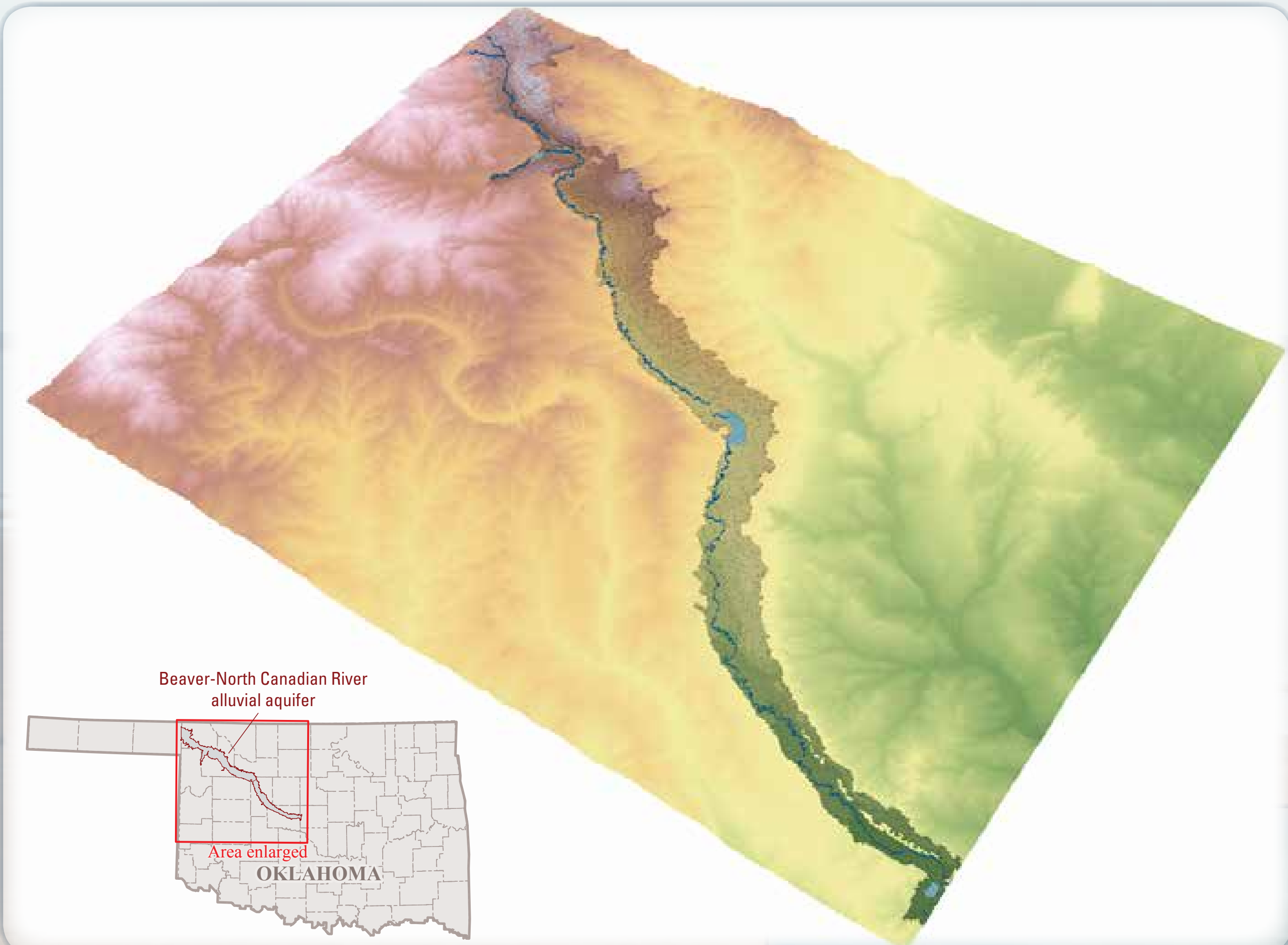
Prepared in cooperation with the Oklahoma Water Resources Board

Hydrogeological Framework, Numerical Simulation of Groundwater Flow, and Effects of Projected Water Use and Drought for the Beaver-North Canadian River Alluvial Aquifer, Northwestern Oklahoma



Scientific Investigations Report 2015–5183

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

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Top, Canton Lake. Photo by Kevin Smith, U.S. Geological Survey Oklahoma Water Science Center.

