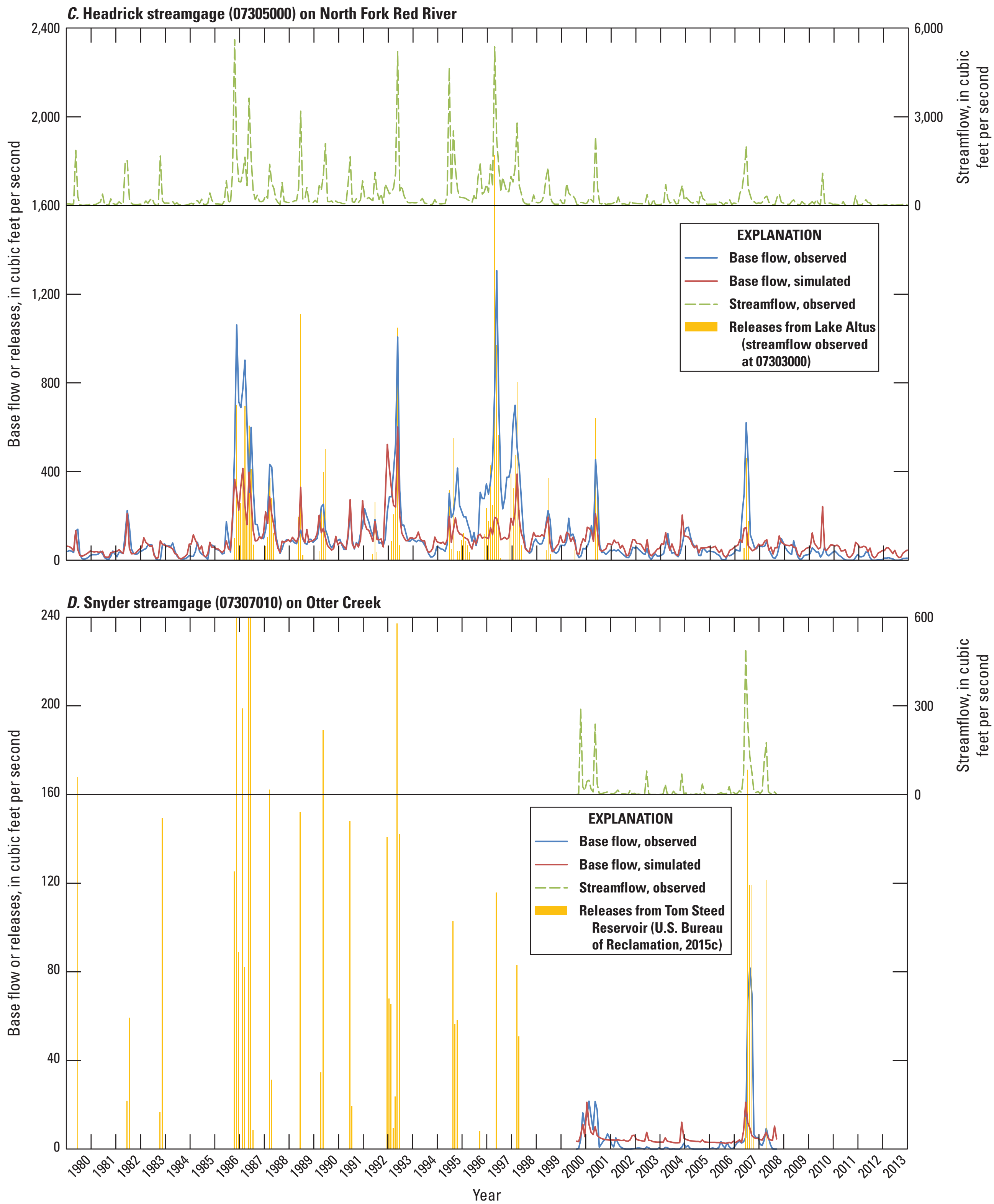


Figure 29. Observed streamflow, observed base flow, and simulated base flow at *A*, Sweetwater streamgage (07301420) on Sweetwater Creek; *B*, Carter streamgage (07301500) on North Fork Red River; *C*, Headrick streamgage (07305000) on North Fork Red River; and *D*, Snyder streamgage (07307010) on Otter Creek for the numerical groundwater-flow model of the North Fork Red River aquifer, southwest Oklahoma, 1980–2013.—Continued

Table 12. Statistical summary of base-flow residuals for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.

[Residual is calculated as the observed minus the simulated value; thus, a negative number indicates higher simulated than observed values. ft^3/s, cubic foot per second; RMSE, root-mean-square error; ±, plus or minus]

Station	Available data in the study period 1980–2013		Drainage area (square miles)	Observed base flow (ft^3/s)			Simulated base flow (ft^3/s)			Base-flow residuals (ft^3/s)			RMSE percentage of range in observed base flow
	Begin	End		Minimum	Mean[1]	Maximum	Minimum	Mean	Maximum	Mean	75th-percentile range	RMSE	
Sweetwater streamgage (07301420) on Sweetwater Creek	4/22/1986	12/31/2013	437	0.0	14.6	65.5	1.7	14.3	59.5	0.2	±1.6	1.4	2.2
Carter streamgage (07301500) on North Fork Red River	1/1/1980	12/31/2013	2,652	0.0	54.6	477.2	9.4	61.5	266.2	-6.8	±30.3	40.8	8.6
Carl streamgage (07303400) on Elm Fork Red River	10/1/1994	12/31/2013	438	0.2	15.5	124.2	1.4	21.2	129.6	-5.6	±6.1	9.5	7.7
Hobart streamgage (07304500) on Elk Creek	1/1/1980	9/30/1993	549	0.1	36.0	356.6	0.0	35.9	385.6	0.0	±4.1	6.4	1.8
Headrick streamgage (07305000) on North Fork Red River	1/1/1980	12/31/2013	4,560	0.0	111.6	1,306.6	6.7	88.3	600.3	23.3	±46.0	127.2	9.7
Snyder streamgage (07307010) on Otter Creek	7/1/2000	10/5/2008	162	0.0	4.8	81.9	2.6	4.9	21.1	-0.1	±3.8	12.0	14.7

[1]Mean observed base flow may differ from values in table 2 because of rounding and inclusion of partial years of record.

Table 13. Statistical summary of lake-stage residuals for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.

[RMSE, root-mean-square error; ±, plus or minus]

Observation	Lake stage		
	Minimum	Mean	Maximum
Observed, in feet	1,523	1,546	1,561
Simulated, in feet	1,526	1,546	1,561
Mean residual, in feet		0.4	
RMSE, in feet		3.7	
75th-percentile residual range, in feet		±4.2	

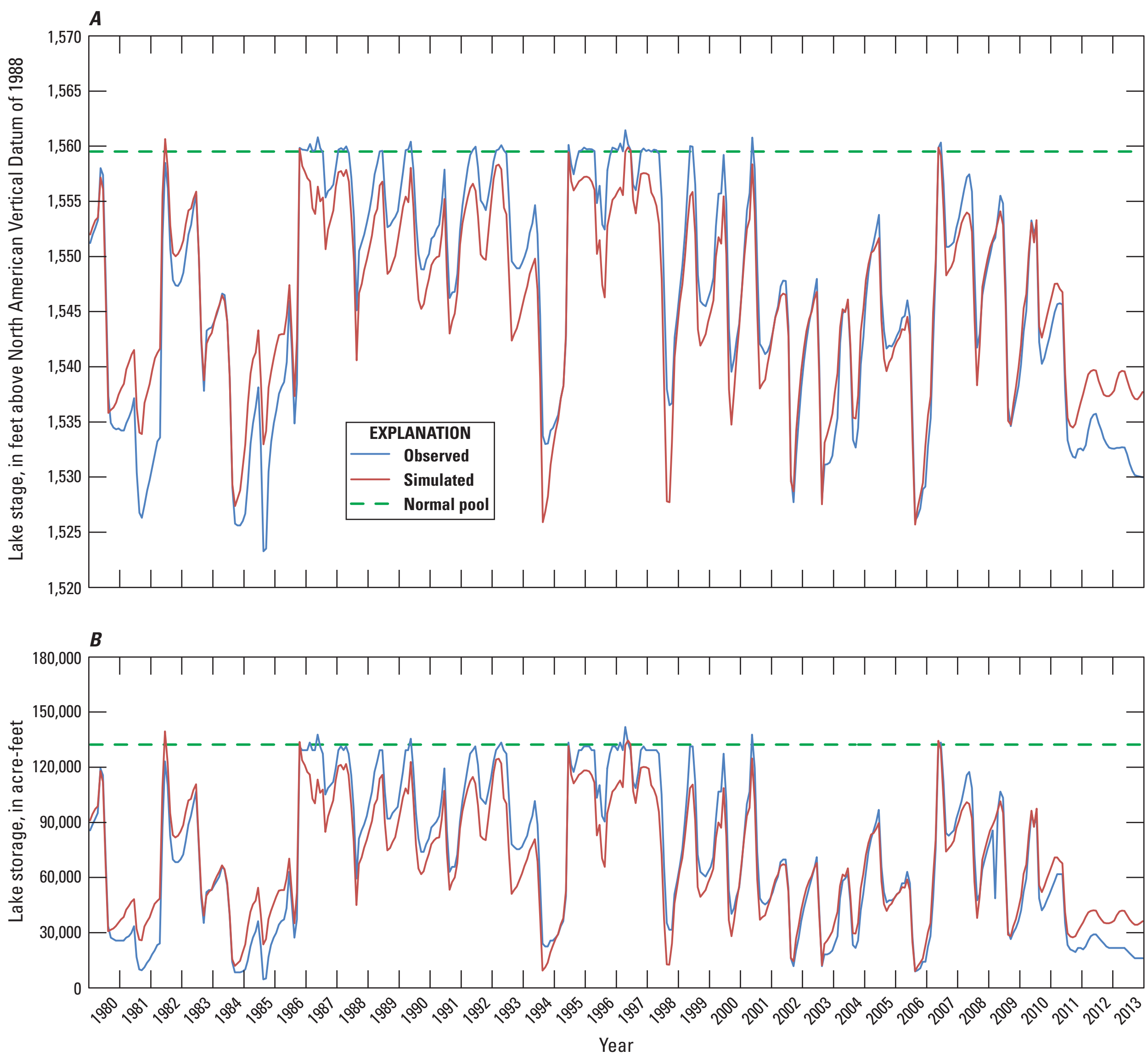


Figure 30. Lake Altus *A*, stage and *B*, simulated storage for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.

Calibrated Water Budget

The calibrated water budget (table 14) lists mean annual inflows and outflows for the calibrated numerical model for the period 1980–2013; a sub-accounting for areas upgradient and downgradient from Lake Altus was computed by using the ZONEBUDGET utility (Harbaugh, 1990). The calibrated water budget shows more inflow and outflow categories than the conceptual model (table 8), because subcomponents of the net water-budget categories can be quantified in the calibrated water budget. Simulated recharge (79 percent of inflows) was the largest inflow for the calibrated numerical model; seepage from streams was about 14 percent, lakebed seepage was about 4 percent, and lateral groundwater inflow was about 3 percent of inflows. Seepage to streams (56 percent of outflows) was the largest outflow for the calibrated numerical model; saturated-zone ET was about 23 percent, lateral groundwater outflow (with springs and seeps) was about 10 percent, well withdrawals were about 8 percent, and lakebed seepage was about 2 percent of outflows.

Recharge for the calibrated numerical model (about 122,000 acre-ft/yr or 2.94 in/yr over the aquifer area of 497,582 acres, table 14) was about 6 percent greater than that of the conceptual model (fig. 16, table 8). Net streambed seepage for the calibrated numerical model was about 4 percent less than that of the conceptual model. This difference could be caused in part by streambed seepage between Carter (07301500) and Lake Altus that was not estimated in the conceptual model. Saturated-zone ET for the calibrated numerical model, which was estimated by using many assumptions, was about 40 percent greater than that of the conceptual model (but less than the saturated-zone ET for the similar Reach I calibrated numerical models of Ryter and Correll [2016] and Ellis and others [2017]). The 67-percent (about 4,800-acre-ft/yr) increase in simulated lateral flow, seeps, and springs as compared to the conceptual model reflects uncertainty in estimating these components without published flow rates. The simulated well withdrawals were about 16 percent less than the conceptual-model well withdrawals because of (1) previously described thresholds (see Well Withdrawals section of this report) applied to permits and wells and (2) a lack of adequate simulated saturation in some areas of the terrace; well withdrawal rates specified in the model are automatically reduced when the simulated saturated thickness nears zero.

Table 14. Mean annual water budget for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.

[All units in acre-feet per year; net budget totals are calculated as inflow minus outflow; therefore, positive values indicate net inflow, and negative numbers indicate net outflow; components may not sum to totals because of rounding]

Water-budget category	Upgradient from Lake Altus	Downgradient from Lake Altus	Total	Percentage of water budget
Inflow				
Recharge	68,054	54,247	[1]122,301	79%
Streambed seepage from streams	9,597	12,082	21,679	14%
Lakebed seepage inflow	5,009	1,320	6,328	4%
Lateral groundwater inflow	4,701	0	4,701	3%
Total inflow	**87,360**	**67,648**	**155,009**	**100%**
Outflow				
Streambed seepage to streams	43,879	46,530	90,409	56%
Saturated-zone evapotranspiration	21,868	15,591	37,459	23%
Lateral groundwater outflow, springs, and seeps	7,529	9,223	16,752	10%
Well withdrawals	11,472	1,899	13,371	8%
Lakebed seepage outflow	2,630	667	3,297	2%
Total outflow	**87,377**	**73,910**	**161,288**	**100%**
Net water-budget totals				
Net streambed seepage	–34,282	–34,448	–68,730	
Net lateral flow, springs, and seeps	–2,828	–9,223	–12,051	
Net lakebed seepage	2,379	652	3,031	
Net change in groundwater storage[2]	4,165	2,117	6,282	

[1]Equals 2.94 inches per year over the aquifer area of 497,582 acres.

[2]Positive net change in groundwater storage indicates loss of groundwater storage from the aquifer; loss of groundwater storage is reported as an aquifer inflow in the numerical groundwater-flow model mass balance.

Simulated groundwater storage generally increased during a relatively long period of above-average precipitation (fig. 3) and recharge (fig. 31) in 1985–2000. This period was followed by a period of generally near-average to below-average precipitation (fig. 3) and recharge (fig. 31) during 2001–13 when simulated groundwater storage decreased, particularly during 2010–13. The period 2010–13 coincides with a regional drought in southwest Oklahoma (fig. 3). A correlated water-level response to these precipitation trends is demonstrated in the hydrographs of water-table-altitude observation wells located in the terrace, particularly wells 9089, 9096, 9100, 9101, 9108, and 9109 (fig. 28). Because recharge accounts for nearly 80 percent of the total calibrated model inflow to the aquifer (fig. 16; table 14), changes in precipitation have a large effect on groundwater storage and the annual water budget. The annual water budget during years when recharge was large relative to the period of record mean, such as 1986–87 and 1995 (fig. 31), was greater than the annual water budget during other years of the study period. At the end of the study period, mean simulated outflows exceeded inflows by about 6,300 acre-ft/yr (table 14). This difference is equivalent to a cumulative net change in groundwater storage

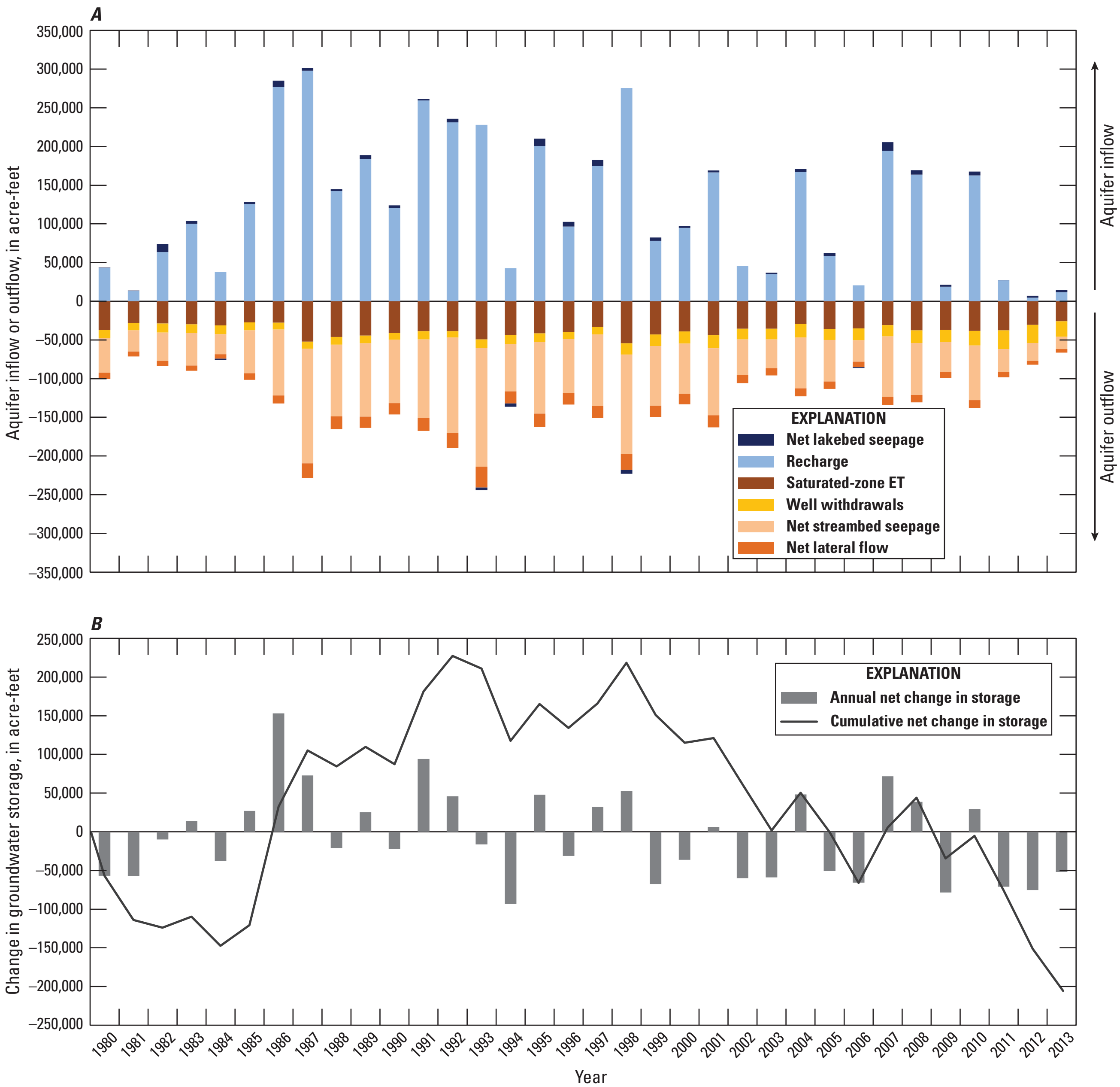


Figure 31. *A*, Annual inflows and outflows and *B*, annual change in groundwater storage for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.

of about 214,000 acre-ft (fig. 31) for 1980–2013 (34 years), or a cumulative net water-level decline of about 3.6 ft. This net change in groundwater storage was about the same as the one calculated from annual water-level measurements for the conceptual model (6,150 acre-ft/yr, table 8).

Mean monthly simulated aquifer inflows, primarily from recharge and seepage from streams, tended to be greatest during May and June (fig. 32*A*), which corresponds to the months of greatest precipitation (fig. 4). Mean monthly simulated aquifer outflows, primarily from seepage to streams, saturated-zone ET, and well withdrawals, were greatest in July and August (fig. 32*A*). During those summer months, seepage to streams was reduced by water-level declines from large saturated-zone ET outflows and well withdrawals (mostly for irrigation use). In July, mean saturated-zone ET equaled or exceeded all other outflows and nearly equaled the sum of all inflows (fig. 32*A*). Though mean inflows exceeded mean outflows in 9 of 12 months, the magnitude of mean outflows in July and August (fig. 32*B*) caused mean annual outflows to exceed mean annual inflows for the study period (table 14).