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SALLY JEWELL, Secretary

U.S. Geological Survey
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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^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)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°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.

Abbreviations

BFI	base-flow index, and a computer program that uses daily streamflow records with a hydrograph recession method to separate base flow from runoff
R^2	coefficient of determination
DEM	digital elevation model
EPS	equal proportionate share
ET	evapotranspiration
GHB	general-head boundary
GPS	Global Positioning System
Kh	horizontal hydraulic conductivity
NLCD	National Land Cover Database
OCWP	Oklahoma Comprehensive Water Plan
OWRB	Oklahoma Water Resources Board
RMSE	root-mean-square error
SWB	soil-water balance
Sy	specific yield
SFR2	Streamflow-Routing package version 2
USGS	U.S. Geological Survey
WTF	water-table fluctuation

Hydrogeological Framework, Numerical Simulation of Groundwater Flow, and Effects of Projected Water Use and Drought for the Beaver-North Canadian River Alluvial Aquifer, Northwestern Oklahoma

By Derek W. Ryter and Jessica S. Correll

Abstract

This report describes a study of the hydrology, hydrogeological framework, numerical groundwater-flow models, and results of simulations of the effects of water use and drought for the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma. The purpose of the study was to provide analyses, including estimating equal-proportionate-share (EPS) groundwater-pumping rates and the effects of projected water use and droughts, pertinent to water management of the Beaver-North Canadian River alluvial aquifer for the Oklahoma Water Resources Board.

The Beaver-North Canadian River alluvial aquifer consists of unconsolidated sand, gravel, silt, and clay in varying proportions that underlies the Beaver and North Canadian River Valleys for approximately 175 miles (mi) from the Oklahoma Panhandle to the western edge of Oklahoma City in central Oklahoma. The aquifer as delineated for this study varies from 4 to 12 mi wide and is as thick as 308 feet (ft) in the northwest where the aquifer includes the Ogallala Formation.

There are two distinct but in most areas hydraulically connected alluvial units that compose the Beaver-North Canadian River alluvial aquifer: a Quaternary-age topographically higher terrace deposit and a topographically lower, younger alluvium along the active river channel that includes active and Quaternary-age alluvium. The Beaver River composes the headwaters of the North Canadian River, which begins at the confluence of the Beaver River and Wolf Creek. The aquifer is divided for water management into two geographic areas: Reach I upstream from Canton Dam and Reach II downstream from Canton Dam. Reach I covers an area of approximately 874 square miles (mi^2), and Reach II covers an area of approximately 371 mi^2. The Beaver-North Canadian River alluvial aquifer crosses several climatic zones, from semiarid in the west to continental subhumid in the east. Mean annual precipitation varies from 23.5 inches (in.) in the western part of this aquifer to 35.7 in. in the east.

Surface-water demands were met through numerous temporary and permanent surface-water diversions from the Beaver and North Canadian Rivers during the period of study. During the study period, seven diversions removed a mean annual 2,000 acre-feet (acre-ft) of water from Reach I. There were 14 diversions from Reach II with a mean annual permitted volume of approximately 81,000 acre-ft, including diversion into the Lake Hefner Canal for the Oklahoma City public water supply. During the period of this study, 17 temporary surface-water diversion permits were active in Reach I, with total permitted volumes of 2,000 acre-ft, and 41 diversions were active in Reach II, with total permitted volumes of 38,000 acre-ft. The total water use for each temporary permit was assumed to be taken over the 3-month period allotted to temporary withdrawal permits.

The groundwater-use analysis full period of record, 1967–2011, was divided into two sub-intervals because of varying water use, 1970–80 and 1981–2011. Groundwater use in Reach I and Reach II was substantially greater from 1970 to 1980 compared to the rest of the period, and the sub-period 1981–2011 was used because this period includes recent population growth and modern irrigation methods. The total mean annual groundwater use in Reach I was 15,309 acre-feet per year (acre-ft/yr) during 1967–2011; 20,724 acre-ft/yr during 1970–80, and 13,739 acre-ft/yr during 1981–2011. Total mean annual groundwater use in Reach II was similar but slightly less than in Reach I, with 14,098 acre-ft/yr during 1967–2011; 19,963 acre-ft/yr during 1970–80; and 12,285 acre-ft/yr during 1981–2011.

Irrigation composed 72 percent of groundwater use in Reach I and 48 percent of groundwater use in Reach II during the 1967–2011 period. Public water supply was a much smaller proportion of total groundwater use in Reach I (15 percent) than in Reach II (39 percent). The proportion of groundwater use for power was 10 percent in Reach I and 5.2 percent in Reach II. All other water-use categories in Reach I only composed 2.2 percent of groundwater use in Reach I. In Reach II, industrial, mining, and commercial categories combined accounted for 4.4 percent of groundwater

use; recreation, fish, and wildlife groundwater use accounted for 2.3 percent; and nonirrigated agriculture accounted for 1.5 percent of groundwater use.

Permian-age bedrock underlies the Beaver-North Canadian River alluvial aquifer. In the east, the Dog Creek Shale, the Duncan Sandstone, and the Blaine and Chickasha Formations, none of which are notable sources of groundwater in the study area, underlie the Beaver-North Canadian River alluvial aquifer. In the northwestern part of Reach I, bedrock is composed of the Rush Springs and Marlow Formations, which are productive aquifers in some areas. The Cloud Chief Formation is not a source of groundwater.

One hydrogeological unit was delineated in the Beaver-North Canadian River alluvial aquifer, composed of the terrace deposits and alluvium, with limited flow between this unit and bedrock units. Groundwater in this aquifer generally flows from northwest to southeast and across the aquifer toward the Beaver and North Canadian Rivers.

Groundwater recharge from precipitation was estimated for the entire Beaver-North Canadian River alluvial aquifer and then itemized for both reaches by using a soil-water-balance (SWB) model. At two locations in Reach I, a water-table fluctuation method was used to estimate local recharge. Total mean annual groundwater recharge from the soil-water-balance method was estimated to be approximately 136,400 acre-ft in Reach I and 82,400 acre-ft in Reach II; the mean annual recharge for both reaches combined was approximately 218,800 acre-ft. Two sites in Reach I located at observation wells with continuous water-level measurements and nearby streamflow-gaging stations with precipitation gages were used to estimate the percentage of precipitation that becomes groundwater recharge. The Woodward site was located at observation well OW-4 near the Woodward, Okla. (07237500), streamflow-gaging station. Total precipitation and recharge for the Woodward and Seiling sites were calculated for the water year 2013. The Woodward site had a total of 14.18 in. of precipitation and 6.3 in. of recharge was calculated, equaling 44 percent of precipitation. The mean percentage of precipitation that was estimated to become recharge in the SWB model for the period 1980–2011 at that location was 9.2 percent, although adjacent SWB-model cells were as high as 20 percent of precipitation. The Seiling site had a total of 26.84 in. of precipitation during the water year 2013, and a total of 6.9 in. of recharge was estimated, equaling 25.9 percent of precipitation. At the Seiling site, the mean percentage of precipitation that became recharge in the SWB model for the period 1980–2011 was 23.0 percent.

The principal inflow to the Beaver-North Canadian River alluvial aquifer was estimated to be surface recharge from precipitation, and plant evapotranspiration was estimated to be the greatest discharge, followed by stream and lake base flow, groundwater pumping, and flow to seeps and springs along the eastern margin of the aquifer. Reach I also included inflow from the High Plains aquifer as lateral inflow of groundwater, though this flow was estimated to be a very minor component of the total water budget. Most of the Beaver and North Canadian Rivers were determined to be gaining streamflow from groundwater, but several reaches in Reach I upstream from Wolf Creek were determined to be losing streamflow through infiltration to the aquifer.