Simulated storage in Lake Altus decreased by about 25,000 acre-ft during the study period 1980–2013 (fig. 33*B*). Lake Altus and the surrounding North Fork Red River aquifer are hydrologically connected, so some declines in Lake Altus stage and storage were expected to occur during periods of declining water-table altitudes in the aquifer. Simulated annual lakebed seepage to the aquifer and direct lake-surface precipitation, however, were a minimal part of the Lake Altus water budget (fig. 33*A*). Periods of decreased Lake Altus stage and storage typically occurred during years of decreased base flow (figs. 30, 33, and 19*B*). Because nearly half of the streamflow in the North Fork Red River upstream from Lake Altus (at the Carter streamgage [07301500]) occurs as base flow (fig. 19*B*, table 2), water-table-altitude declines in the aquifer upgradient from Lake Altus had a greater effect on simulated Lake Altus stage and storage than did water-table-altitude declines near Lake Altus.

Calibrated Parameter Values and Sensitivities

A sensitivity analysis was performed by using sensitivities generated by PEST (Doherty, 2010) to ensure that the parameters used during the calibration process were effective in reducing the objective function and the numerical model error. During calibration, PEST records the sensitivity of each calibration target to regular percentage changes in parameters. These sensitivities are a measure of the change in residuals affected by adjustments to a parameter; parameters with greater sensitivities more greatly affect residuals. Sensitivities were calculated by using the Jacobian matrix output from PEST and were summed for each parameter group (fig. 34).

The observation groups were most sensitive to changes in the recharge and hydraulic conductivity parameters (fig. 34). Recharge was the largest aquifer inflow (table 14), which, when combined with the high hydraulic conductivity alluvium and terrace deposits, affected the water-table altitude, base flows, streambed seepage, and lake stage. Several water-table-altitude observations were located near drain cells along the southernmost model boundary, and these observations had a relatively large sensitivity to the drain conductance. Also, several drain cells were located near Lake Altus (drn4, fig. 21), resulting in a relatively large sensitivity to the drain conductance. Saturated-zone ET changes resulted in a large sensitivity for the lake-stage observations because surface-water inflows contributed the majority of inflow to Lake Altus. The observation groups also were sensitive to changes in Sy. The GHB cells in the model were located only at the Texas border (fig. 21); therefore, most observation groups had little sensitivity to changes in the GHB conductance values. The lake-stage observation group typically had the greatest sensitivity of the four observation groups; this observation group was most sensitive to recharge and least sensitive to GHB conductance (fig. 34).

Recharge multipliers applied to the monthly SWB grids increased the mean annual recharge from about 87,000 acre-ft/yr (fig. 22) to about 122,000 acre-ft/yr (table 14). Recharge for 72 percent of the stress periods was less than 20 percent of the mean recharge for the study period. Recharge multipliers applied in the remaining 28 percent of the stress periods, therefore, caused the majority of the increase in mean annual recharge for the calibrated model. Monthly mean calibrated recharge was greater than monthly mean precalibrated recharge for all months except April (fig. 35). With the exception of April, monthly mean calibrated recharge was 27–85 percent greater than the respective monthly mean precalibrated recharge (fig. 35).

Upgradient from Lake Altus, calibrated Kh ranged from about 8 to 114 ft/d and averaged 36.5 ft/d (fig. 36, table 10). Downgradient from Lake Altus, calibrated Kh ranged from about 16 to 119 ft/d and averaged 57.8 ft/d (fig. 36, table 10). About 0.5 percent of the calibrated Kh values in the numerical model were outside of the Kh range (1–97 ft/d) defined in the hydrogeologic framework. The increase in mean calibrated Kh from upgradient to downgradient from Lake Altus is consistent with even greater mean Kh (117 ft/d) reported for the most downgradient aquifer, the Tillman Terrace aquifer (Osborn, 2002; fig. 1). The calibrated Sy (0.12) was unchanged from the hydrogeologic framework.

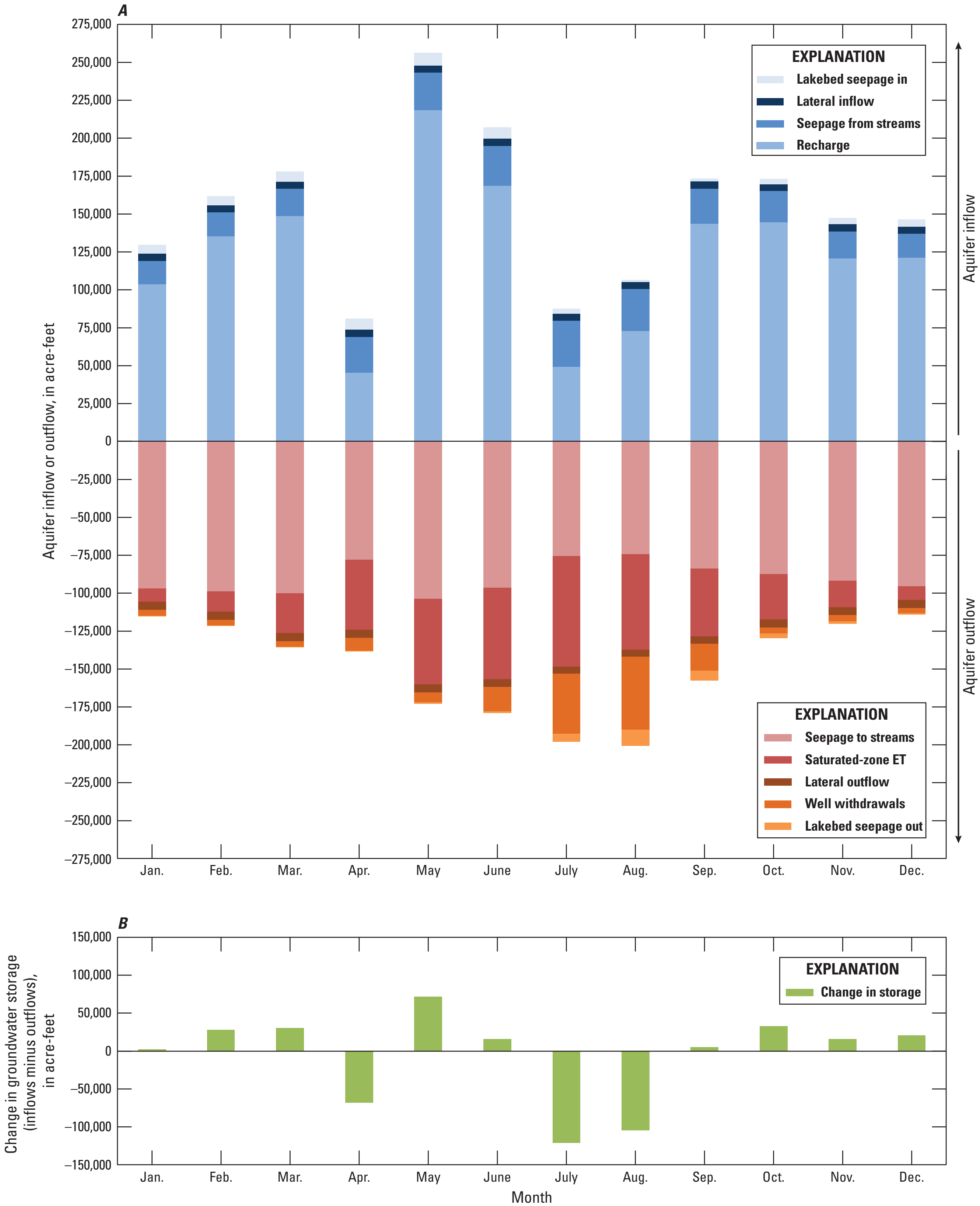


Figure 32. *A*, Mean monthly aquifer inflows and outflows and *B*, mean monthly change in groundwater storage for the North Fork Red River aquifer, 1980–2013.

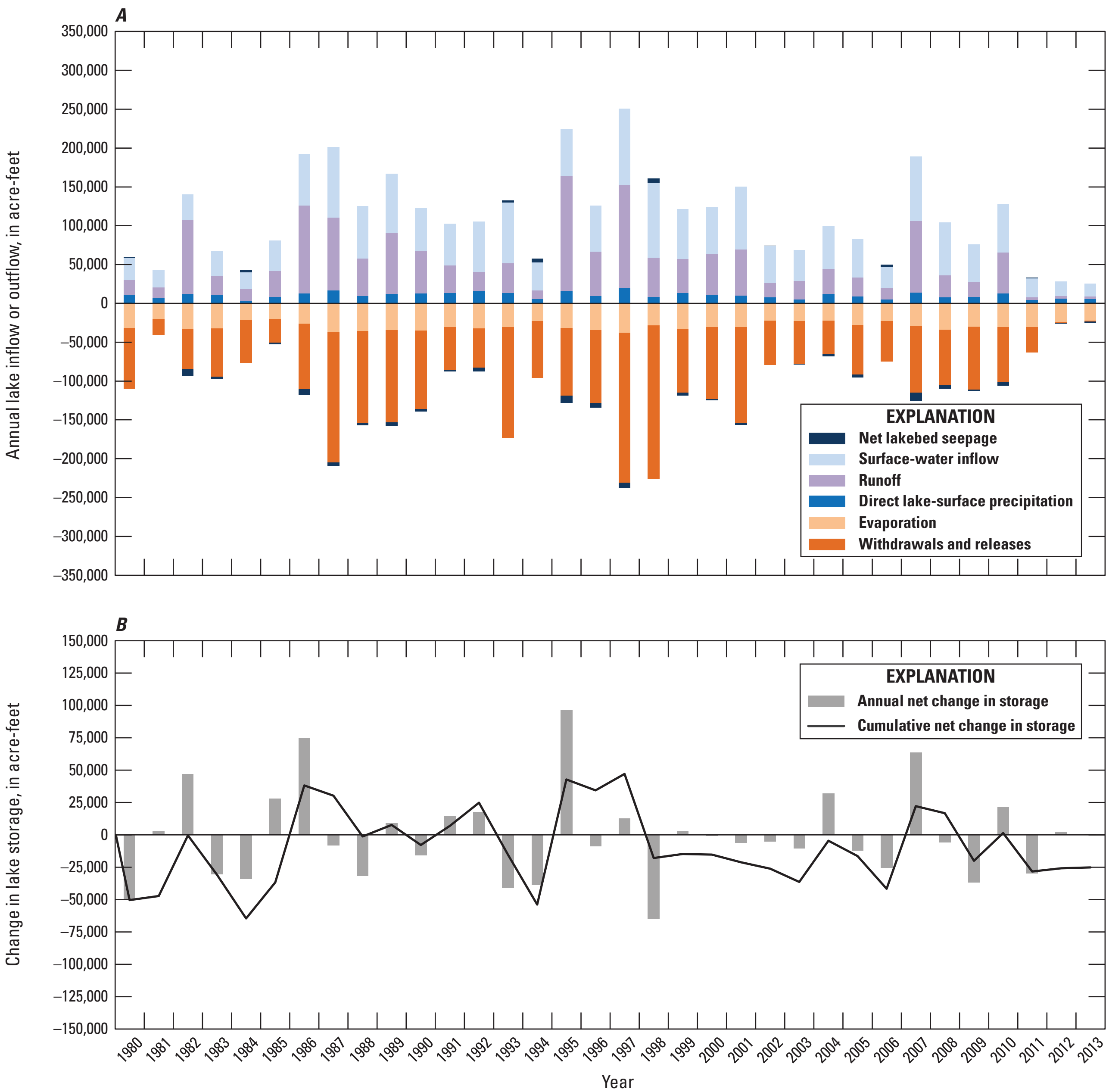


Figure 33. *A*, Annual lake inflows and outflows and *B*, change in lake storage for Lake Altus in the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013.

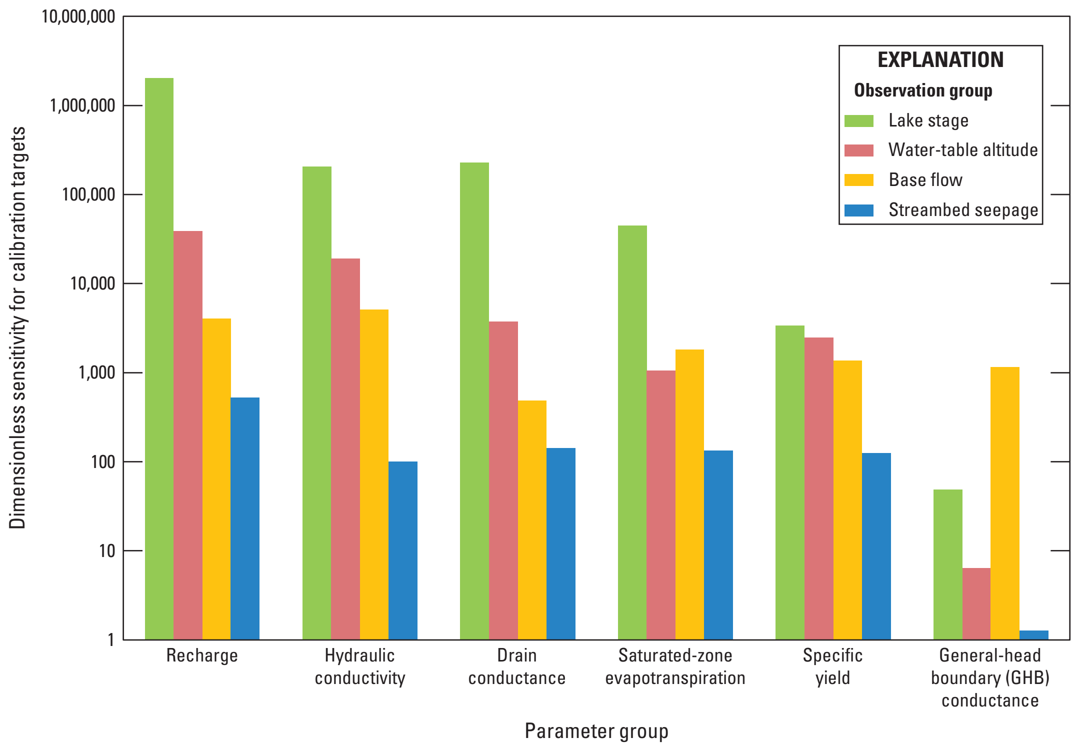


Figure 34. Observation group sensitivity by parameter group in the numerical groundwater-flow model for the North Fork Red River aquifer, 1980–2013.

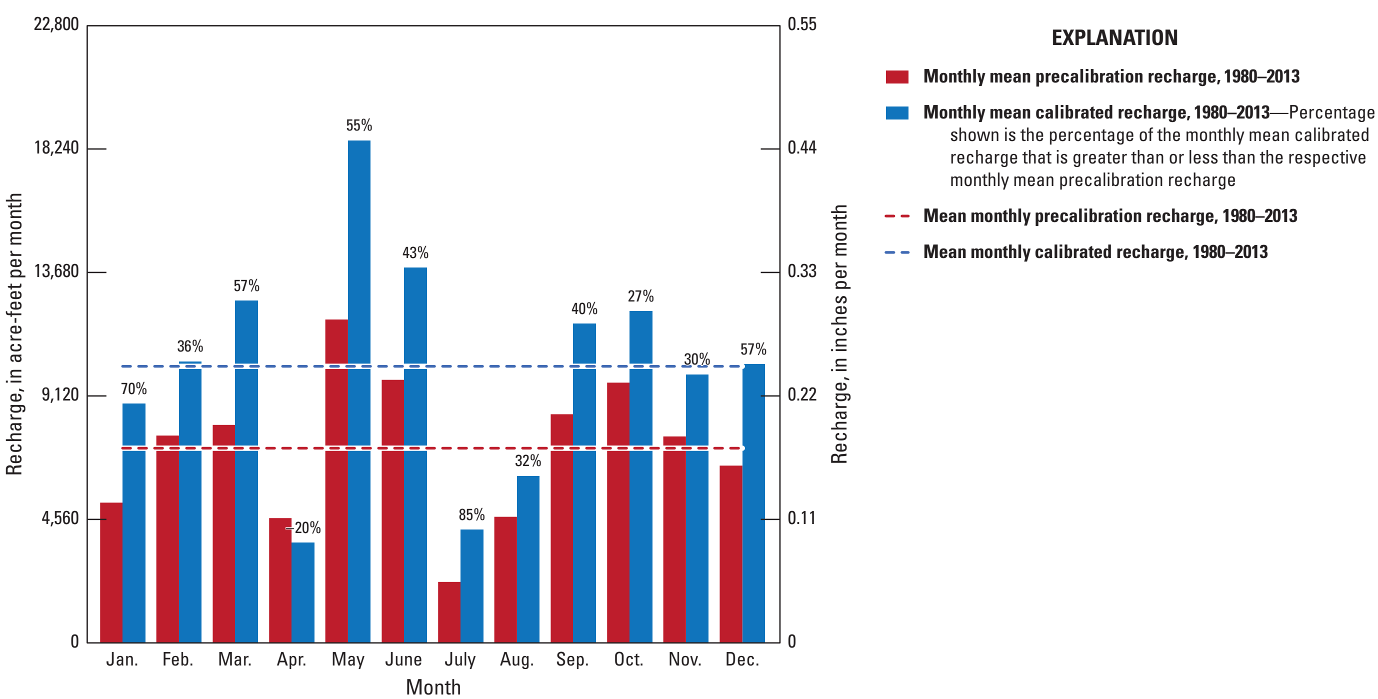


Figure 35. Monthly mean precalibration recharge and monthly mean calibrated recharge for the numerical groundwater-flow model of the North Fork Red River aquifer, 1980–2013. Note that aquifer area of 497,582 acres was used to convert acre-feet to inches.

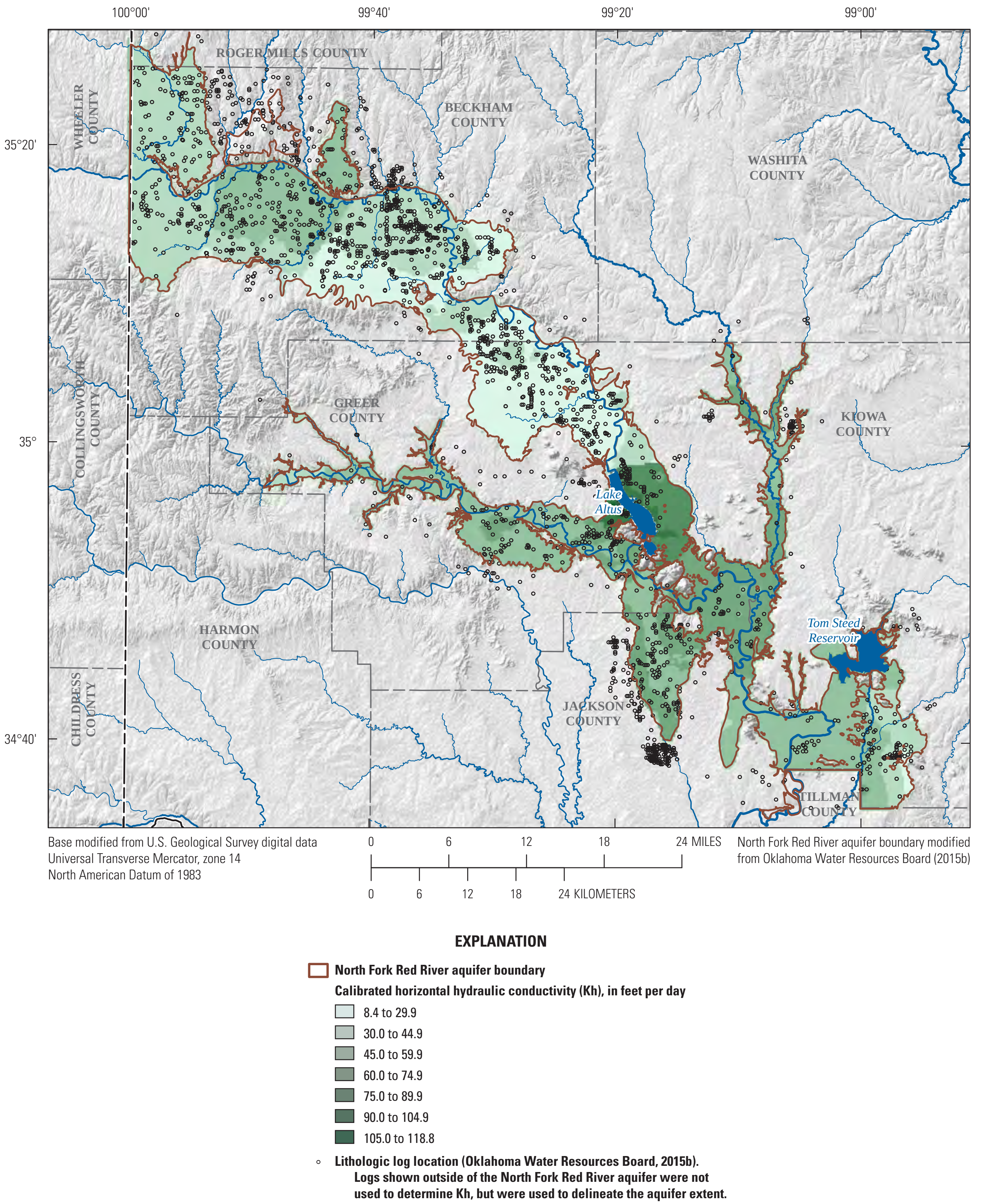


Figure 36. Horizontal hydraulic conductivity (Kh) for the calibrated numerical groundwater-flow model of the North Fork Red River aquifer, southwest Oklahoma.