Aquifer hydrogeologic characteristics were estimated from borehole lithologic logs, well-construction information, and published aquifer tests and during numerical model calibration. The maximum saturated aquifer thickness in Reach I was estimated to be 308 ft, and the mean thickness was estimated to be 36 ft. The maximum saturated thickness in Reach II was estimated to be 86 ft, and the mean thickness was estimated to be 29 ft. Mean hydraulic conductivity of Reach I was estimated to be 70 feet per day (ft/d) with a range of 7–279 ft/d. Mean hydraulic conductivity in Reach II was estimated to be 92 ft/d with a range of 4–279 ft/d.

Both reach models were calibrated manually by using trial-and-error adjustment of recharge, hydraulic conductivity, specific yield, and conductance of boundary conditions. The Reach I model used 28 head observations during the steady-state period of 1980 and 487 head observations during the transient period of 1981–2011. The root-mean-square error of head residuals (observed minus simulated head) was 3.86 ft, and 83 percent of head residuals were between -5 and 5 ft. The Reach II model was calibrated to 75 steady-state head observations and 134 head observations during the transient period. The root-mean-square error of head residuals for that reach was 3.58 ft, and similar to Reach I, 85 percent of residuals were between -5 and 5 ft.

Several analyses were performed by using the numeric groundwater-flow models as predictive tools, including estimating the EPS pumping rate for both reaches. The EPS is defined by the Oklahoma Water Resources Board as an annual per-acre groundwater-pumping rate that will reduce saturated thickness in half of the aquifer to 5 ft or less over a period of 20 years; additional estimates were made for periods of 40 and 50 years. Other analyses included using models to estimate the effects of groundwater pumping and a prolonged drought on groundwater in storage and streamflow and lake storage of water.

The EPS pumping rate was found to be approximately 0.57 acre-feet per acre per year ([acre-ft/acre]/yr) in Reach I and 0.73 (acre-ft/acre)/yr in Reach II for a 20-year period. For a 40-year period, the annual EPS pumping rate was determined to be 0.54 (acre-ft/acre)/yr in Reach I and 0.61 (acre-ft/acre)/yr in Reach II. For a 50-year period, the EPS pumping rate was determined to be 0.53 (acre-ft/acre)/yr in Reach I and 0.61 (acre-ft/acre)/yr in Reach II.

Groundwater pumping at the 2011 rate for 50 years resulted in a 3.6-percent decrease in the amount of water in groundwater storage in Reach I and a decrease of 2.5 percent in the amount of groundwater in storage in Reach II. A cumulative 32-percent increase in pumping greater than the 2011 rate over a period of 50 years caused a decrease in groundwater storage of 4.0 percent in Reach I and 3.3 percent in Reach II.

A hypothetical severe drought was simulated by using aquifer recharge flow rates during the drought year of 2011 for a period of 10 years. All other flows including evapotranspiration and groundwater pumping were set at estimated 2011 rates. The hypothetical drought caused a decrease in water in aquifer storage by about 7 percent in Reach I and 7 percent in Reach II. Another analysis of the effects of hypothetical drought estimated the effects of drought on streamflow and lake storage. The hypothetical drought was simulated by decreasing recharge by 75 percent for a selected 10-year period (1994–2004) during the 1980–2011 simulation. In Reach I, the amounts of water stored in Canton Lake and streamflow at the Seiling, Okla., streamflow-gaging station were analyzed. Streamflow at the Seiling station decreased by a mean of 75 percent and was still diminished by 10 percent after 2011. In Reach II, the effect of drought on the streamflow at the Yukon, Okla., streamflow-gaging station was examined. The greatest mean streamflow decrease was approximately 60 percent during the simulated drought, and after 2011, the mean decrease in streamflow was still about 5 percent. Canton Lake storage decreased by as much as 83 percent during the simulated drought and did not recover by 2011.