Differences in Numerical Groundwater-Flow Models

Though the Kent (1980) hydrologic investigation and the one described in this report both used numerical models to simulate groundwater flow, those investigations had a number of differences regarding the study area conceptualization and numerical model inputs. The Kent (1980) numerical model area was 536 mi^2, which was about 31 percent smaller than the numerical model area described in this report (777 mi^2). The Kent (1980) numerical model used the Trescott and others (1976) code with a cell size of 2,640 by 2,640 ft, and the investigation described in this report used the updated MODFLOW-NWT code with a cell size of 886 by 886 ft, or about one-ninth the area of the Kent (1980) model cells. The conceptual model of Kent (1980) used a mean Kh of about 92 ft/d, whereas the mean Kh determined from the results of the hydrogeologic framework for this investigation was 52 ft/d (46 ft/d for the calibrated numerical model). Maps of transmissivity from Kent (1980), however, suggest that much smaller values of Kh may have been used in the Kent (1980) calibrated numerical model. The Sy value (0.12) used in the calibrated numerical model described in this report was about half of that used in the Kent (1980) calibrated numerical model (0.246).

Recharge for the numerical model of Kent (1980) was 2.28 in/yr, or 9.38 percent of the Kent (1980) mean annual precipitation (24.28 in/yr); recharge for the calibrated numerical model described in this report was about 122,000 acre-ft/yr (2.94 in/yr over the aquifer area of 497,582 acres, table 14), or 10.1 percent of the mean annual precipitation during 1980–2013 (29.2 in/yr, table 3). Unlike the numerical model described in this report, however, the Kent (1980) numerical model supplemented recharge from precipitation with estimated recharge from irrigation return flow. The Kent (1980) numerical model simulated total streamflow, but the numerical model described in this report simulated only base flow, excepting Lake Altus. Many other differences in the numerical models could be listed, but those listed here were expected to have the greatest influence on simulated groundwater flow and availability in each model.

Groundwater Availability Scenarios

Three types of predictive scenarios were run on the calibrated numerical model. These scenarios were used to (1) estimate the equal-proportionate-share (EPS) pumping rate that guarantees a minimum 20-, 40-, and 50-year life of the aquifer, (2) quantify the potential effects of projected well withdrawals on groundwater storage over a 50-year period, and (3) simulate the potential effects of a hypothetical (10-year) drought on base flow and groundwater storage. Groundwater storage was calculated by multiplying the Sy (0.12) by the saturated thickness in each active model cell. The inputs and outputs for the groundwater-availability scenarios are available in Smith and others (2017).

Equal Proportionate Share

EPS scenarios for the North Fork Red River aquifer were run for periods of 20, 40, and 50 years. The 2013 simulated water table from the calibrated numerical model was used as the starting water table in each EPS scenario. Model inputs for recharge, saturated-zone ET, Tom Steed Reservoir stage, and stream inflows to the model active area were configured as the mean of each annual period used in the calibrated numerical model. Annual stress periods were used in these scenarios instead of the monthly stress periods to simplify the analysis and improve model stability. To determine the EPS pumping rate, hypothetical wells were placed in each layer 1 active cell (covering 18 acres) and pumped at the same rate for the duration of the scenario. If at the end of the scenario more than 50 percent of the active cells had a saturated thickness of at least 5 ft, the pumping rate was increased by about 35 cubic feet per day (1 cubic meter per day). The scenario was repeated until 50 percent of the cells had a saturated thickness of less than 5 ft. To account for potential climate variability, this process was repeated with recharge increased and decreased by 10 percent.

The 20-, 40-, and 50-year EPS pumping rates under normal recharge conditions were 0.59, 0.52, and 0.52 acre-foot per acre per year, respectively (fig. 37, table 15; values rounded to the nearest hundredth). Given the 497,582-acre aquifer area, these rates correspond to annual yields of about 294,000, 259,000, and 259,000 acre-ft/yr, respectively. For the 20-year EPS scenario, decreasing and increasing recharge by 10 percent resulted in a 5–7-percent change in the EPS pumping rate; for the 40- and 50-year EPS scenarios, decreasing and increasing recharge by 10 percent resulted in a 6–8-percent change in the EPS pumping rate (fig. 37, table 15).

Groundwater storage at the end of the 20-year EPS scenario was about 951,000 acre-ft, or about 1,317,000 acre-ft (58 percent) less than the starting EPS scenario storage. This decrease in storage was equivalent to a mean water-level decline of about 22 ft. Most areas of the active alluvium near the North Fork Red River, Elk Creek, and Elm Fork Red River remained partially saturated through the end of the EPS scenario because of streambed seepage (fig. 38). Where the terrace was sufficiently thick—about 80 ft or greater—or a shallow hydraulic gradient was present, partial saturation was sustained though the entire EPS scenario (fig. 38). At the end of the 20-year EPS scenario, the greatest remaining saturated thickness was in the network of paleochannels along the Beckham County Fault (fig. 12). Saturated thickness greater than 5 ft also remained along Elk Creek, Sweetwater Creek, Elm Fork Red River, and North Fork Red River (except for the reach between the Carter streamgage [07301500] and Lake Altus), which were sustained by simulated SFR inflows (ELK,

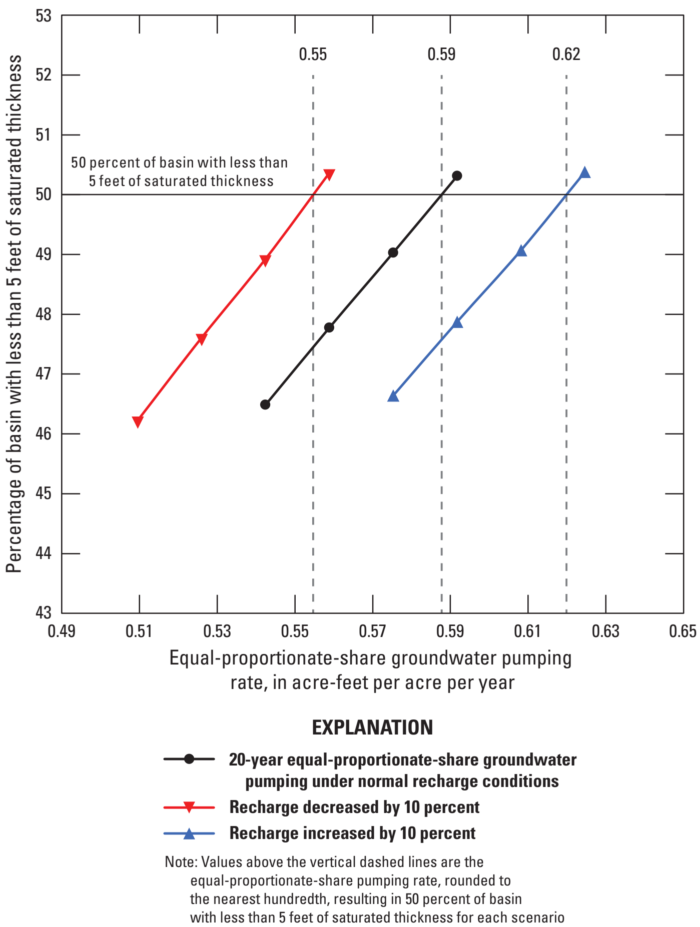


Figure 37. Percentage of the North Fork Red River aquifer with less than 5 feet of saturated thickness after 20 years of continuous equal-proportionate-share groundwater pumping.

Table 15. Equal-proportionate-share (EPS) pumping rates for the North Fork Red River aquifer, southwest Oklahoma.

Period (years)	EPS pumping rate (acre-feet per acre per year)		
	Recharge reduced by 10 percent	Normal recharge	Recharge increased by 10 percent
20	0.55	0.59	0.62
40	0.49	0.52	0.56
50	0.48	0.52	0.56

SWEE, EFRR, and NFRR, respectively) (fig. 38). Other terrace areas generally had less than 5 ft of saturated thickness except for areas near the Texas border, where saturated thickness was sustained by GHB cells, and near Lake Altus and Tom Steed Reservoir, where saturated thickness was sustained by lakebed seepage (fig. 38).

At the end of the 20-year EPS scenario, mean annual base-flow declines of 100 and 86 percent occurred at the Carter streamgage (07301500) and Headrick streamgage (07305000), respectively, compared to the start of the EPS scenario. The decrease in base flow was greater upstream from Lake Altus because of the smaller inflows to Sweetwater Creek and the North Fork Red River from Texas compared to inflows to the Elm Fork Red River and Elk Creek. The aquifer water table was below the bottom of the streams during most of the EPS scenario, resulting in streambed seepage outflows from the stream to the aquifer (losing streams). With the exception of streams receiving base-flow inflows from outside the active model area, the majority of streams in the study area were dry (base flow of 0.0–5.0 ft^3/s) at the end of the 20-year EPS scenario (fig. 38).

For the 40-year and 50-year EPS scenarios, most (90 percent) of the dewatering of the aquifer occurred during the first 20 years (fig. 39). During that time, annual EPS pumping decreased in the numerical model as the thinner parts of the aquifer went dry. Annual storage changes decreased as annual EPS pumping decreased, and approximate steady-state conditions were reached after about 30 years (fig. 39). These approximate steady-state conditions explain why the 40- and 50-year EPS pumping rates are the same. Groundwater storage at the end of the 50-year EPS scenario was about 948,000 acre-ft, or about 1,320,000 acre-ft (58 percent) less than the starting EPS scenario storage.

Lake Altus storage was reduced to zero after 6–7 years of EPS pumping in each scenario. Surface-water inflow from the North Fork Red River was the primary inflow to Lake Altus (fig. 33), so Lake Altus storage quickly decreased when the North Fork Red River ceased flowing. When the EPS scenarios were run without simulating Lake Altus, the EPS decreased by less than 0.1 acre-foot per acre per year for each scenario.

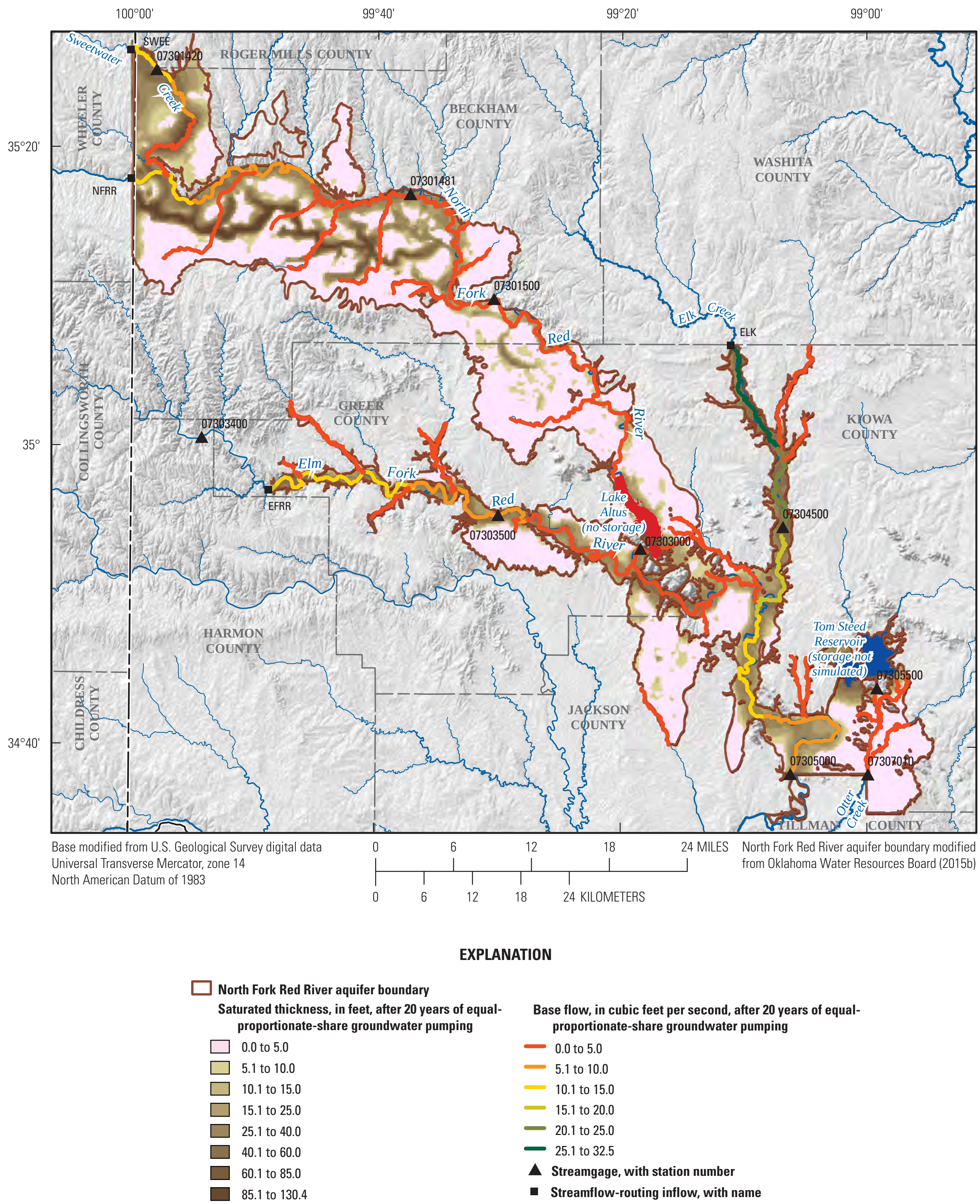


Figure 38. Simulated saturated thickness and base flow after 20 years of continuous equal-proportionate-share groundwater pumping in the North Fork Red River aquifer, southwest Oklahoma.

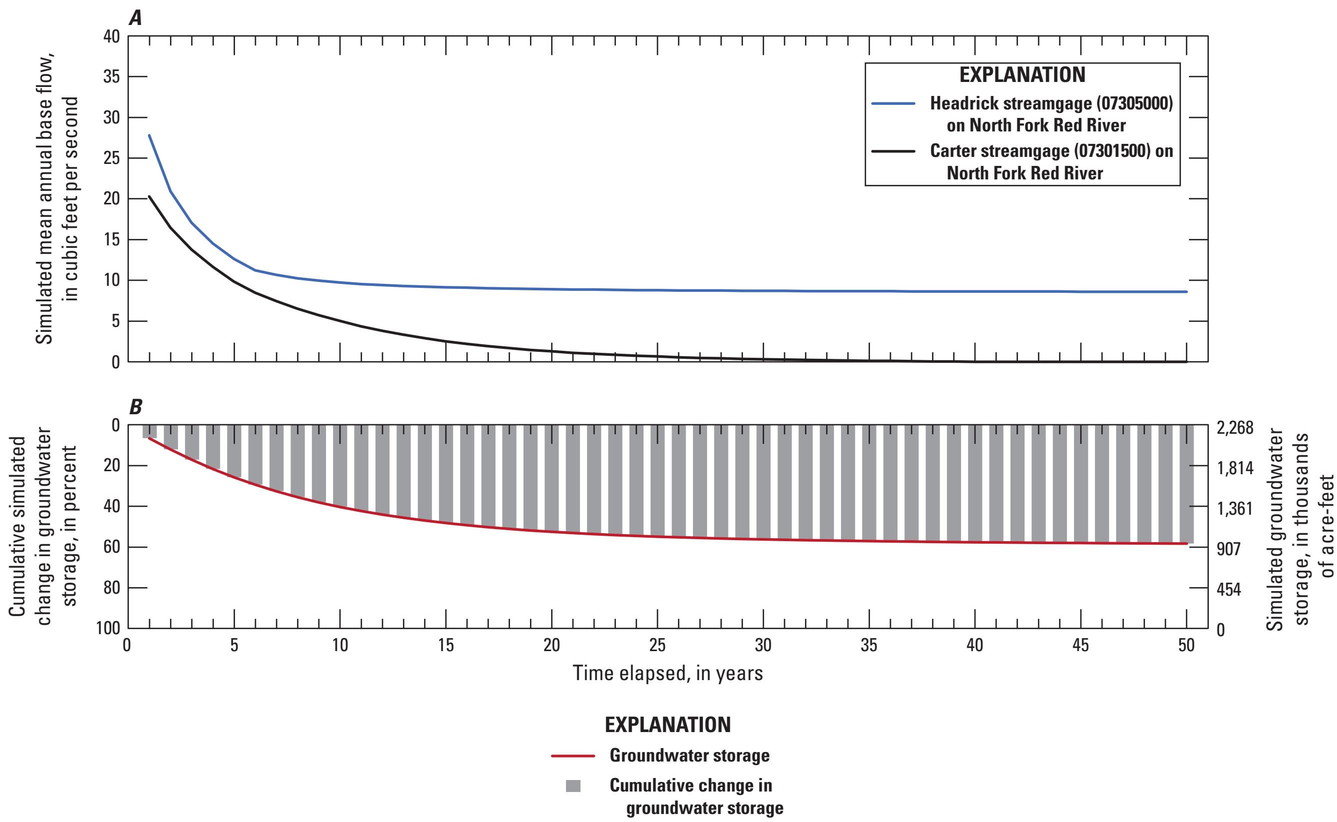


Figure 39. Changes in *A*, simulated base flow and *B*, simulated groundwater storage during 50 years of continuous equal-proportionate-share groundwater pumping in the North Fork Red River aquifer, southwest Oklahoma.

Projected (50-Year) Pumping

Projected 50-year pumping scenarios were used to simulate the effects of selected well withdrawal rates on groundwater storage of the North Fork Red River aquifer and base flows in the North Fork Red River upstream from Lake Altus. The effects of well withdrawals were evaluated by comparing changes in groundwater storage (and base flow) between four 50-year scenarios using (1) no groundwater pumping, (2) mean pumping rates for the study period (1980–2013), (3) 2013 pumping rates, and (4) increasing demand pumping rates. The increasing demand pumping rates assumed a 20.4-percent increase in pumping over 50 years based on 2010–60 demand projections for southwest Oklahoma (OWRB, 2012b). The projected water-use scenarios began in 1980 and ran until 2029. The scenarios did not begin in 2013 and run until 2062 because the calibrated numerical model ended in drought conditions, and the low initial (2013) groundwater storage caused all four scenarios to show non-intuitive gradual increases in groundwater storage. Model stresses were configured as the mean of each monthly stress period from the calibrated model, and the scenarios assumed that future climate conditions were similar to those of the 1980–2013 study period.

Groundwater storage after 50 years with no pumping was about 2,606,000 acre-ft, or 137,000 acre-ft (5.5 percent) greater than the initial groundwater storage; this groundwater storage increase is equivalent to a mean water-level increase of 2.3 ft (fig. 40, table 16). Groundwater storage after 50 years with the mean pumping rate for the study period (1980–2013) was about 2,476,000 acre-ft, or about 7,000 acre-ft (0.3 percent) greater than the initial groundwater storage; this groundwater storage increase is equivalent to a mean water-level increase of 0.1 ft (fig. 40, table 16). Groundwater storage at the end of the 50-year period with 2013 pumping rates was about 2,398,000 acre-ft, or about 70,000 acre-ft (2.8 percent) less than the initial storage; this groundwater storage decrease is equivalent to a mean water-level decline of 1.2 ft (fig. 40, table 16). Groundwater storage at the end of the 50-year period with increasing demand pumping rates was about 2,361,000 acre-ft, or about 107,000 acre-ft (4.3 percent) less than the initial storage; this groundwater storage decrease is equivalent to a mean water-level decline of 1.8 ft (fig. 40, table 16).

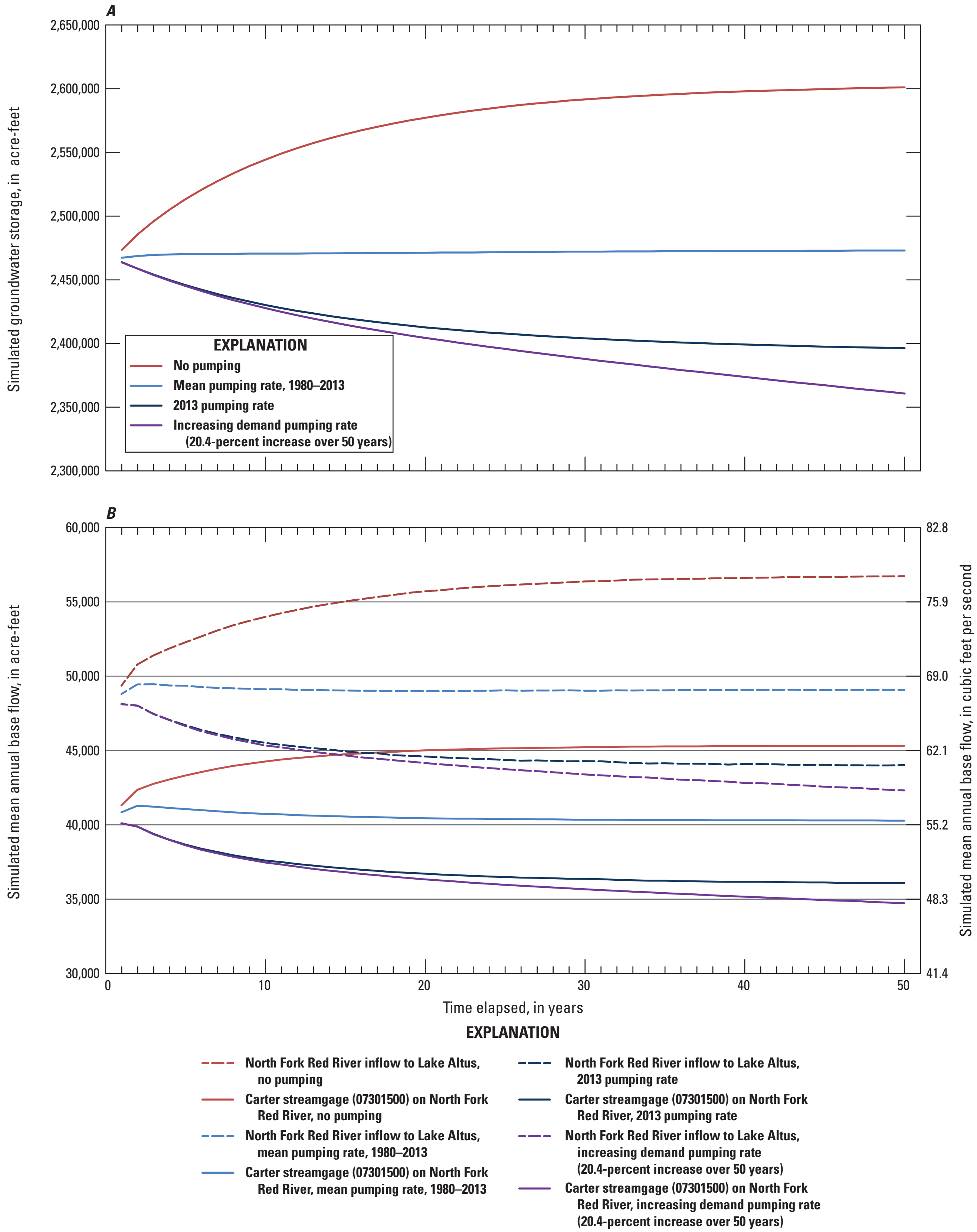


Figure 40. *A*, Simulated groundwater storage and *B*, simulated mean annual base flow through 50 years of groundwater pumping at selected rates in the North Fork Red River aquifer, southwest Oklahoma.

Table 16. Changes in groundwater storage and mean annual base flow after 50 years of groundwater pumping at selected rates for the North Fork Red River aquifer, southwest Oklahoma.

[Values reported may vary from those calcluated using this table because of rounding errors]

Projected (50-year) pumping scenario	Groundwater storage				
	Groundwater storage at beginning of scenario (acre-feet)	Groundwater storage at end of scenario (acre-feet)	Change in groundwater storage (acre-feet)	Change in groundwater storage (percent)	Mean change in water table (feet)
No pumping	2,469,000	2,606,000	137,000	5.5	2.3
Mean pumping rate, 1980–2013	2,469,000	2,476,000	7,000	0.3	0.1
2013 pumping rate	2,468,000	2,398,000	–70,000	–2.8	–1.2
Increasing demand pumping rate (20.4-percent increase over 50 years)	2,468,000	2,361,000	–107,000	–4.3	–1.8

Projected (50-year) pumping scenario	Mean annual base flow at Carter streamgage (07301500) on North Fork Red River			
	Mean base flow for first year of scenario (acre-feet)	Mean base flow for last year of scenario (acre-feet)	Change in base flow (acre-feet)	Change in base flow (percent)
No pumping	41,278	45,284	4,005	9.7
Mean pumping rate, 1980–2013	40,799	40,246	–552	–1.4
2013 pumping rate	40,072	36,042	–4,029	–10.1
Increasing demand pumping rate (20.4-percent increase over 50 years)	40,066	34,687	–5,380	–13.4

Projected (50-year) pumping scenario	Mean annual base flow at North Fork Red River inflow to Lake Altus			
	Mean base flow for first year of scenario (acre-feet)	Mean base flow for last year of scenario (acre-feet)	Change in base flow (acre-feet)	Change in base flow (percent)
No pumping	49,313	56,683	7,370	14.9
Mean pumping rate, 1980–2013	48,757	49,034	277	0.6
2013 pumping rate	48,083	43,983	–4,099	–8.5
Increasing demand pumping rate (20.4-percent increase over 50 years)	48,078	42,272	–5,806	–12.1

Mean annual base flow simulated at the Carter streamgage (07301500) on North Fork Red River increased by about 4,000 acre-ft (10 percent) after 50 years with no pumping and decreased by about 5,400 acre-ft (13 percent) after 50 years with increasing demand pumping rates (fig. 40, table 16). Mean annual base flow simulated at the North Fork Red River inflow to Lake Altus increased by about 7,400 acre-ft (15 percent) after 50 years with no pumping and decreased by about 5,800 acre-ft (12 percent) after 50 years with increasing demand pumping rates (fig. 40, table 16).

Hypothetical (10-Year) Drought

A hypothetical 10-year drought scenario was used to simulate the effects of a prolonged period of reduced recharge on groundwater storage and Lake Altus stage and storage. The period of January 1984 to December 1993, which had base flows similar to the mean annual base flow for the study period, was chosen as the simulated drought period. Drought effects were quantified by comparing the results of the drought scenario to those of the calibrated numerical model (no drought). To simulate the hypothetical drought, recharge in the calibrated numerical model was reduced by 50 percent during the simulated drought period (1984–1993). Upstream inflows to the North Fork Red River and tributaries were reduced by 37 percent, which was the mean decrease in annual base flow during the drought of years 1976–81 as compared to the study period 1980–2013 at the Carter (07301500) and Carl (07303400) streamgages (Barlow and others, 2015; USGS, 2015a). The rates of direct lake-surface precipitation (a small component of the lake inflows, fig. 33*A*), evaporation, and nonstream runoff to Lake Altus were unchanged from the calibrated numerical model. Withdrawals from lake storage also were unchanged, with the exception of monthly withdrawals in six stress periods (in months 121–156) that were reduced by 25 percent to fix model instability problems caused by near-zero storage in Lake Altus.

Groundwater storage at the end of the drought period (month 120) was about 2,271,000 acre-ft, or about 426,000 acre-ft (15.8 percent) less than the groundwater storage of the calibrated numerical model (fig. 41). This decrease in groundwater storage is equivalent to a mean water-table-altitude decline of 7.1 ft.

The largest water-level declines (as great as 49 ft) occurred in the terrace areas most upgradient from the North Fork Red River and tributaries. Excluding areas near Lake Altus, Tom Steed Reservoir, and the Texas border, groundwater storage in the upgradient terrace was supplied entirely by recharge, so decreases in recharge have substantial effects on terrace water levels. The decreased saturated thickness in some areas of the terrace caused a reduction in simulated well withdrawals as compared to the calibrated numerical model. The saturated thickness of areas near the North Fork Red River and major tributaries changed little during the hypothetical drought, but the simulated base flow in streams in those areas decreased rapidly. After 12 months of the hypothetical drought, simulated base flows at the Sweetwater (07301420), Carter (07301500), and Headrick (07305000) streamgages had all decreased by greater than 30 percent as compared to the calibrated numerical model (fig. 42). At the end of the 10-year hypothetical drought period, simulated base flows at the Sweetwater (07301420), Carter (07301500), Headrick (07305000), and Snyder (07307010) streamgages had decreased by about 37, 61, 44, and 45 percent, respectively (fig. 42).

Substantial declines in the Lake Altus stage began around month 30 (fig. 43) in conjunction with base-flow decreases of more than 50 percent at the Carter streamgage (07301500) (fig. 42*B*). These lake-stage declines outpaced water-level declines in the surrounding aquifer. During the drought, simulated storage in seven monthly stress periods (in July and August between months 55 and 128) decreased below the dead pool storage of 633 acre-ft (U.S. Bureau of Reclamation, 2015b). The minimum Lake Altus storage simulated during the drought period was 403 acre-ft in month 116 (fig. 43), which was a decline of 92 percent from the nondrought storage. The drought effects persisted years after the end of the simulated drought, and the minimum Lake Altus storage during the study period (350 acre-ft) was simulated in month 129 (fig. 43). Reduced base flows in the North Fork Red River were the primary cause of simulated Lake Altus storage declines.

Because Lake Altus storage approached zero during the summer months of the hypothetical 10-year drought (fig. 43), the numerical model automatically reduced withdrawal rates from Lake Altus by about 12 percent. After the end of the hypothetical 10-year drought period, withdrawal rates from Lake Altus remained about 10 percent lower than nondrought conditions until August 2011. From August 2011 to June 2015, water was not withdrawn from Lake Altus for irrigation use at LAID, and the observed lake stage was at or below 1,536 ft (U.S. Bureau of Reclamation, 2015b) (fig. 30). At this stage, Lake Altus storage was about 30,000 acre-ft (12 percent of the normal-pool storage capacity) (fig. 30). If this storage threshold for withdrawals was implemented during the hypothetical 10-year drought scenario, withdrawals from Lake Altus would not occur during 60 percent of summer months, when irrigation demand was largest.

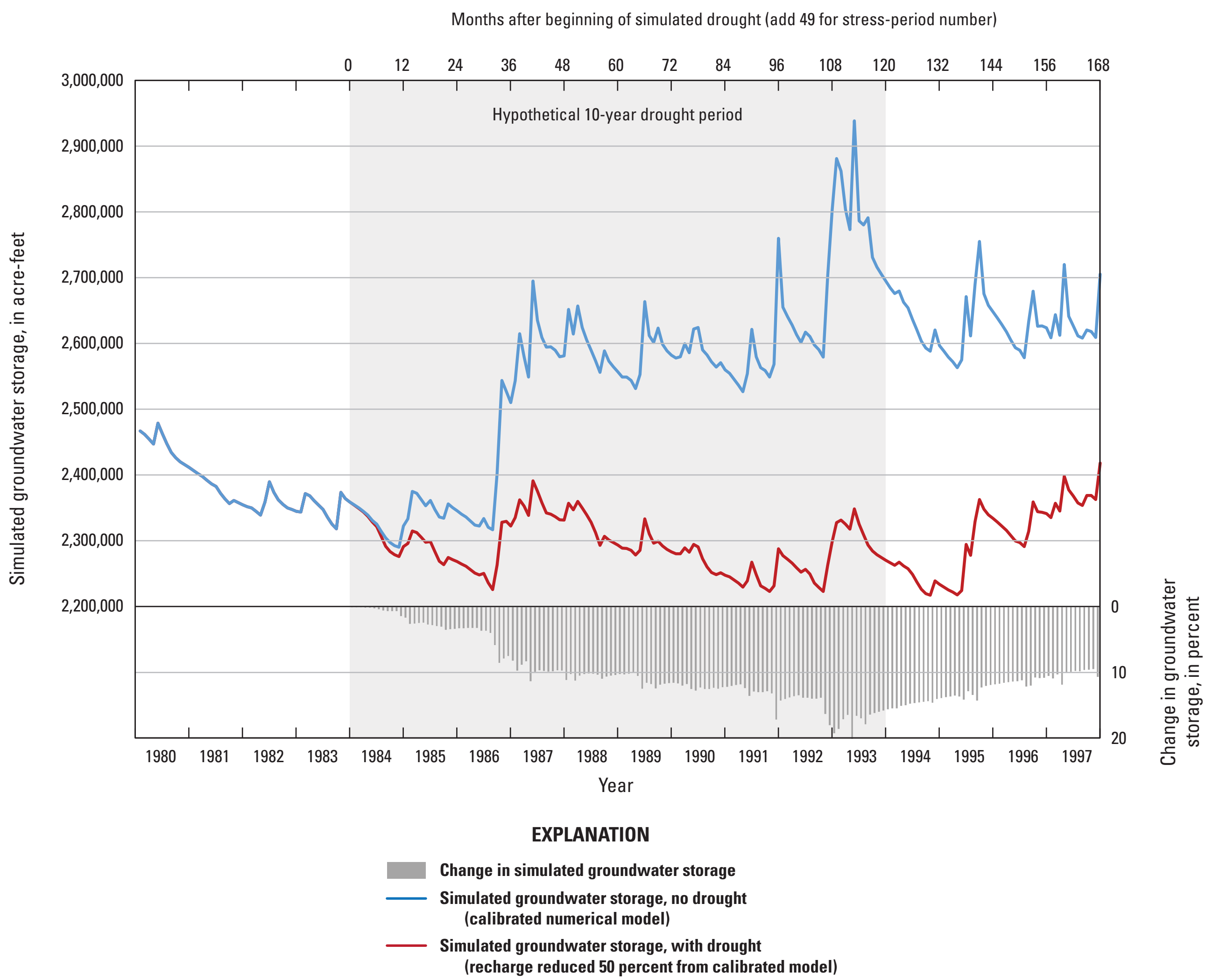


Figure 41. Changes in groundwater storage resulting from a hypothetical 10-year drought (1984–93) for the North Fork Red River aquifer, 1980–97.

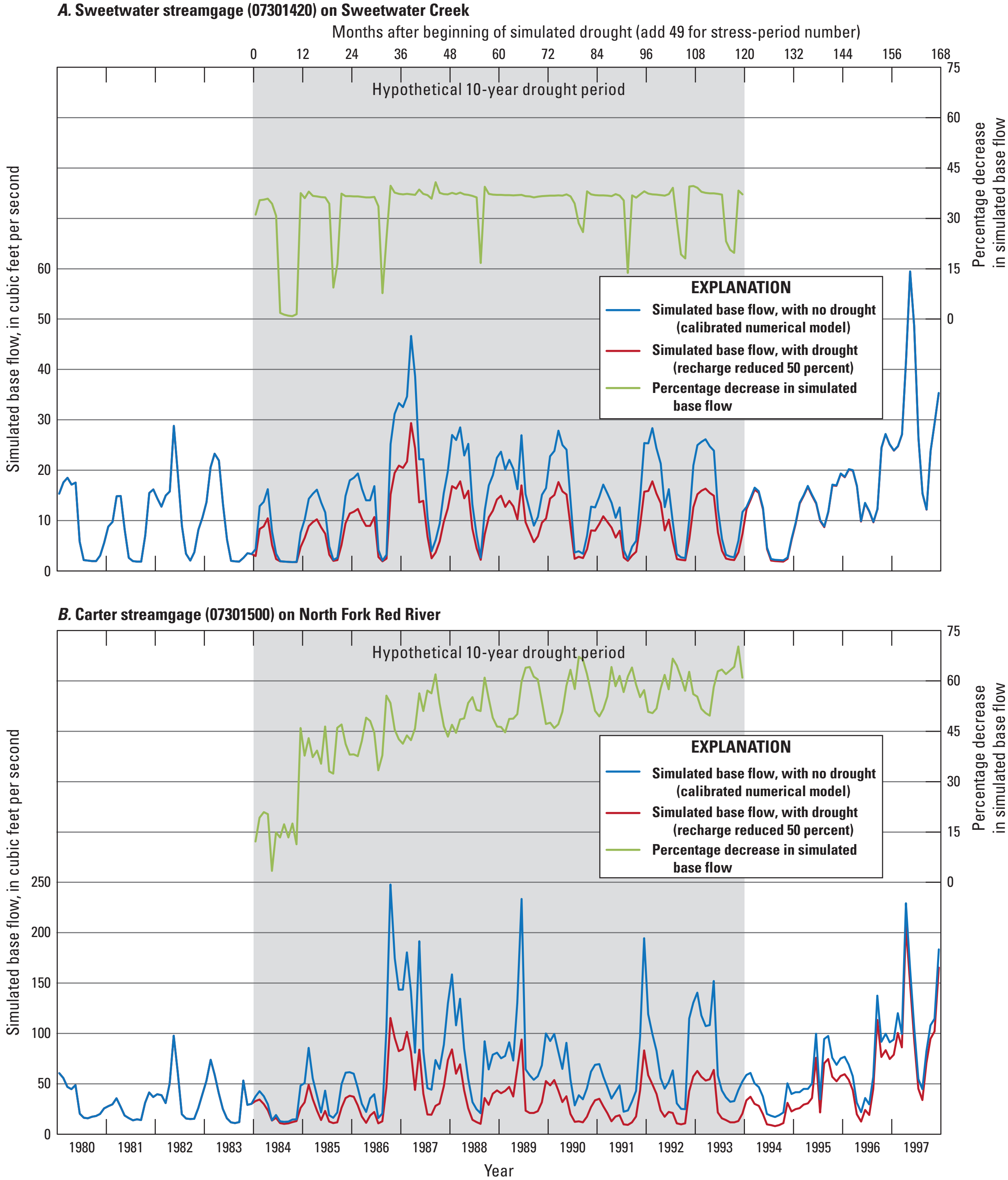


Figure 42. Changes in simulated base flow at *A*, Sweetwater streamgage (07301420) on Sweetwater Creek; *B*, Carter streamgage (07301500) on North Fork Red River; *C*, Headrick streamgage (07305000) on North Fork Red River; and *D*, Snyder streamgage (07307010) on Otter Creek resulting from a hypothetical 10-year drought (1984–93) for the North Fork Red River aquifer, 1980–97.