Introduction

The Beaver-North Canadian River alluvial aquifer is a long, narrow surficial aquifer that underlies the Beaver and North Canadian River Valley in western and northwestern Oklahoma (fig. 1). The Beaver-North Canadian River alluvial aquifer is one of several alluvial aquifers along rivers that cross western Oklahoma, including the adjacent Cimarron and Canadian Rivers, and is a source of water for Oklahoma City, local municipalities, domestic supplies, wildlife, agriculture, and oilfield uses. The Beaver River enters the Oklahoma Panhandle from New Mexico and composes the headwaters of the North Canadian River at the confluence of Beaver River with Wolf Creek (fig. 1).

Because of increasing water demands, depletion of water in the High Plains aquifer to the west, and recurring droughts, effective water resources management of the Beaver-North Canadian River alluvial aquifer is essential. Effective management required an updated comprehensive study of the hydrogeologic system of this aquifer. Streamflows in the Beaver and North Canadian Rivers have decreased since 1971, at least in part because of groundwater depletion and reduced stream base flow from the area underlain by the High Plains aquifer (Wahl and Tortorelli, 1997). These trends could reduce available surface water for Oklahoma City during dry periods. The 2012 Oklahoma Comprehensive Water Plan (OCWP) (Oklahoma Water Resources Board, 2012) identified watershed basin 51, which includes the downstream half of the Beaver-North Canadian River alluvial aquifer, as a “hot spot” for water-supply shortages. The total water demand in central Oklahoma is projected to increase by approximately 32 percent from 2010 to 2060, during which surface-water and groundwater shortfalls are forecast (Oklahoma Water Resources Board, 2012). A priority recommendation of the OCWP was to complete updates of hydrologic investigations and to analyze groundwater and surface-water interactions in selected aquifers in Oklahoma, including the Beaver-North Canadian River alluvial aquifer. The study described in this report is a cooperative effort between the U.S. Geological Survey (USGS) and the Oklahoma Water Resources Board (OWRB) to provide an updated analysis of the hydrology, hydrogeology, and groundwater-flow system, and new numerical groundwater-flow models with predictive simulations of selected future scenarios for the Beaver-North Canadian River alluvial aquifer.

Purpose and Scope

The purpose of this report is to describe the hydrology, hydrogeological framework, and groundwater flow, including flow between groundwater and surface water, in the Beaver-North Canadian River alluvial aquifer in northwestern Oklahoma. This report describes the methods, construction, calibration, and results of numerical groundwater-flow models used to simulate groundwater flow, forward simulations used to calculate equal-proportionate-share (EPS) groundwater-pumping rates, and the effects of various 50-year future scenarios including increased groundwater pumping and severe droughts on the groundwater system.

Location and Description of Study Area

The study area is defined as the extent of the Beaver-North Canadian River alluvial aquifer as delineated by the OWRB (Oklahoma Water Resources Board, 2012). The width of the Beaver-North Canadian River alluvial aquifer varies from 4 to 12 miles (mi). This aquifer underlies approximately 1,245 square miles (mi^2) of land along approximately 175 mi of the Beaver and North Canadian Rivers from the Oklahoma Panhandle to the western edge of Oklahoma City (fig. 1). The aquifer is divided into two water-management subareas referred to as “Reach I” and “Reach II” by the OWRB (Oklahoma Water Resources Board, 2012). Reach I includes the Beaver-North Canadian River alluvial aquifer from the northwestern end, where it is defined by the OWRB as beginning at the western boundary of Harper County, to Canton Dam. The area of Reach I is approximately 874 mi^2, and the area of Reach II is approximately 371 mi^2. Reach II extends from Canton Dam to the western edge of Oklahoma City where the aquifer narrows and available groundwater is limited. Reach I and Reach II are hydraulically connected; the location of the division between the two areas is for water management and is not at the location of a groundwater boundary.

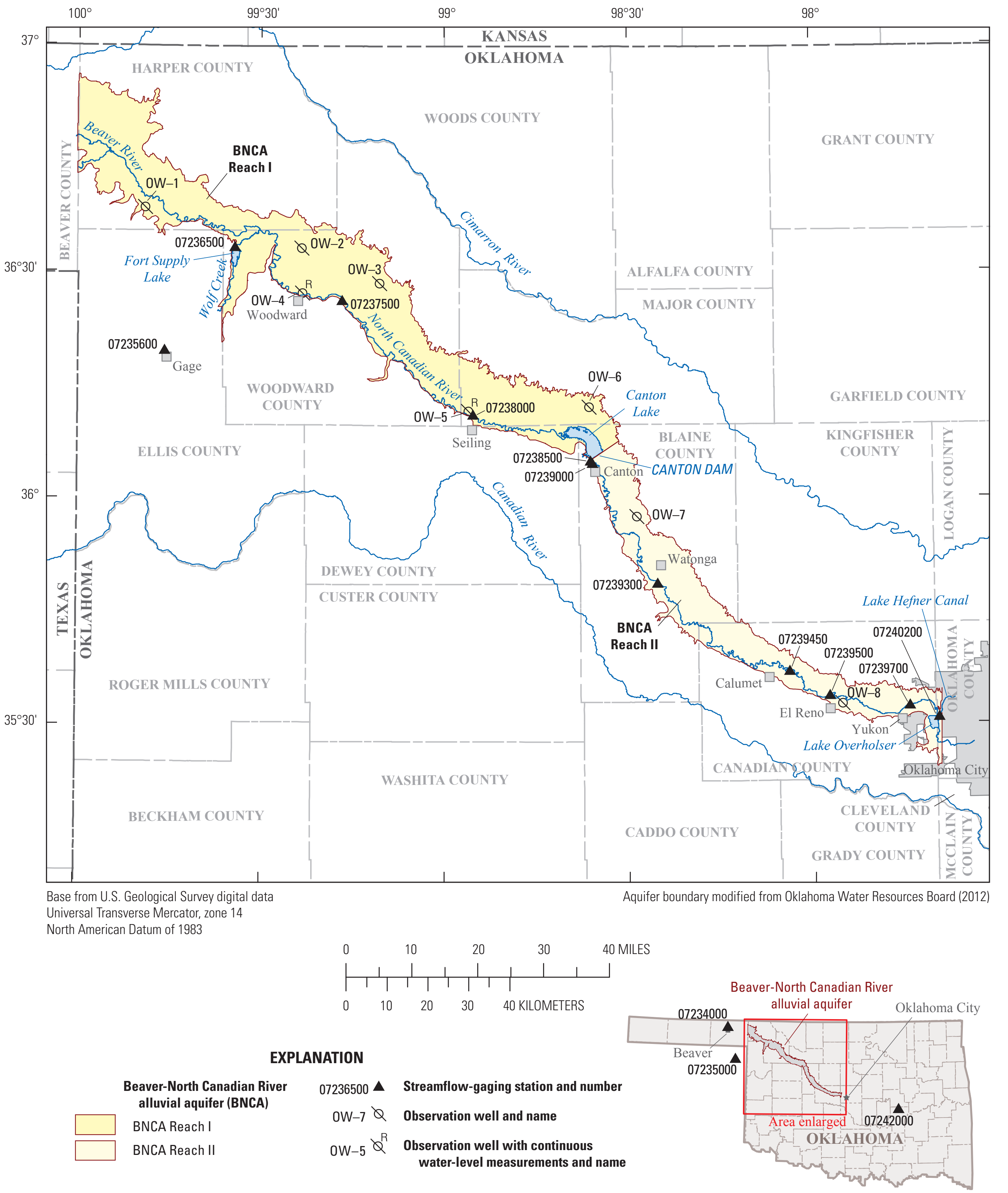


Figure 1. Locations of the Beaver-North Canadian River alluvial aquifer, reaches, hydrological features, observation wells, streamflow-gaging stations, and cities, northwestern Oklahoma.