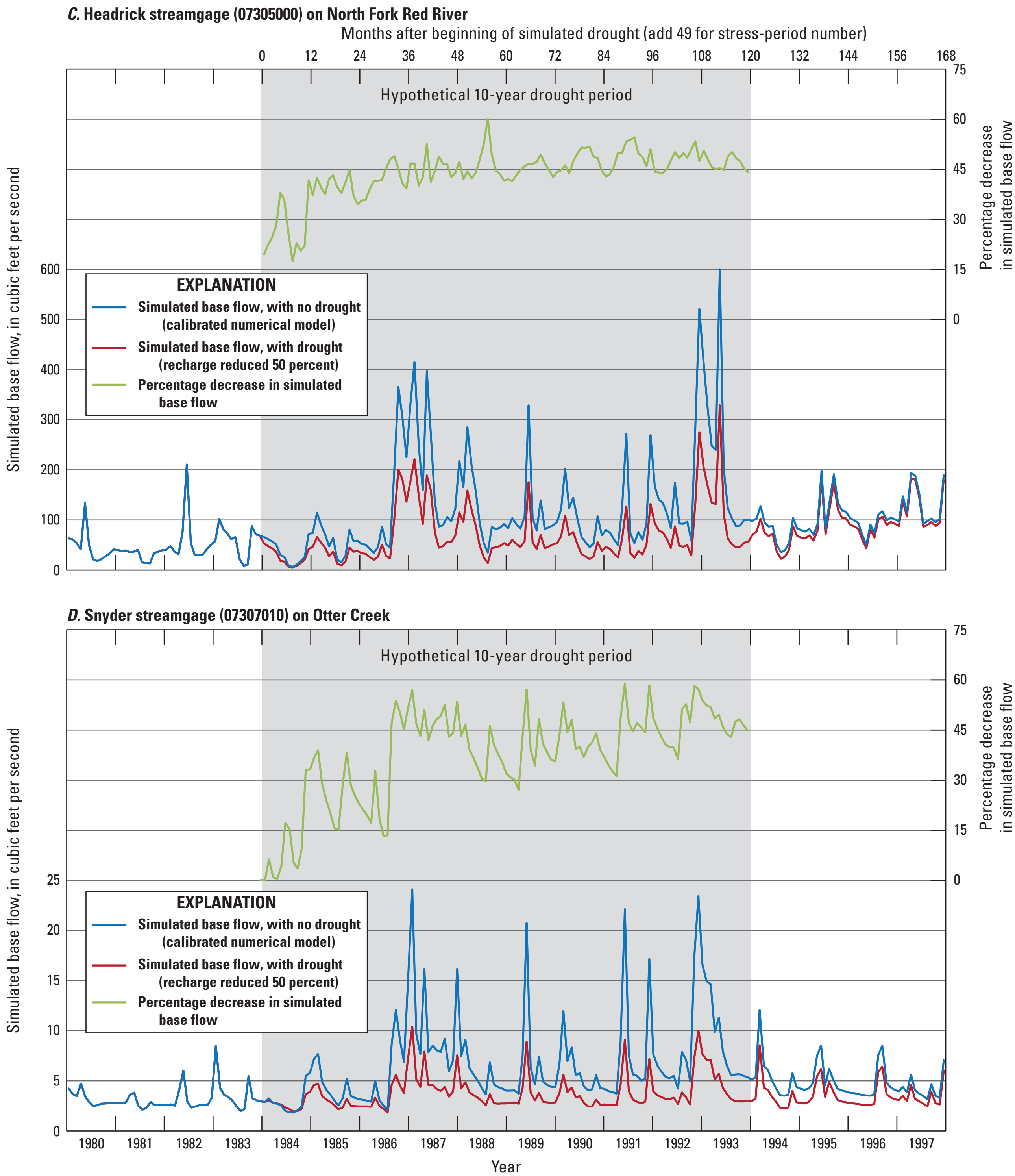


Figure 42. Changes in simulated base flow at *A*, Sweetwater streamgage (07301420) on Sweetwater Creek; *B*, Carter streamgage (07301500) on North Fork Red River; *C*, Headrick streamgage (07305000) on North Fork Red River; and *D*, Snyder streamgage (07307010) on Otter Creek resulting from a hypothetical 10-year drought (1984–93) for the North Fork Red River aquifer, 1980–97.—Continued

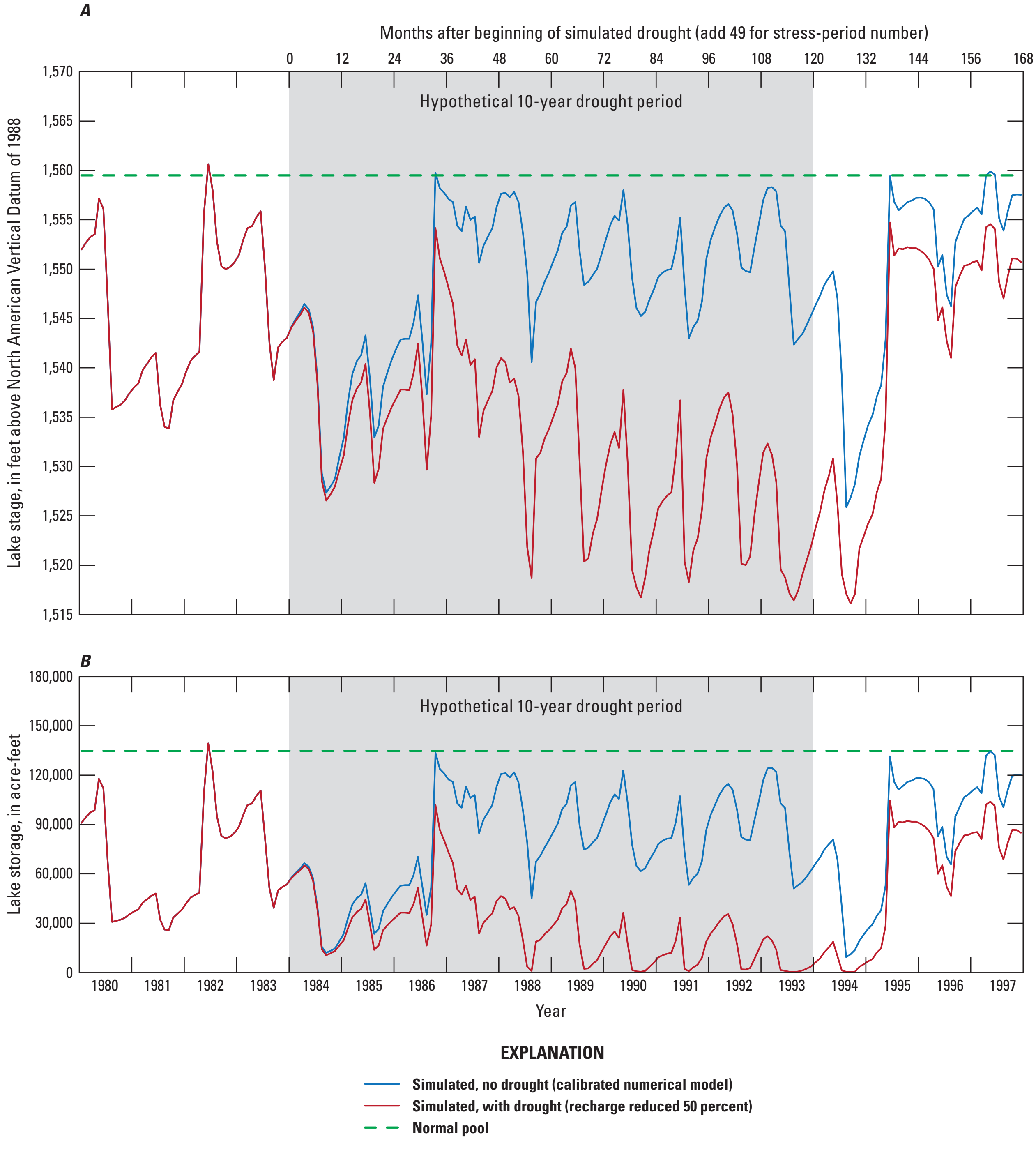


Figure 43. Changes in *A*, Lake Altus stage and *B*, Lake Altus storage resulting from a hypothetical 10-year drought (1984–93) for the North Fork Red River aquifer, 1980–97.

Model Limitations

Some assumptions and simplifications were necessary in the simulation of groundwater flow. The use of the MODFLOW code required the assumptions that groundwater flows are governed by Darcy's Law (Darcy, 1856), water is incompressible and of uniform density, and the aquifer hydrogeology can be simulated appropriately by the cell size and number of layers present. Computing and time limitations prevented the use of cell sizes that could better represent the true variability of hydrogeologic characteristics; therefore, results generated by the model may be more applicable to a regional, rather than local, area.

An uneven spatial and temporal distribution of water-table-altitude observations caused data gaps in the calibration data. Though the simulated water table in areas with fewer observations is in an expected water-table-altitude range, more site-specific and local calibration target data could facilitate a more detailed characterization of water-table conditions. Additionally, base-flow gain to the North Fork Red River is based on the simulated water table and may not be well represented in locations where water-table-altitude observation data were relatively sparse.

The stream network used in the numerical model is a simplification of the actual stream geometry and hydraulic properties. Refined measurement of the stream channel width and streambed conductance at the local scale might improve the numerical model calibration because these factors control the amount of streambed seepage exchange with the aquifer. The numerical model was calibrated primarily to base-flow estimates; therefore, collection of more streamflow and base-flow data during other hydrologic conditions also could further reduce uncertainty in local-scale simulation results.

Lake Altus inflows (base flows) simulated by the numerical model are likely to be of interest to surface-water resource managers. Because no streamgages are located between Carter (07301500) and Lake Altus (a distance of about 27 river miles), additional streambed seepage may occur in this reach that was not represented in the calibrated numerical model. Additional long-term streamgage data near the lake inflow point and seasonal synoptic base-flow measurements over a range of hydrologic conditions would be needed to increase confidence that the calibrated numerical model was adequately reproducing observed base flows in that reach.

Exact amounts of annual groundwater use are unknown because groundwater wells are not metered, and groundwater-use data are based on estimates submitted to the OWRB by permit holders. Additionally, groundwater use by domestic wells, though assumed to be relatively small, was not included in the numerical model.

Summary

On September 8, 1981, the Oklahoma Water Resources Board (OWRB) established regulatory limits on the maximum annual yield of groundwater (343,042 acre-feet per year) and equal-proportionate-share (EPS) pumping rate (1.0 acre-foot per acre per year) for the North Fork Red River aquifer. The maximum annual yield and EPS were based on a hydrologic investigation that used a numerical groundwater-flow model to evaluate the effects of potential groundwater withdrawals on groundwater availability in the North Fork Red River aquifer. The OWRB is statutorily required (every 20 years) to update the hydrologic investigation on which the maximum annual yield and EPS were based. Because 20 years have elapsed since the final order was issued, the U.S. Geological Survey, in cooperation with the OWRB, conducted an updated hydrologic investigation and evaluated the effects of potential groundwater withdrawals on groundwater flow and availability in the North Fork Red River aquifer in Oklahoma. This report describes a hydrologic investigation of the North Fork Red River aquifer that includes an updated summary of the aquifer hydrogeology. As part of this investigation, groundwater flow and availability were simulated by using a numerical groundwater-flow model.

The North Fork Red River aquifer in Beckham, Greer, Jackson, Kiowa, and Roger Mills Counties in Oklahoma is composed of about 777 square miles (497,582 acres) of alluvium and terrace deposits along the North Fork Red River and tributaries, including Sweetwater Creek, Elk Creek, Otter Creek, and Elm Fork Red River. The North Fork Red River is the primary source of surface-water inflow to Lake Altus, which overlies the North Fork Red River aquifer. Lake Altus is a U.S. Bureau of Reclamation reservoir with the primary purpose of supplying irrigation water to the Lugert-Altus Irrigation District. The mean annual precipitation and the mean annual temperature in the study area for the period of record 1895–2015 were about 27.6 inches per year and about 61.2 degrees Fahrenheit, respectively. The mean annual temperature was about 0.4 degree Fahrenheit greater and the mean annual precipitation was about 1.6 inches per year greater for the study period 1980–2013 compared to the period of record. The mean annual reported groundwater use was 15,279 acre-feet per year for the period of record 1967–2013 and 15,859 acre-feet per year for the period 1980–2013. The year with the greatest reported groundwater use (26,714 acre-feet) was 2011. Though three of the four greatest individual users of groundwater were municipalities, irrigation was the major groundwater-use type for the period of record 1967–2013.

A hydrogeologic framework was developed for the North Fork Red River aquifer and included a definition of the aquifer extent and potentiometric surface, as well as a description of the textural and hydraulic properties of aquifer materials. The estimated horizontal hydraulic conductivity determined for lithologic logs in the North Fork Red River aquifer ranged from 3 to 97 feet per day, with a mean of 52 feet per day. Based on available multi-well aquifer test data and published studies, a mean specific yield value of 0.12 was estimated for the North Fork Red River aquifer. The hydrogeologic framework was used in the construction of a numerical groundwater-flow model of the North Fork Red River aquifer described in this report.

A conceptual model of aquifer inflows and outflows was developed for the North Fork Red River aquifer to constrain the construction and calibration of a numerical groundwater-flow model that reasonably represented the groundwater-flow system. The conceptual-model water budget estimated mean annual inflows to and outflows from the North Fork Red River aquifer for the period 1980–2013 and included a sub-accounting of mean annual inflows and outflows for the portions of the aquifer that were upgradient and downgradient from Lake Altus. Recharge is the predominant inflow to the North Fork Red River aquifer. Based on estimated annual recharge rates from published studies and selected methods, the mean annual recharge rate to the North Fork Red River aquifer for the period 1980–2013 was estimated to be about 2.77 inches per year or 9.5 percent of the mean annual precipitation (29.2 inches per year) for the same period. This 1980–2013 mean annual recharge rate is equivalent to a mean annual recharge volume of about 115,000 acre-feet per year. Streambed seepage is the predominant outflow from the North Fork Red River aquifer. The annual net streambed seepage upgradient from Lake Altus was estimated to be 27,824 acre-feet per year, and the annual net streambed seepage downgradient from Lake Altus was estimated to be 44,010 acre-feet per year.

The numerical groundwater-flow model simulated the period 1980–2013 and was calibrated to water-table-altitude observations at selected wells, monthly base flow at selected streamgages, net streambed seepage as estimated for the conceptual model, and Lake Altus stage. Groundwater-availability scenarios were performed by using the calibrated numerical groundwater-flow model to (1) estimate the EPS pumping rate that guarantees a minimum 20-, 40-, and 50-year life of the aquifer, (2) quantify the potential effects of projected well withdrawals on groundwater storage over a 50-year period, and (3) simulate the potential effects of a hypothetical (10-year) drought on base flow and groundwater storage. The results of the groundwater-availability scenarios could be used by the OWRB to reevaluate the maximum annual yield of groundwater from the North Fork Red River aquifer.

EPS scenarios for the North Fork Red River aquifer were run for periods of 20, 40, and 50 years. The 20-, 40-, and 50-year EPS pumping rates under normal recharge conditions were 0.59, 0.52, and 0.52 acre-foot per acre per year, respectively. Given the 497,582-acre aquifer area, these rates correspond to annual yields of about 294,000, 259,000, and 259,000 acre-feet per year, respectively. For the 20-year EPS scenario, decreasing and increasing recharge by 10 percent resulted in a 5–7-percent change in the EPS pumping rate; for the 40- and 50-year EPS scenarios, decreasing and increasing recharge by 10 percent resulted in a 6–8-percent change in the EPS pumping rate. Groundwater storage at the end of the 20-year EPS scenario was about 951,000 acre-feet, or about 1,317,000 acre-feet (58 percent) less than the starting EPS scenario storage. This decrease in storage was equivalent to a mean water-level decline of about 22 feet. Most areas of the active alluvium near the North Fork Red River, Elk Creek, and Elm Fork Red River remained partially saturated through the end of the EPS scenario because of streambed seepage. Lake Altus storage was reduced to zero after 6–7 years of EPS pumping in each scenario.

Projected 50-year pumping scenarios were used to simulate the effects of selected well withdrawal rates on groundwater storage of the North Fork Red River aquifer and base flows in the North Fork Red River upstream from Lake Altus. The effects of well withdrawals were evaluated by comparing changes in groundwater storage and base flow between four 50-year scenarios using (1) no groundwater pumping, (2) mean pumping rates for the study period (1980–2013), (3) 2013 pumping rates, and (4) increasing demand pumping rates. The increasing demand pumping rates assumed a 20.4-percent increase in pumping over 50 years based on 2010–60 demand projections for southwest Oklahoma.

Groundwater storage after 50 years with no pumping was about 2,606,000 acre-feet, or 137,000 acre-feet (5.5 percent) greater than the initial groundwater storage; this groundwater storage increase is equivalent to a mean water-level increase of 2.3 feet. Groundwater storage after 50 years with the mean pumping rate for the study period (1980–2013) was about 2,476,000 acre-feet, or about 7,000 acre-feet (0.3 percent) greater than the initial groundwater storage; this groundwater storage increase is equivalent to a mean water-level increase of 0.1 foot. Groundwater storage at the end of the 50-year period with 2013 pumping rates was about 2,398,000 acre-feet, or about 70,000 acre-feet (2.8 percent) less than the initial storage; this groundwater storage decrease is equivalent to a mean water-level decline of 1.2 feet. Groundwater storage at the end of the 50-year period with increasing demand pumping rates was about 2,361,000 acre-feet, or about 107,000 acre-feet (4.3 percent) less than the initial storage; this groundwater storage decrease is equivalent to a mean water-level decline of 1.8 feet. Mean annual base flow simulated at the Carter streamgage (07301500) on North Fork Red River increased by about 4,000 acre-feet (10 percent) after 50 years with no pumping and decreased by about 5,400 acre-feet (13 percent) after 50 years with increasing demand pumping rates. Mean annual base flow simulated at the North Fork Red River inflow to Lake Altus increased by about 7,400 acre-feet (15 percent) after 50 years with no pumping and decreased by about 5,800 acre-feet (12 percent) after 50 years with increasing demand pumping rates.

A hypothetical 10-year drought scenario was used to simulate the effects of a prolonged period of reduced recharge on groundwater storage and Lake Altus stage and storage. Drought effects were quantified by comparing the results of the drought scenario to those of the calibrated numerical model (no drought). To simulate the hypothetical drought, recharge in the calibrated numerical model was reduced by 50 percent during the simulated drought period (1984–93). Groundwater storage at the end of the drought period was about 2,271,000 acre-feet, or about 426,000 acre-feet (15.8 percent) less than the groundwater storage of the calibrated numerical model. This decrease in groundwater storage is equivalent to a mean water-table-altitude decline of 7.1 feet. At the end of the 10-year hypothetical drought period, base flows at the Sweetwater (07301420), Carter (07301500), Headrick (07305000), and Snyder (07307010) streamgages had decreased by about 37, 61, 44, and 45 percent, respectively. The minimum Lake Altus storage simulated during the drought period was 403 acre-feet, which was a decline of 92 percent from the nondrought storage. Reduced base flows in the North Fork Red River were the primary cause of Lake Altus storage declines.

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Table 1. Selected data-collection stations in and near the North Fork Red River aquifer study area, southwest Oklahoma.

[NAVD 88, North American Vertical Datum of 1988; >, greater than; SFR, Streamflow-Routing package; LAK, Lake package; WTF, water-table fluctuation method; SWB, Soil-Water Balance; m/d/y, month/day/year; --, not applicable or unknown]

Map name[1] (figs. 1–2)	Station identifier	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)	County	Period of record (may contain gaps) or single measurement date (m/d/y)		Land-surface altitude (feet above NAVD 88)
						Begin	End	
Continuous-record streamgages (U.S. Geological Survey, 2015a)								
07301300	Shamrock streamgage	North Fork Red River near Shamrock, Tex.	35.2642	-100.2418	Wheeler	2/19/1964	present (2015)	--
07301410	Kelton streamgage	Sweetwater Creek near Kelton, Tex.	35.4731	-100.1210	Wheeler	11/16/1961	present (2015)	--
07301420	Sweetwater streamgage	Sweetwater Creek near Sweetwater, Okla.	35.4223	-99.9693	Beckham	4/22/1986	present (2015)	--
07301500	Carter streamgage	North Fork Red River near Carter, Okla.	35.1681	-99.5073	Beckham	10/1/1944	present (2015)	--
07303000	Lugert streamgage	North Fork Red River below Altus Dam near Lugert, Okla.	34.8895	-99.3070	Greer	10/1/2007	present (2015)	--
07303400	Carl streamgage	Elm Fork of North Fork Red River (Elm Fork Red River) near Carl, Okla.	35.0117	-99.9037	Harmon	10/1/1959	present (2015)	--
07304500	Hobart streamgage	Elk Creek near Hobart, Okla.	34.9142	-99.1140	Kiowa	10/1/1904	9/30/1993	--
07305000	Headrick streamgage	North Fork Red River near Headrick, Okla.	34.6381	-99.1037	Tillman	4/1/1905	present (2015)	--
07307010	Snyder streamgage	Otter Creek near Snyder, Okla.	34.6378	-98.9987	Kiowa	7/1/2000	10/5/2008	--
Climate stations (Oklahoma Mesonet, 2015)								
--	ALTU	Altus	34.58722	-99.33808	Jackson	1/1/1994	present (2015)	1,365
--	CHEY	Cheyenne	35.54615	-99.72790	Roger Mills	1/1/1994	present (2015)	2,277
--	ERIC	Erick	35.20494	-99.80344	Beckham	1/1/1994	present (2015)	1,978
HOBA	HOBA	Hobart	34.98971	-99.05283	Kiowa	1/1/1994	present (2015)	1,568
--	HOLL	Hollis	34.68550	-99.83331	Harmon	1/1/1994	present (2015)	1,631
--	MANG	Mangum	34.83592	-99.42398	Greer	1/1/1994	present (2015)	1,509
--	RETR	Retrop	35.12275	-99.36001	Washita	1/1/1994	present (2015)	1,765
--	TIPT	Tipton	34.43972	-99.13755	Tillman	1/1/1994	present (2015)	1,270

Map name[1] (figs. 1–2)	Station identifier	Well or hole depth (feet)	Drainage area (square miles)			Regulated (> 20 percent of contributing drainage area behind large dams)	Use in numerical groundwater-flow model
			Total	Contrib-uting	Noncon-tributing		
			Continuous-record streamgages (U.S. Geological Survey, 2015a)				
07301300	Shamrock streamgage	--	1,369	817	552	yes; since 1930s by Lake McClellan, Tex., and since 1980s by floodwater-retarding structures	SFR inflow
07301410	Kelton streamgage	--	297	281	16	no	SFR inflow
07301420	Sweetwater streamgage	--	437	410	27	no	Recharge (RORA), manual and automated calibration
07301500	Carter streamgage	--	2,652	2,073	579	yes; since 1930s by Lake McClellan (Tex.) and since 1960s by floodwater-retarding structures	Outflow, manual and automated calibration
07303000	Lugert streamgage	--	2,832	2,253	579	yes; since 1945 by Lake Altus	LAK releases
07303400	Carl streamgage	--	438	438	0	no	SFR inflow
07304500	Hobart streamgage	--	549	549	0	yes; since 1960s by floodwater-retarding structures and since 1970s by Bretch Canal	SFR inflow
07305000	Headrick streamgage	--	4,560	3,981	579	yes; since 1940s by Lake Altus	Outflow, manual and automated calibration
07307010	Snyder streamgage	--	162	162	0	yes; since 1970s by Tom Steed Reservoir and floodwater-retarding structures	Outflow, manual calibration
			Climate stations (Oklahoma Mesonet, 2015)				
--	ALTU	--	--	--	--	--	Recharge (SWB)
--	CHEY	--	--	--	--	--	Recharge (SWB)
--	ERIC	--	--	--	--	--	Recharge (SWB)
HOBA	HOBA	--	--	--	--	--	Recharge (SWB)
--	HOLL	--	--	--	--	--	Recharge (SWB)
--	MANG	--	--	--	--	--	Recharge (SWB)
--	RETR	--	--	--	--	--	Recharge (SWB)
--	TIPT	--	--	--	--	--	Recharge (SWB)

Table 1. Selected data-collection stations in and near the North Fork Red River aquifer study area, southwest Oklahoma.—Continued

[NAVD 88, North American Vertical Datum of 1988; >, greater than; SFR, Streamflow-Routing package; LAK, Lake package; WTF, water-table fluctuation method; SWB, Soil-Water Balance; m/d/y, month/day/year; --, not applicable or unknown]

Map name[1] (figs. 1–2)	Station identifier	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)	County	Period of record (may contain gaps) or single measurement date (m/d/y)		Land-surface altitude (feet above NAVD 88)
						Begin	End	
Climate stations (National Climatic Data Center, 2015)								
--	USC00345648	Mayfield	35.3392	-99.8769	--	3/14/1948	2/29/2012	2,005
342944	USC00342944	Erick	35.2164	-99.8628	--	9/1/1904	present (2015)	2,060
349668	USC00349668	Willow	35.0522	-99.5125	--	9/1/1980	present (2015)	1,745
--	USC00410157	Allison	35.6103	-100.1022	--	8/1/2001	present (2015)	2,600
340184	USC00340184	Altus Dam	34.8847	-99.2964	--	8/1/1945	present (2015)	1,525
--	USC00349212	Vinson	34.9003	-99.8614	--	2/26/1940	present (2015)	1,880
--	USC00349213	Vinson 6 NW	34.9578	-99.9414	--	6/15/2011	present (2015)	1,912
347952	USC00347952	Sayre	35.3061	-99.6275	--	6/1/1936	present (2015)	1,900
--	USC00418235	Shamrock	35.2	-100.25	--	7/1/1929	9/30/1987	2,323
--	USC00342125	Cordell	35.3008	-98.9958	--	7/1/1936	1/22/2013	1,564
--	USC00418236	Shamrock 2	35.215	-100.2503	--	9/1/1962	present (2015)	2,360
--	USC00344202	Hobart	35.0258	-99.1058	--	5/1/2010	present (2015)	1,552
--	USW00093986	Hobart Municipal Airport	34.9894	-99.0525	--	1/1/1910	present (2015)	1,556
--	USC00419662	Wheeler	35.4375	-100.2753	--	4/1/1979	present (2015)	2,495
--	USC00347565	Retrop	35.1597	-99.3658	--	9/9/1980	present (2015)	1,780
--	USC00419565	Wellington	34.8422	-100.2103	--	4/1/1912	present (2015)	2,040
--	USC00345509	Mangum	34.8911	-99.5017	--	1/1/1920	present (2015)	1,595
--	USC00343998	Headrick	34.6286	-99.1394	--	2/1/1993	present (2015)	1,357
--	USC00348016	Sedan	34.9692	-98.7603	--	7/1/1993	1/22/2013	1,475
--	USC00349629	Wichita Mtn WLR	34.7325	-98.7125	--	1/1/1906	present (2015)	1,665
--	USW00003981	Frederick Municipal Airport	34.3622	-98.9761	--	2/1/1998	present (2015)	1,267
--	USC00341738	Cheyenne	35.6	-99.6833	--	7/1/1923	12/31/1994	2,005
--	USC00343353	Frederick	34.3861	-99.02	--	5/1/1904	3/29/2011	1,285
--	USC00348652	Sweetwater	35.4219	-99.9053	--	9/17/1982	1/22/2013	2,160

Map name[1] (figs. 1–2)	Station identifier	Well or hole depth (feet)	Drainage area (square miles)			Regulated (> 20 percent of contributing drainage area behind large dams)	Use in numerical groundwater-flow model
			Total	Contrib-uting	Noncon-tributing		
Climate stations (National Climatic Data Center, 2015)							
--	USC00345648	--	--	--	--	--	Recharge (SWB)
342944	USC00342944	--	--	--	--	--	Recharge (SWB)
349668	USC00349668	--	--	--	--	--	Recharge (SWB)
--	USC00410157	--	--	--	--	--	Recharge (SWB)
340184	USC00340184	--	--	--	--	--	Recharge (SWB)
--	USC00349212	--	--	--	--	--	Recharge (SWB)
--	USC00349213	--	--	--	--	--	Recharge (SWB)
347952	USC00347952	--	--	--	--	--	Recharge (SWB)
--	USC00418235	--	--	--	--	--	Recharge (SWB)
--	USC00342125	--	--	--	--	--	Recharge (SWB)
--	USC00418236	--	--	--	--	--	Recharge (SWB)
--	USC00344202	--	--	--	--	--	Recharge (SWB)
--	USW00093986	--	--	--	--	--	Recharge (SWB)
--	USC00419662	--	--	--	--	--	Recharge (SWB)
--	USC00347565	--	--	--	--	--	Recharge (SWB)
--	USC00419565	--	--	--	--	--	Recharge (SWB)
--	USC00345509	--	--	--	--	--	Recharge (SWB)
--	USC00343998	--	--	--	--	--	Recharge (SWB)
--	USC00348016	--	--	--	--	--	Recharge (SWB)
--	USC00349629	--	--	--	--	--	Recharge (SWB)
--	USW00003981	--	--	--	--	--	Recharge (SWB)
--	USC00341738	--	--	--	--	--	Recharge (SWB)
--	USC00343353	--	--	--	--	--	Recharge (SWB)
--	USC00348652	--	--	--	--	--	Recharge (SWB)

Table 1. Selected data-collection stations in and near the North Fork Red River aquifer study area, southwest Oklahoma.—Continued

[NAVD 88, North American Vertical Datum of 1988; >, greater than; SFR, Streamflow-Routing package; LAK, Lake package; WTF, water-table fluctuation method; SWB, Soil-Water Balance; m/d/y, month/day/year; --, not applicable or unknown]

Map name[1] (figs. 1–2)	Station identifier	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)	County	Period of record (may contain gaps) or single measurement date (m/d/y)		Land-surface altitude (feet above NAVD 88)
						Begin	End	
--	USW00003932	Clinton Sherman Airport	35.21	-99.12	--	8/17/1958	present (2015)	1,922
346035	USC00346035	Moravia	35.1464	-99.4956	--	8/1/1941	present (2015)	1,690
--	USC00347727	Roosevelt	34.8511	-99.0208	--	11/26/1943	present (2015)	1,462
--	USC00347579	Reydon	35.6256	-99.9106	--	11/15/1941	4/30/2007	2,385
--	USC00344249	Hollis 5 E	34.6808	-99.8136	--	8/1/1922	1/22/2013	1,621
--	USC00411408	Canadian 22 SE	35.6467	-100.0658	--	3/1/2003	2/1/2015	2,533
348299	USC00348299	Snyder	34.6867	-98.9483	--	9/1/1906	1/22/2013	1,370
--	USC00340179	Altus Irig Res Station	34.5903	-99.3344	--	5/1/1903	1/22/2013	1,380
--	USC00342849	Elk City 4 W	35.3925	-99.5064	--	5/1/1904	present (2015)	2,120
Continuous water-level recorder wells (U.S. Geological Survey, 2015a)								
CR1	351521099522901	09N-25W-17 BCC NFRR 01	35.255967	-99.874842	Beckham	4/18/2013	1/14/2015	2,033.77
CR2	350755099283201	08N-22W-25 CDD 1 NFRR 02	35.132094	-99.475564	Beckham	4/17/2013	1/15/2015	1,730.73
CR3	345759099163401	06N-20W-26 ADC 1 NFRR 03	34.966564	-99.276242	Kiowa	4/18/2013	1/14/2015	1,567.99
Geoprobe hydraulic profiling tool test holes								
HPT1	351800099524801	10N-25W-31 ADC 1	35.300113	-99.879995	Beckham	4/1/2014		1,923.2
HPT2	351759099492401	10N-25W-35 BCC 1	35.299716	-99.823350	Beckham	4/1/2014		1,904.5
HPT4	351552099414001	09N-24W-12 CDB 1	35.264451	-99.694512	Beckham	4/2/2014		1,823.4
HPT5	350949099302701	08N-22W-15 DCB 1	35.163637	-99.507607	Beckham	4/2/2014		1,685.0
Multi-well aquifer test locations (Kent, 1980; Paukstaitis, 1981; U.S. Geological Survey, 2015a)								
AT2	351339099424001	09N-24W-26 BDA 1	35.227551	-99.711487	Beckham	11/15/1954	11/19/1954	--
AT3	351438099370801	09N-23W-22 ABC 1	35.243940	-99.619262	Beckham	11/12/1954	11/17/1954	--
AT1	351657099584701	09N-26W-05 CAB 1	35.282552	-99.980108	Beckham	12/7/1954	12/9/1954	--
AT4	--	--	34.969435	-99.321235	Kiowa	3/15/1979	3/18/1979	--
Water-quality stations (Oklahoma Water Resources Board, 2015c)								
--	93413	NFRED-003	35.246670	-99.648080	Beckham	July–August, 2014		--
--	44829	NFRED-004	35.250939	-99.932832	Beckham	July–August, 2014		--
--	124090	NFRED-005	34.926030	-99.325240	Greer	July–August, 2014		--
--	78679	NFRED-007	35.210742	-99.541983	Beckham	July–August, 2014		--
--	21104	NFRED-008	35.264902	-99.672168	Beckham	July–August, 2014		--
--	53182	NFRED-009	35.059587	-99.337239	Kiowa	July–August, 2014		--
--	89166	NFRED-011	35.017180	-99.363960	Greer	July–August, 2014		--
--	52044	NFRED-016	35.370513	-99.914917	Beckham	July–August, 2014		--
--	57632	NFRED-019	35.205450	-99.674444	Beckham	July–August, 2014		--
--	27186	NFRED-021	34.884525	-99.339545	Greer	July–August, 2014		--
--	148351	NFRED-022	34.862925	-99.342301	Greer	July–August, 2014		--

Map name[1] (figs. 1–2)	Station identifier	Well or hole depth (feet)	Drainage area (square miles)			Regulated (> 20 percent of contributing drainage area behind large dams)	Use in numerical groundwater-flow model
			Total	Contrib-uting	Noncon-tributing		
--	USW00003932	--	--	--	--	--	Recharge (SWB)
346035	USC00346035	--	--	--	--	--	Recharge (SWB)
--	USC00347727	--	--	--	--	--	Recharge (SWB)
--	USC00347579	--	--	--	--	--	Recharge (SWB)
--	USC00344249	--	--	--	--	--	Recharge (SWB)
--	USC00411408	--	--	--	--	--	Recharge (SWB)
348299	USC00348299	--	--	--	--	--	Recharge (SWB)
--	USC00340179	--	--	--	--	--	Recharge (SWB)
--	USC00342849	--	--	--	--	--	Recharge (SWB)
Continuous water-level recorder wells (U.S. Geological Survey, 2015a)							
CR1	351521099522901	117	--	--	--	--	--
CR2	350755099283201	75.4	--	--	--	--	--
CR3	345759099163401	59.45	--	--	--	--	Recharge (WTF)
Geoprobe hydraulic profiling tool test holes							
HPT1	351800099524801	18.9	--	--	--	--	Hydraulic properties
HPT2	351759099492401	40.4	--	--	--	--	Hydraulic properties
HPT4	351552099414001	25.0	--	--	--	--	Hydraulic properties
HPT5	350949099302701	30.9	--	--	--	--	Hydraulic properties
Multi-well aquifer test locations (Kent, 1980; Paukstaitis, 1981; U.S. Geological Survey, 2015a)							
AT2	351339099424001	--	--	--	--	--	Hydraulic properties
AT3	351438099370801	--	--	--	--	--	Hydraulic properties
AT1	351657099584701	--	--	--	--	--	Hydraulic properties
AT4	--	--	--	--	--	--	Hydraulic properties
Water-quality stations (Oklahoma Water Resources Board, 2015c)							
--	93413	--	--	--	--	--	Groundwater quality
--	44829	--	--	--	--	--	Groundwater quality
--	124090	--	--	--	--	--	Groundwater quality
--	78679	--	--	--	--	--	Groundwater quality
--	21104	--	--	--	--	--	Groundwater quality
--	53182	--	--	--	--	--	Groundwater quality
--	89166	--	--	--	--	--	Groundwater quality
--	52044	--	--	--	--	--	Groundwater quality
--	57632	--	--	--	--	--	Groundwater quality
--	27186	--	--	--	--	--	Groundwater quality
--	148351	--	--	--	--	--	Groundwater quality

Table 1. Selected data-collection stations in and near the North Fork Red River aquifer study area, southwest Oklahoma.—Continued

[NAVD 88, North American Vertical Datum of 1988; >, greater than; SFR, Streamflow-Routing package; LAK, Lake package; WTF, water-table fluctuation method; SWB, Soil-Water Balance; m/d/y, month/day/year; --, not applicable or unknown]

Map name[1] (figs. 1–2)	Station identifier	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)	County	Period of record (may contain gaps) or single measurement date (m/d/y) Begin	End	Land-surface altitude (feet above NAVD 88)
--	27136	NFRED-023	35.266728	-99.634720	Beckham	July–August, 2014		--
--	44825	NFRED-024	35.267222	-99.796015	Beckham	July–August, 2014		--
--	21131	NFRED-036	35.246866	-99.679087	Beckham	July–August, 2014		--
--	80060	NFRED-044	35.339491	-99.778398	Beckham	July–August, 2014		--
--	118864	NFRED-052	35.205117	-99.725950	Beckham	July–August, 2014		--
--	21327	NFRED-070	35.298109	-99.857739	Beckham	July–August, 2014		--
--	21540	NFRED-073	34.893647	-99.335095	Greer	July–August, 2014		--
--	80000	NFRED-078	35.299360	-99.823090	Beckham	July–August, 2014		--
--	118145	NFRED-098	35.288040	-99.704080	Beckham	July–August, 2014		--
Water-quality stations (U.S. Geological Survey, 2015a)								
--	343755099061001	02N-18W-21 BD 1	34.632016	-99.103135	Jackson	9/1/1947		--
--	343920098584001	02N-17W-10 C 1	34.655626	-98.978132	Kiowa	8/15/1958		--
--	344037099032901	02N-18W-02 A 1	34.677014	-99.058412	Kiowa	8/8/1959		--
--	344037099032902	02N-18W-02 A 2	34.677014	-99.058412	Kiowa	8/8/1959		--
--	344100098581001	03N-17W-34 CCD 1	34.683402	-98.969798	Kiowa	2/15/1961		--
--	345400099166501	05N-20W-24 B 1	34.900060	-99.268416	Kiowa	8/4/1959		--
--	345450099282501	05N-22W-13 AAA 1	34.913948	-99.473977	Greer	12/23/1953		--
--	345820099164501	06N-20W-26 A 1	34.972280	-99.279526	Kiowa	4/25/1961		--
--	351218099394501	09N-23W-32 CCC 1	35.205052	-99.662874	Beckham	2/26/1952		--
--	351301099485301	09N-25W-35 BAA 4	35.216996	-99.815102	Beckham	2/26/1952		--
--	351312099513501	09N-25W-29 DDD 1	35.220052	-99.860103	Beckham	2/27/1952		--
--	351336099341901	09N-22W-30 CBA 1	35.226718	-99.572316	Beckham	11/1/1951		--
--	351336099342401	09N-22W-30 BCD 1	35.226718	-99.573705	Beckham	11/1/1951		--
--	351339099424001	09N-24W-26 BDA 1	35.227551	-99.711487	Beckham	11/15/1954		--
--	351439099364001	09N-23W-23 BBC 1	35.244218	-99.611484	Beckham	11/1/1951		--
--	351447099542001	09N-26W-19 AAA 1	35.246441	-99.905939	Beckham	3/5/1952		--
--	351520099404001	09N-23W-07 CB 1	35.255607	-99.678153	Beckham	11/28/1962		--
--	351555099431401	09N-24W-10 DDD 1	35.265329	-99.720933	Beckham	2/14/1952		--
--	351614099383602	09N-23W-09 BCD 2	35.270607	-99.643708	Beckham	11/2/1951		--
--	351657099584701	09N-26W-05 CAB 1	35.282552	-99.980108	Beckham	12/7/1954		--
--	351800099510001	10N-25W-35 CBB 1	35.300051	-99.850382	Beckham	3/2/1952		--
Water-table-altitude observation and Mass Measurement Program wells (Oklahoma Water Resources Board, 2015b); Land-surface elevations from U.S. Geological Survey (2015b)								
9088	350727099274901	08N-21W-31 CBB 1	35.123125	-99.464492	Beckham	3/5/1980	present (2015)	1,734.8
9089	350839099303001	08N-22W-27 AAD 1	35.142600	-99.501253	Beckham	3/5/1980	present (2015)	1,706.7
9090	351030099385401	08N-23W-17 AAB 1	35.174764	-99.649906	Beckham	3/6/1980	present (2015)	1,906.0
9092	351122099435501	08N-24W-09 AAB 1	35.189406	-99.734072	Beckham	3/6/1980	1/20/2000	1,954.1

Map name[1] (figs. 1–2)	Station identifier	Well or hole depth (feet)	Drainage area (square miles)			Regulated (> 20 percent of contributing drainage area behind large dams)	Use in numerical groundwater-flow model
			Total	Contrib-uting	Noncon-tributing		
--	27136	--	--	--	--	--	Groundwater quality
--	44825	--	--	--	--	--	Groundwater quality
--	21131	--	--	--	--	--	Groundwater quality
--	80060	--	--	--	--	--	Groundwater quality
--	118864	--	--	--	--	--	Groundwater quality
--	21327	--	--	--	--	--	Groundwater quality
--	21540	--	--	--	--	--	Groundwater quality
--	80000	--	--	--	--	--	Groundwater quality
--	118145	--	--	--	--	--	Groundwater quality
Water-quality stations (U.S. Geological Survey, 2015a)							
--	343755099061001	9	--	--	--	--	Groundwater quality
--	343920098584001	50	--	--	--	--	Groundwater quality
--	344037099032901	--	--	--	--	--	Groundwater quality
--	344037099032902	--	--	--	--	--	Groundwater quality
--	344100098581001	53	--	--	--	--	Groundwater quality
--	345400099166501	70	--	--	--	--	Groundwater quality
--	345450099282501	35	--	--	--	--	Groundwater quality
--	345820099164501	15	--	--	--	--	Groundwater quality
--	351218099394501	63	--	--	--	--	Groundwater quality
--	351301099485301	22	--	--	--	--	Groundwater quality
--	351312099513501	49	--	--	--	--	Groundwater quality
--	351336099341901	58	--	--	--	--	Groundwater quality
--	351336099342401	60.3	--	--	--	--	Groundwater quality
--	351339099424001	188	--	--	--	--	Groundwater quality
--	351439099364001	95	--	--	--	--	Groundwater quality
--	351447099542001	68	--	--	--	--	Groundwater quality
--	351520099404001	36	--	--	--	--	Groundwater quality
--	351555099431401	27	--	--	--	--	Groundwater quality
--	351614099383602	60	--	--	--	--	Groundwater quality
--	351657099584701	102	--	--	--	--	Groundwater quality
--	351800099510001	--	--	--	--	--	Groundwater quality
Water-table-altitude observation and Mass Measurement Program wells (Oklahoma Water Resources Board, 2015b); Land-surface elevations from U.S. Geological Survey (2015b)							
9088	350727099274901	76	--	--	--	--	Calibration
9089	350839099303001	50	--	--	--	--	Calibration
9090	351030099385401	80	--	--	--	--	Calibration
9092	351122099435501	142	--	--	--	--	Calibration

Table 1. Selected data-collection stations in and near the North Fork Red River aquifer study area, southwest Oklahoma.—Continued

[NAVD 88, North American Vertical Datum of 1988; >, greater than; SFR, Streamflow-Routing package; LAK, Lake package; WTF, water-table fluctuation method; SWB, Soil-Water Balance; m/d/y, month/day/year; --, not applicable or unknown]

Map name[1] (figs. 1–2)	Station identifier	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)	County	Period of record (may contain gaps) or single measurement date (m/d/y)		Land-surface altitude (feet above NAVD 88)
						Begin	End	
9093	351129099415601	08N-24W-02 DCD 1	35.190528	-99.699808	Beckham	1/21/1986	2/6/1990	1,921.3
9094	351215099292401	08N-22W-02 ABB 1	35.203983	-99.492533	Beckham	3/19/1981	present (2015)	1,852.6
9095	351216099483501	09N-25W-35 DDD 1	35.207297	-99.806075	Beckham	3/6/1980	2/8/2000	1,991.4
9096	351222099395801	09N-23W-32 CCB 1	35.207914	-99.661567	Beckham	3/5/1980	present (2015)	1,882.7
9097	351242099420601	09N-24W-36 BCC 1	35.212608	-99.698836	Beckham	3/7/1980	2/6/1990	1,918.5
9098	351301099323301	09N-22W-33 BBB 1	35.217650	-99.540775	Beckham	3/5/1980	present (2015)	1,781.2
9099	351306099515501	09N-26W-33 BBB 1	35.218147	-99.963903	Beckham	3/6/1980	2/21/1996	2,089.1
9100	351308099353601	09N-23W-25 CCD 1	35.219678	-99.591186	Beckham	3/17/1981	present (2015)	1,853.0
9101	351327099595901	09N-26W-30 CBA 1	35.225547	-99.995850	Beckham	3/6/1980	present (2015)	2,146.7
9102	351334099344001	09N-22W-30 BCC 1	35.226989	-99.575067	Beckham	3/5/1980	1/27/1998	1,786.7
9103	351347099324101	09N-22W-29 AAD 1	35.230336	-99.542769	Beckham	3/5/1980	2/22/1996	1,765.1
9104	351353099383101	09N-23W-28 BAA 1	35.232681	-99.639411	Beckham	3/5/1980	2/13/1991	1,890.4
9105	351353099482701	09N-25W-25 BBB 1	35.233372	-99.805669	Beckham	3/6/1980	3/9/1999	2,008.3
9106	351400099533501	09N-25W-31 BCB 1	35.214633	-99.893617	Beckham	3/6/1980	1/28/2013	2,031.2
9107	351402099533501	09N-25W-19 CCC 1	35.234356	-99.894219	Beckham	3/6/1980	3/19/2001	1,995.0
9108	351413099451601	09N-24W-21 CBC 2	35.237525	-99.752531	Beckham	3/7/1980	2/23/2014	1,930.7
9109	351426099372701	09N-23W-22 BDD 1	35.246361	-99.621225	Beckham	3/5/1980	1/30/2013	1,860.2
9110	351433099544101	09N-26W-24 BCA 1	35.242552	-99.911772	Beckham	3/6/1980	2/21/1996	2,041.2
9111	351446099362401	09N-23W-23 BAA 2	35.246162	-99.607039	Beckham	3/5/1980	2/22/1996	1,840.6
9112	351452099494701	09N-25W-15 DDC 1	35.249042	-99.826822	Beckham	3/6/1980	3/14/1994	2,006.5
9113	351512099411001	09N-24W-13 DAA 1	35.254786	-99.683769	Beckham	3/19/1981	3/17/2010	1,859.0
9114	351512099472401	09N-24W-18 CBB 1	35.255353	-99.788100	Beckham	3/6/1980	2/24/2012	1,937.5
9115	351518099375901	09N-23W-16 ADD 1	35.255078	-99.629367	Beckham	3/19/1981	1/20/2000	1,863.1
9116	351525099560801	09N-26W-15 ADB 2	35.258089	-99.932758	Beckham	3/6/1980	3/9/1999	1,999.2
9117	351557099522601	09N-25W-08 CAC 1	35.265885	-99.874271	Beckham	3/6/1980	2/21/1996	2,000.9
9118	351617099482701	09N-25W-12 BCB 1	35.271667	-99.803819	Beckham	3/6/1980	1/1/2007	1,971.4
9119	351617099590301	09N-26W-08 BCB 1	35.271756	-99.981142	Beckham	3/6/1980	3/17/2010	2,065.4
9120	351637099521001	09N-25W-05 DCC 1	35.277417	-99.868419	Beckham	3/6/1980	3/7/2007	1,986.8
9121	351755099563201	10N-26W-34 BDD 1	35.298663	-99.942607	Beckham	3/6/1980	3/10/1999	2,032.1
9122	352328099560001	11N-26W-34 AAA 1	35.393153	-99.929408	Beckham	3/6/1980	present (2015)	2,100.9
9123	352426099572801	11N-26W-21 DCC 1	35.408200	-99.955608	Beckham	3/6/1980	present (2015)	2,104.2
9438	345356099212801	05N-20W-19 BBB 1	34.899881	-99.356489	Greer	2/27/1980	2/11/2014	1,525.9
9439	345356099224001	05N-21W-23 AAA 1	34.899736	-99.379369	Greer	2/27/1980	2/20/2001	1,532.7

Map name[1] (figs. 1–2)	Station identifier	Well or hole depth (feet)	Drainage area (square miles)			Regulated (> 20 percent of contributing drainage area behind large dams)	Use in numerical groundwater-flow model
			Total	Contrib-uting	Noncon-tributing		
9093	351129099415601	--	--	--	--	--	Calibration
9094	351215099292401	210	--	--	--	--	Calibration
9095	351216099483501	86	--	--	--	--	Calibration
9096	351222099395801	--	--	--	--	--	Calibration
9097	351242099420601	123	--	--	--	--	Calibration
9098	351301099323301	74	--	--	--	--	Calibration
9099	351306099515501	33	--	--	--	--	Calibration
9100	351308099353601	148	--	--	--	--	Calibration
9101	351327099595901	70	--	--	--	--	Calibration
9102	351334099344001	67	--	--	--	--	Calibration
9103	351347099324101	64	--	--	--	--	Calibration
9104	351353099383101	--	--	--	--	--	Calibration
9105	351353099482701	100	--	--	--	--	Calibration
9106	351400099533501	35	--	--	--	--	Calibration
9107	351402099533501	36	--	--	--	--	Calibration
9108	351413099451601	59	--	--	--	--	Calibration
9109	351426099372701	--	--	--	--	--	Calibration
9110	351433099544101	217	--	--	--	--	Calibration
9111	351446099362401	113	--	--	--	--	Calibration
9112	351452099494701	--	--	--	--	--	Calibration
9113	351512099411001	30	--	--	--	--	Calibration
9114	351512099472401	120	--	--	--	--	Calibration
9115	351518099375901	130	--	--	--	--	Calibration
9116	351525099560801	150	--	--	--	--	Calibration
9117	351557099522601	160	--	--	--	--	Calibration
9118	351617099482701	130	--	--	--	--	Calibration
9119	351617099590301	63	--	--	--	--	Calibration
9120	351637099521001	--	--	--	--	--	Calibration
9121	351755099563201	--	--	--	--	--	Calibration
9122	352328099560001	32	--	--	--	--	Calibration
9123	352426099572801	90	--	--	--	--	Calibration
9438	345356099212801	49	--	--	--	--	Calibration
9439	345356099224001	50	--	--	--	--	Calibration

Table 1. Selected data-collection stations in and near the North Fork Red River aquifer study area, southwest Oklahoma.—Continued

[NAVD 88, North American Vertical Datum of 1988; >, greater than; SFR, Streamflow-Routing package; LAK, Lake package; WTF, water-table fluctuation method; SWB, Soil-Water Balance; m/d/y, month/day/year; --, not applicable or unknown]

Map name[1] (figs. 1–2)	Station identifier	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)	County	Period of record (may contain gaps) or single measurement date (m/d/y)		Land-surface altitude (feet above NAVD 88)
						Begin	End	
9440	345403099202501	05N-20W-17 CCC 1	34.900893	-99.340640	Greer	2/27/1980	3/8/1996	1,532.3
9441	345409099220801	05N-21W-13 CDA 1	34.902560	-99.369252	Greer	2/27/1980	3/8/1996	1,531.0
9442	345554099281201	05N-22W-12 DCD 1	34.914747	-99.471750	Greer	2/27/1980	1/13/2006	1,567.4
9443	345514099240701	05N-21W-10 DBB 1	34.920614	-99.402308	Greer	3/10/1983	3/8/1996	1,554.4
9444	345528099255801	05N-21W-08 ADB 1	34.925200	-99.433750	Greer	2/27/1980	present (2015)	1,553.6
9445	345541099193001	05N-20W-08 AAA 1	34.928114	-99.325361	Greer	2/27/1980	1/29/1998	1,584.4
9446	345547099302701	05N-22W-03 DCC 1	34.929780	-99.507867	Greer	2/27/1980	3/8/1996	1,547.0
9447	345554099313001	05N-22W-04 DCB 1	34.931589	-99.528775	Greer	2/27/1980	1/19/2005	1,551.9
9448	345758099345601	06N-23W-25 BDC 1	34.965875	-99.585192	Greer	3/28/1980	present (2015)	1,629.2
9449	345818099413201	06N-24W-25 BBAC 1	34.971722	-99.692596	Greer	2/28/1980	3/12/1997	1,625.7
9450	350055099204901	06N-20W-07 ABA 1	35.015747	-99.348425	Greer	3/3/1980	present (2015)	1,658.8
9451	350121099232701	06N-21W-02 CBA 1	35.022844	-99.392531	Greer	3/8/1980	present (2015)	1,679.7
9452	350239099265301	07N-21W-31 AAA 1	35.044278	-99.449364	Greer	3/3/1980	3/14/2000	1,689.1
9453	350411099274101	07N-21W-19 BCA 1	35.069522	-99.465514	Greer	3/26/1981	present (2015)	1,750.4
9454	350457099254201	07N-21W-16 CCB 1	35.076222	-99.429422	Greer	3/5/1980	present (2015)	1,709.3
9455	350457099271701	07N-21W-18 ACC 1	35.082554	-99.455088	Greer	3/5/1980	3/15/1994	1,751.1
9456	350516099243901	07N-21W-15 BBB 1	35.086775	-99.411875	Greer	3/5/1980	1/1/2004	1,712.7
9457	350516099282801	07N-22W-13 BAA 1	35.086892	-99.475683	Greer	3/5/1980	3/22/1995	1,769.7
9458	350523099303501	07N-22W-10 CDD 1	35.088972	-99.503475	Greer	3/5/1980	present (2015)	1,792.1
9459	350529099255801	07N-21W-08 DDB 1	35.091443	-99.433143	Greer	3/5/1980	3/11/1996	1,719.4
9460	350615099242301	07N-21W-03 CDC 1	35.102453	-99.406267	Greer	3/5/1980	present (2015)	1,651.0
9461	350641099274901	07N-21W-06 BCC 1	35.109575	-99.465675	Greer	3/5/1980	1/1/2007	1,747.1
9462	350701099302701	07N-22W-03 ABB 1	35.115958	-99.508781	Greer	3/5/1980	1/1/2004	1,779.7
9502	344637099152801	04N-20W-36 BDC 1	34.777009	-99.258140	Jackson	3/14/1979	3/31/1994	1,689.4
9533	343820098592501	02N-17W-16 DCC 1	34.638960	-98.990632	Kiowa	1/1/1975	1/5/2003	1,330.8
9534	343846099000501	02N-17W-17 ADD 1	34.644542	-99.001514	Kiowa	3/27/1979	present (2015)	1,321.8
9535	343903098580001	02N-17W-15 AAA 1	34.652414	-98.968122	Kiowa	3/27/1979	present (2015)	1,342.2
9536	343913098564801	02N-17W-12 CCC 1	34.653158	-98.949856	Kiowa	3/27/1979	1/14/2015	1,350.5
9537	343913098592601	02N-17W-09 DCC 1	34.653682	-98.990910	Kiowa	3/24/1981	3/4/1994	1,329.5
9538	344005098591001	02N-17W-04 DDC 1	34.667011	-98.987122	Kiowa	3/24/1981	2/18/2014	1,337.6

Map name[1] (figs. 1–2)	Station identifier	Well or hole depth (feet)	Drainage area (square miles)			Regulated (> 20 percent of contributing drainage area behind large dams)	Use in numerical groundwater-flow model
			Total	Contrib-uting	Noncon-tributing		
9440	345403099202501	58	--	--	--	--	Calibration
9441	345409099220801	50	--	--	--	--	Calibration
9442	345554099281201	--	--	--	--	--	Calibration
9443	345514099240701	66	--	--	--	--	Calibration
9444	345528099255801	52	--	--	--	--	Calibration
9445	345541099193001	57	--	--	--	--	Calibration
9446	345547099302701	28	--	--	--	--	Calibration
9447	345554099313001	24	--	--	--	--	Calibration
9448	345758099345601	47	--	--	--	--	Calibration
9449	345818099413201	24	--	--	--	--	Calibration
9450	350055099204901	52	--	--	--	--	Calibration
9451	350121099232701	75	--	--	--	--	Calibration
9452	350239099265301	68	--	--	--	--	Calibration
9453	350411099274101	67	--	--	--	--	Calibration
9454	350457099254201	71	--	--	--	--	Calibration
9455	350457099271701	--	--	--	--	--	Calibration
9456	350516099243901	--	--	--	--	--	Calibration
9457	350516099282801	82	--	--	--	--	Calibration
9458	350523099303501	72	--	--	--	--	Calibration
9459	350529099255801	70	--	--	--	--	Calibration
9460	350615099242301	49	--	--	--	--	Calibration
9461	350641099274901	--	--	--	--	--	Calibration
9462	350701099302701	113	--	--	--	--	Calibration
9502	344637099152801	--	--	--	--	--	Calibration
9533	343820098592501	55	--	--	--	--	Calibration
9534	343846099000501	40	--	--	--	--	Calibration
9535	343903098580001	45	--	--	--	--	Calibration
9536	343913098564801	48	--	--	--	--	Calibration
9537	343913098592601	49	--	--	--	--	Calibration
9538	344005098591001	44	--	--	--	--	Calibration

Table 1. Selected data-collection stations in and near the North Fork Red River aquifer study area, southwest Oklahoma.—Continued

[NAVD 88, North American Vertical Datum of 1988; >, greater than; SFR, Streamflow-Routing package; LAK, Lake package; WTF, water-table fluctuation method; SWB, Soil-Water Balance; m/d/y, month/day/year; --, not applicable or unknown]

Map name[1] (figs. 1–2)	Station identifier	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)	County	Period of record (may contain gaps) or single measurement date (m/d/y)		Land-surface altitude (feet above NAVD 88)
						Begin	End	
9539	344149098582301	03N-17W-27 DCC 1	34.696044	-98.973492	Kiowa	3/27/1979	present (2015)	1,351.8
9540	344210098593501	03N-17W-28 CA 1	34.700344	-98.992775	Kiowa	1/28/1976	present (2015)	1,353.7
9542	344637099085401	04N-19W-36 ACC 1	34.777009	-99.148692	Kiowa	3/24/1981	1/16/1996	1,398.3
9543	344745099083001	04N-19W-25 AAA 1	34.797353	-99.141792	Kiowa	3/13/1979	present (2015)	1,408.9
9544	344821099082201	04N-18W-19 BCC 1	34.804831	-99.141456	Kiowa	3/13/1979	3/22/1999	1,405.1
9545	345659099162001	06N-20W-35 DAA 1	34.950294	-99.272633	Kiowa	1/1/1977	present (2015)	1,561.7
9546	345732099181801	06N-20W-27 CCC 1	34.958947	-99.305360	Kiowa	1/1/1977	3/22/1995	1,578.9
9547	345751099185801	06N-20W-28 CAA 1	34.964224	-99.316472	Kiowa	3/8/1979	3/11/1996	1,570.4
9548	345818099193001	06N-20W-29 AAA 1	34.971724	-99.325361	Kiowa	3/27/1979	2/4/2003	1,572.7
9549	345824099165901	06N-20W-23 CDC 1	34.972561	-99.285403	Kiowa	1/1/1977	present (2015)	1,591.1
9550	345824099185001	06N-20W-21 DCC 2	35.004878	-99.315158	Kiowa	1/1/1977	3/25/2010	1,587.5
9551	345831099191401	06N-20W-21 CCA 1	34.976347	-99.320603	Kiowa	1/1/1977	2/5/2003	1,580.2
9552	345844099193001	06N-20W-20 DAA 1	34.978946	-99.325361	Kiowa	1/1/1977	2/4/2003	1,577.6
9553	345857099193001	06N-20W-20 ADA 2	34.983828	-99.325422	Kiowa	3/8/1977	present (2015)	1,582.4
Water-table-altitude observation wells (U.S. Geological Survey, 2015a); Land-surface elevations from U.S. Geological Survey (2015b)								
--	351125099414301	08N-24W-02 DDD 1	35.190330	-99.695653	Beckham	3/3/1952	1/8/1985	1,917.1
--	350806099302701	08N-22W-27 DCB 1	35.135053	-99.507868	Beckham	4/8/1980		1,732.2
--	352525099543501	11N-26W-13 CCC 1	35.423661	-99.910109	Roger Mills	11/5/1980		2,164.4
--	351646099515801	09N-25W-05 D 1	35.279496	-99.866493	Beckham	2/18/1981		1,960.3
--	352433099550501	11N-26W-23 DDB 1	35.409217	-99.918442	Beckham	8/23/1981		2,156.1
--	350809099304701	08N-22W-27 C 1	35.135887	-99.513424	Beckham	8/31/1981		1,738.5
--	351518099535301	09N-26W-13 ADD 1	35.255052	-99.898438	Beckham	10/23/1981		2,017.0
--	345348099292601	05N-22W-23 ABCC 1	34.897281	-99.493422	Greer	5/15/1986	10/13/1987	1,590.6
--	343819099060001	02N-18W-16 CDC 1	34.638517	-99.100017	Kiowa	9/10/2003		1,312.9
--	343851099055401	02N-18W-16 BDA 1	34.647383	-99.098317	Jackson	9/10/2003		1,314.4
--	352035099570501	10N-26W-16 ACD 1	35.343125	-99.951464	Beckham	12/5/2012		2,048.8
--	352100099593201	10N-26W-07 CDD 1	35.350089	-99.992344	Beckham	12/5/2012		2,102.4
--	351438099513101	09N-25W-21 BCB 1	35.243983	-99.858708	Beckham	12/6/2012		2,034.2
--	351453099502901	09N-25W-16 DDD 1	35.248236	-99.841428	Beckham	12/6/2012		2,030.9
--	351534099563201	09N-26W-15 BAC 1	35.259503	-99.942417	Beckham	12/6/2012		2,000.1
--	351545099522001	09N-25W-08 CCD 1	35.262664	-99.872258	Beckham	12/6/2012		2,012.3
--	351639099472301	09N-25W-01 DDD 1	35.277656	-99.789989	Beckham	12/6/2012		1,946.1
--	351232099424901	09N-24W-34 DAD 1	35.208953	-99.713631	Beckham	12/7/2012		1,932.1

Map name[1] (figs. 1–2)	Station identifier	Well or hole depth (feet)	Drainage area (square miles)			Regulated (> 20 percent of contributing drainage area behind large dams)	Use in numerical groundwater-flow model
			Total	Contrib-uting	Noncon-tributing		
9539	344149098582301	61	--	--	--	--	Calibration
9540	344210098593501	40	--	--	--	--	Calibration
9542	344637099085401	--	--	--	--	--	Calibration
9543	344745099083001	31	--	--	--	--	Calibration
9544	344821099082201	23	--	--	--	--	Calibration
9545	345659099162001	--	--	--	--	--	Calibration
9546	345732099181801	38	--	--	--	--	Calibration
9547	345751099185801	57	--	--	--	--	Calibration
9548	345818099193001	62	--	--	--	--	Calibration
9549	345824099165901	38	--	--	--	--	Calibration
9550	345824099185001	59	--	--	--	--	Calibration
9551	345831099191401	66	--	--	--	--	Calibration
9552	345844099193001	64	--	--	--	--	Calibration
9553	345857099193001	68	--	--	--	--	Calibration
Water-table-altitude observation wells (U.S. Geological Survey, 2015a); Land-surface elevations from U.S. Geological Survey (2015b)							
--	351125099414301	29	--	--	--	--	Calibration
--	350806099302701	30	--	--	--	--	Calibration
--	352525099543501	89.5	--	--	--	--	Calibration
--	351646099515801	40	--	--	--	--	Calibration
--	352433099550501	215	--	--	--	--	Calibration
--	350809099304701	56	--	--	--	--	Calibration
--	351518099535301	70	--	--	--	--	Calibration
--	345348099292601	50	--	--	--	--	Calibration
--	343819099060001	19.88	--	--	--	--	Calibration
--	343851099055401	17.5	--	--	--	--	Calibration
--	352035099570501	--	--	--	--	--	Calibration
--	352100099593201	65	--	--	--	--	Calibration
--	351438099513101	220	--	--	--	--	Calibration
--	351453099502901	150	--	--	--	--	Calibration
--	351534099563201	150	--	--	--	--	Calibration
--	351545099522001	173	--	--	--	--	Calibration
--	351639099472301	100	--	--	--	--	Calibration
--	351232099424901	110	--	--	--	--	Calibration

Table 1. Selected data-collection stations in and near the North Fork Red River aquifer study area, southwest Oklahoma.—Continued

[NAVD 88, North American Vertical Datum of 1988; >, greater than; SFR, Streamflow-Routing package; LAK, Lake package; WTF, water-table fluctuation method; SWB, Soil-Water Balance; m/d/y, month/day/year; --, not applicable or unknown]

Map name[1] (figs. 1–2)	Station identifier	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)	County	Period of record (may contain gaps) or single measurement date (m/d/y)		Land-surface altitude (feet above NAVD 88)
						Begin	End	
--	351327099363701	09N-23W-26 CBB 1	35.224406	-99.610497	Beckham	12/7/2012		1,870.9
--	350201099244001	07N-21W-34 CBC 1	35.033611	-99.411139	Greer	12/11/2012		1,650.9
--	350244099281601	07N-22W-25 DCD 1	35.045678	-99.471278	Greer	12/11/2012		1,710.8
--	350541099275501	07N-21W-07 BCC 1	35.094931	-99.465492	Greer	12/11/2012		1,759.3
--	350701099302301	08N-22W-34 DCD 1	35.117100	-99.506450	Beckham	12/11/2012		1,781.3
--	345737099343801	06N-23W-25 DCA 1	34.960497	-99.577417	Greer	12/12/2012		1,619.7
--	351120099325101	08N-22W-08 BAB 1	35.189100	-99.547739	Beckham	12/17/2012		1,765.4
--	351213099304801	08N-22W-03 BAB 1	35.203875	-99.513478	Beckham	12/17/2012		1,800.4
--	351402099304001	09N-22W-22 DCD 1	35.234078	-99.511275	Beckham	12/17/2012		1,837.7
--	350010099220001	06N-21W-12 DCD 1	35.002953	-99.366808	Greer	12/18/2012		1,678.0
--	350029099212001	06N-20W-07 CAB 1	35.008317	-99.355772	Greer	12/18/2012		1,670.6
--	350051099214001	06N-21W-12 AAA 1	35.014203	-99.361208	Greer	12/18/2012		1,662.7
--	350214099213701	07N-21W-36 ADD 1	35.037356	-99.360406	Greer	12/18/2012		1,663.1
--	350238099234401	07N-21W-27 DDD 1	35.044142	-99.395794	Greer	12/18/2012		1,628.5
--	350412099234301	07N-21W-22 AAD 1	35.070189	-99.395450	Greer	12/18/2012		1,701.6
--	350846099300701	08N-22W-22 DDD 1	35.146281	-99.502092	Beckham	12/18/2012		1,697.6
--	350921099342001	08N-23W-24 ADA 1	35.155956	-99.572406	Beckham	12/18/2012		1,711.7
--	345541099164901	05N-20W-11 ABB 1	34.928217	-99.280411	Kiowa	12/19/2012		1,571.6
--	345729099182401	06N-20W-27 CCC 2	34.958097	-99.306928	Kiowa	12/19/2012		1,577.4
--	345811099193101	06N-20W-29 AAD 1	34.969992	-99.325297	Kiowa	12/19/2012		1,573.3
--	350332099203301	07N-20W-20 CCC 1	35.058936	-99.342739	Kiowa	12/19/2012		1,622.5
--	350337099210401	07N-20W-19 DCC 1	35.060294	-99.351219	Kiowa	12/19/2012		1,613.9
--	350356099204801	07N-20W-19 DAB 1	35.065689	-99.346842	Kiowa	12/19/2012		1,620.7
--	345451099155801	05N-20W-13 BAB 1	34.914267	-99.266247	Kiowa	12/20/2012		1,530.7
--	344843099095701	04N-19W-14 DCD 1	34.812125	-99.165892	Jackson	1/7/2013		1,437.5
--	344845099121101	04N-19W-16 DCC 1	34.812525	-99.203142	Jackson	1/7/2013		1,509.7
--	345032099110801	04N-19W-03 CDD 1	34.842233	-99.185778	Jackson	1/7/2013		1,471.5
--	345054099111801	04N-19W-03 CAB 1	34.848569	-99.188369	Jackson	1/7/2013		1,430.7
--	344220099154801	03N-20W-25 BCB 1	34.705689	-99.263383	Jackson	1/8/2013		1,411.5
--	344327099172701	03N-20W-22 BAA 1	34.724206	-99.291000	Jackson	1/8/2013		1,453.3
--	344636099180901	04N-20W-33 ADC 1	34.776669	-99.302522	Jackson	1/8/2013		1,530.4
--	344650099144801	04N-20W-36 AAD 1	34.780661	-99.246892	Jackson	1/8/2013		1,650.4
--	344838099173001	04N-20W-22 BAA 1	34.810808	-99.291836	Jackson	1/8/2013		1,556.8
--	343840099011201	02N-17W-18 DAA 1	34.644536	-99.020244	Kiowa	1/9/2013		1,369.9
--	343910099041501	02N-18W-11 CCC 1	34.652836	-99.070872	Jackson	1/9/2013		1,399.0
--	344054099045301	03N-18W-34 CDD 1	34.681694	-99.081556	Jackson	1/9/2013		1,349.8
--	344152099021001	03N-18W-25 DDA 1	34.697925	-99.036108	Kiowa	1/9/2013		1,359.7
--	351806099442501	10N-24W-33 ACA 1	35.301775	-99.740531	Beckham	1/10/2013		1,936.5
--	351932099430401	10N-24W-22 DAA 1	35.325736	-99.717928	Beckham	1/10/2013		2,010.2

Map name[1] (figs. 1–2)	Station identifier	Well or hole depth (feet)	Drainage area (square miles)			Regulated (> 20 percent of contributing drainage area behind large dams)	Use in numerical groundwater-flow model
			Total	Contrib-uting	Noncon-tributing		
--	351327099363701	145	--	--	--	--	Calibration
--	350201099244001	40	--	--	--	--	Calibration
--	350244099281601	47	--	--	--	--	Calibration
--	350541099275501	72	--	--	--	--	Calibration
--	350701099302301	127	--	--	--	--	Calibration
--	345737099343801	60	--	--	--	--	Calibration
--	351120099325101	50	--	--	--	--	Calibration
--	351213099304801	56	--	--	--	--	Calibration
--	351402099304001	65	--	--	--	--	Calibration
--	350010099220001	67	--	--	--	--	Calibration
--	350029099212001	81	--	--	--	--	Calibration
--	350051099214001	67	--	--	--	--	Calibration
--	350214099213701	39	--	--	--	--	Calibration
--	350238099234401	30	--	--	--	--	Calibration
--	350412099234301	57	--	--	--	--	Calibration
--	350846099300701	50	--	--	--	--	Calibration
--	350921099342001	40	--	--	--	--	Calibration
--	345541099164901	53.5	--	--	--	--	Calibration
--	345729099182401	39.4	--	--	--	--	Calibration
--	345811099193101	--	--	--	--	--	Calibration
--	350332099203301	65	--	--	--	--	Calibration
--	350337099210401	33	--	--	--	--	Calibration
--	350356099204801	16.5	--	--	--	--	Calibration
--	345451099155801	29.5	--	--	--	--	Calibration
--	344843099095701	30	--	--	--	--	Calibration
--	344845099121101	54.28	--	--	--	--	Calibration
--	345032099110801	33.5	--	--	--	--	Calibration
--	345054099111801	25	--	--	--	--	Calibration
--	344220099154801	43.2	--	--	--	--	Calibration
--	344327099172701	44.5	--	--	--	--	Calibration
--	344636099180901	--	--	--	--	--	Calibration
--	344650099144801	40	--	--	--	--	Calibration
--	344838099173001	72	--	--	--	--	Calibration
--	343840099011201	22.9	--	--	--	--	Calibration
--	343910099041501	32.6	--	--	--	--	Calibration
--	344054099045301	21	--	--	--	--	Calibration
--	344152099021001	15.9	--	--	--	--	Calibration
--	351806099442501	--	--	--	--	--	Calibration
--	351932099430401	37.1	--	--	--	--	Calibration

Table 1. Selected data-collection stations in and near the North Fork Red River aquifer study area, southwest Oklahoma.—Continued

[NAVD 88, North American Vertical Datum of 1988; >, greater than; SFR, Streamflow-Routing package; LAK, Lake package; WTF, water-table fluctuation method; SWB, Soil-Water Balance; m/d/y, month/day/year; --, not applicable or unknown]

Map name[1] (figs. 1–2)	Station identifier	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)	County	Period of record (may contain gaps) or single measurement date (m/d/y)		Land-surface altitude (feet above NAVD 88)
						Begin	End	
--	344321099155401	03N-20W-23 AAD 1	34.722664	-99.265144	Jackson	1/16/2013		1,454.5
--	344512099155301	03N-20W-11 AAA 1	34.753414	-99.264967	Jackson	1/16/2013		1,590.8
--	344550099170601	03N-20W-03 ADC 1	34.763994	-99.285161	Jackson	1/16/2013		1,537.2
--	344756099154801	04N-20W-24 CCC 1	34.798928	-99.263528	Jackson	1/16/2013		1,677.0
--	344912099081001	04N-18W-18 BDC 1	34.820011	-99.136289	Kiowa	1/16/2013		1,410.6
--	345013099073001	04N-18W-07 ADA 1	34.837200	-99.125219	Kiowa	1/16/2013		1,423.3
--	343923099062601	02N-18W-08 DAD 1	34.656511	-99.105592	Kiowa	1/17/2013		1,331.2
--	343934099042101	02N-18W-10 DAA 1	34.659456	-99.072736	Kiowa	1/17/2013		1,336.6
--	343934099044401	02N-18W-10 DBB 1	34.659697	-99.079031	Kiowa	1/17/2013		1,334.9
--	345819099075301	06N-18W-19 DDD 1	34.972092	-99.131547	Kiowa	1/17/2013		1,492.3
--	350755099283201	08N-22W-25 CDD 1 NFRR 02	35.132094	-99.475564	Beckham	4/16/2013	1/15/2015	1,732.2
--	351521099522901	09N-25W-17 BCC NFRR 01	35.255967	-99.874842	Beckham	4/16/2013	1/15/2015	2,022.8
Historical water-table-altitude observation wells (U.S. Geological Survey, 2015a)								
10	351125099414301	08N-24W-02 DDD 1	35.190330	-99.695653	Beckham	3/3/1952	1/8/1985	--
1	351636099375001	09N-23W-04 DDD 1	35.276718	-99.630930	Beckham	2/27/1952	8/28/1957	--
53	351619099384501	09N-23W-09 BCB 1	35.271996	-99.646208	Beckham	6/24/1953	5/17/1967	--
40	351727099492501	09N-25W-03 AAA 1	35.290885	-99.823992	Beckham	12/3/1951	8/25/1959	--
35 (9107)	351402099533501	09N-25W-19 CCC 1	35.233941	-99.893438	Beckham	11/15/1951	2/14/1973	--
32 (9106)	351400099533501	09N-25W-31 BCB 1	35.233386	-99.893438	Beckham	11/15/1951	8/19/1986	--
27	351306099564601	09N-25W-34 BBB 1	35.218386	-99.946495	Beckham	8/29/1951	10/8/1969	--
49 (9119)	351617099585201	09N-26W-08 BCB 1	35.271441	-99.981497	Beckham	11/6/1951	12/29/1970	--
47	351306099515501	09N-26W-33 BBB 1	35.218385	-99.865659	Beckham	11/7/1951	12/29/1970	--
33	351215099552001	09N-26W-36 CDC 1	35.204219	-99.922605	Beckham	11/8/1951	6/26/1962	--
Synoptic streamflow measurement station (U.S. Geological Survey, 2015a)								
--	07301300	North Fork Red River near Shamrock, TX	35.264216	-100.241786	Wheeler	3/11/2013		--
--	07301315	North Fork Red River near Texola, OK	35.294497	-99.990109	Beckham	3/11/2013		--
--	07301410	Sweetwater Creek near Kelton, TX	35.473104	-100.120950	Wheeler	3/11/2013		--
--	07301420	Sweetwater Creek near Sweetwater, OK	35.422272	-99.969277	Beckham	3/11/2013		--
--	07301425	Sweetwater Creek near Texas Line, OK	35.318663	-99.964831	Beckham	3/11/2013		--
--	07301450	North Fork Red River near Erick, OK	35.300051	-99.875383	Beckham	3/13/2013		--
--	073014505	Buffalo Creek near Prentiss, OK	35.384431	-99.828039	Beckham	3/13/2013		--
--	07301452	Starvation Creek near Prentiss, OK	35.323662	-99.758713	Beckham	3/13/2013		--

Map name[1] (figs. 1–2)	Station identifier	Well or hole depth (feet)	Drainage area (square miles)			Regulated (> 20 percent of contributing drainage area behind large dams)	Use in numerical groundwater-flow model
			Total	Contrib-uting	Noncon-tributing		
--	344321099155401	73	--	--	--	--	Calibration
--	344512099155301	73.75	--	--	--	--	Calibration
--	344550099170601	48.4	--	--	--	--	Calibration
--	344756099154801	76	--	--	--	--	Calibration
--	344912099081001	22	--	--	--	--	Calibration
--	345013099073001	34.2	--	--	--	--	Calibration
--	343923099062601	24	--	--	--	--	Calibration
--	343934099042101	21	--	--	--	--	Calibration
--	343934099044401	20.2	--	--	--	--	Calibration
--	345819099075301	20.5	--	--	--	--	Calibration
--	350755099283201	75.4	--	--	--	--	Calibration
--	351521099522901	117	--	--	--	--	Calibration
Historical water-table-altitude observation wells (U.S. Geological Survey, 2015a)							
10	351125099414301	29	--	--	--	--	--
1	351636099375001	33.4	--	--	--	--	--
53	351619099384501	23.7	--	--	--	--	--
40	351727099492501	40	--	--	--	--	--
35 (9107)	351402099533501	36	--	--	--	--	--
32 (9106)	351400099533501	34.8	--	--	--	--	--
27	351306099564601	78.6	--	--	--	--	--
49 (9119)	351617099585201	62.7	--	--	--	--	--
47	351306099515501	32.8	--	--	--	--	--
33	351215099552001	26.9	--	--	--	--	--
Synoptic streamflow measurement station (U.S. Geological Survey, 2015a)							
--	07301300	--	--	--	--	--	Streambed seepage
--	07301315	--	--	--	--	--	Streambed seepage
--	07301410	--	--	--	--	--	Streambed seepage
--	07301420	--	--	--	--	--	Streambed seepage
--	07301425	--	--	--	--	--	Streambed seepage
--	07301450	--	--	--	--	--	Streambed seepage
--	073014505	--	--	--	--	--	Streambed seepage
--	07301452	--	--	--	--	--	Streambed seepage

Table 1. Selected data-collection stations in and near the North Fork Red River aquifer study area, southwest Oklahoma.—Continued

[NAVD 88, North American Vertical Datum of 1988; >, greater than; SFR, Streamflow-Routing package; LAK, Lake package; WTF, water-table fluctuation method; SWB, Soil-Water Balance; m/d/y, month/day/year; --, not applicable or unknown]

Map name[1] (figs. 1–2)	Station identifier	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)	County	Period of record (may contain gaps) or single measurement date (m/d/y)		Land-surface altitude (feet above NAVD 88)
						Begin	End	
--	07301475	Long Creek at Sayre, OK	35.291369	-99.667100	Beckham	3/11/2013		--
--	07301481	North Fork Red River near Sayre, OK	35.284773	-99.622041	Beckham	3/11/2013		--
--	07301489	Timber Creek near Sayre, OK	35.291411	-99.581731	Beckham	3/11/2013		--
--	07301500	North Fork Red River near Carter, OK	35.168108	-99.507313	Beckham	3/11/2013		--
--	07301950	North Fork Red River blw Lake Ck nr Lake Creek, OK	35.053111	-99.371196	Greer	3/12/2013		--
--	07302000	North Fork Red River near Granite, OK	34.973391	-99.333694	Kiowa	3/12/2013		--
--	07303000	North Fork Red River blw Altus Dam nr Lugert, OK	34.889505	-99.307028	Greer	3/12/2013		--
--	07303400	Elm Fork of North Fork Red River near Carl, OK	35.011720	-99.903714	Harmon	3/12/2013		--
--	07303490	Elm Fork of North Fork Red River nr Bloomington OK	34.941731	-99.572319	Greer	3/12/2013		--
--	07303493	Haystack Creek near Bloomington, OK	35.002361	-99.584050	Greer	3/12/2013		--
--	07303500	Elm Fork of North Fork Red River nr Mangum, OK	34.926725	-99.500367	Greer	3/12/2013		--
--	07303900	Elm Fork of North Fork Red River near Granite, OK	34.888600	-99.378869	Greer	3/12/2013		--
--	07304000	North Fork Red River near Lugert, OK	34.865833	-99.310556	Kiowa	3/12/2013		--
--	07304030	North Fork Red River near Warrenn, OK	34.826311	-99.229681	Jackson	3/13/2013		--
--	07304480	Elk Creek at Hobart, OK	34.986731	-99.117489	Kiowa	3/12/2013		--
--	07304600	Elk Creek near Roosevelt, OK	34.832039	-99.124661	Kiowa	3/13/2013		--
--	07304800	North Fork Red River at SH 19 near Warren, OK	34.783100	-99.165339	Jackson	3/13/2013		--
--	07305000	North Fork Red River near Headrick, OK	34.638127	-99.103691	Tillman	3/12/2013		--
--	07305500	West Otter Creek at Snyder Lk nr Mt Park, OK	34.733956	-98.986465	Kiowa	3/12/2013		--
--	07307010	Otter Creek near Snyder, OK	34.637849	-98.998688	Kiowa	3/12/2013		--

[1]Only sites discussed in this report are labeled on figures 1 and 2.

Map name[1] (figs. 1–2)	Station identifier	Well or hole depth (feet)	Drainage area (square miles)			Regulated (> 20 percent of contributing drainage area behind large dams)	Use in numerical groundwater-flow model
			Total	Contrib-uting	Noncon-tributing		
--	07301475	--	--	--	--	--	Streambed seepage
--	07301481	--	--	--	--	--	Streambed seepage
--	07301489	--	--	--	--	--	Streambed seepage
--	07301500	--	--	--	--	--	Streambed seepage
--	07301950	--	--	--	--	--	Streambed seepage
--	07302000	--	--	--	--	--	Streambed seepage
--	07303000	--	--	--	--	--	Streambed seepage
--	07303400	--	--	--	--	--	Streambed seepage
--	07303490	--	--	--	--	--	Streambed seepage
--	07303493	--	--	--	--	--	Streambed seepage
--	07303500	--	--	--	--	--	Streambed seepage
--	07303900	--	--	--	--	--	Streambed seepage
--	07304000	--	--	--	--	--	Streambed seepage
--	07304030	--	--	--	--	--	Streambed seepage
--	07304480	--	--	--	--	--	Streambed seepage
--	07304600	--	--	--	--	--	Streambed seepage
--	07304800	--	--	--	--	--	Streambed seepage
--	07305000	--	--	--	--	--	Streambed seepage
--	07305500	--	--	--	--	--	Streambed seepage
--	07307010	--	--	--	--	--	Streambed seepage

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