Previous Investigations

A hydrogeologic investigation of Reach I is reported in Christenson (1983), and a hydrogeologic investigation of Reach II is reported in Davis and Christenson (1981). Both of those reports included compilations of hydrologic data, descriptions of the hydrogeology and hydrological system, and generalized numerical groundwater-flow models using methods of Trescott (1975) with 1-mi square cells. Both reports included a transient simulation (1975–80) that was used by the OWRB to manage groundwater resources in the respective reaches. The study described in this report is an update of both Davis and Christenson (1981) and Christenson (1983) and uses streamflow measurements from both reports. Model parameters and the hydrogeologic framework from those two reports were not used because the models presented in this report are more detailed and incorporate additional data not available when those two reports were published.

Wahl and Tortorelli (1997) describe a substantial decrease in streamflow after 1971 in the North Canadian River at Woodward, Okla. (07237500), and North Canadian River near Seiling, Okla. (07238000), streamflow-gaging stations. These two stations are referred to in the remainder of this report as the “Woodward streamflow-gaging station” and “Seiling streamflow-gaging station,” respectively (fig. 1). The streamflow decrease was preceded by substantial declines in groundwater levels in the High Plains aquifer upstream from Reach I, with no corresponding decrease in precipitation. The Seiling streamflow-gaging station measures streamflow that includes inflow from the Wolf Creek tributary. The primary reason for the reduced streamflow at these stations was interpreted to be decreased base flow to the Beaver River related to depletion of groundwater in the High Plains aquifer. Base flow in the Beaver River where the river flows over the Beaver-North Canadian River alluvial aquifer was not determined to have a significant trend.

Zume and Tarhule (2008) describe a study that included a multilayer numerical groundwater-flow model of Reach I of the Beaver-North Canadian River alluvial aquifer that examined streamflow depletion from groundwater pumping; however, because model layer details and the values of hydraulic parameters were not reported, parameter values from Zume and Tarhule (2008) were not directly used in the models constructed for the study described in this report.

Mogg and others (1960) is a comprehensive analysis of the Beaver-North Canadian River alluvial aquifer hydrogeology near the southeastern end of Reach II in Canadian County, including hydraulic properties from aquifer tests and textural properties of the aquifer, recharge, and groundwater consumption through evapotranspiration (ET). Information from Mogg and others (1960) was used in the study described in this report. Bingham and Moore (1975) is part of the Oklahoma Geological Survey Hydrologic Atlas that described groundwater resources of the Oklahoma City quadrangle and provided a schematic description of hydrology and aquifer characteristics for this study.

An analysis of streamflow depletion caused by well pumping near the city of El Reno (fig. 1) and results of an aquifer test to estimate aquifer hydraulic properties were reported in Fox and Kizer (2009). Hydraulic properties from Fox and Kizer (2009) were included in the model described in this report.

Heran and others (2003) is a geologic map that covers the entire study area. The geology and hydrology, including information about the underlying bedrock and measurements of the hydraulic properties of the Beaver-North Canadian River alluvial aquifer at two different locations in Woodward County are described in Wood and Stacy (1965). An Oklahoma Geological Survey atlas of the geology and hydrology of the Woodward quadrangle (Morton, 1980) provides background hydrogeologic information. Information from Wood and Stacy (1965) and Morton (1980) was included in the study described in this report.

Land Use and Population

Land use for the study area during 1992, 2001, and 2006 was described by using tabulated and spatially distributed estimated land cover from the National Land Cover Database (NLCD) (Multi-Resolution Land Characteristics Consortium, 2013). Most of the area overlying the Beaver-North Canadian River alluvial aquifer was categorized in these 3 years as rural grazing and cultivated agriculture. Categories of land use in the study area include planted/cultivated cropland, livestock, grassland/herbaceous plants, forest, shrubland, wetland, barren, and developed in small rural communities.

Grassland/herbaceous plants composed 74 percent of the 1992 NLCD classification (Vogelmann and others, 2001) in Reach I—52 percent upland grasses and forbs typically used for grazing and 22 percent planted/cultivated crops. Cultivated crops were almost entirely winter wheat and alfalfa. Other land-use classes included 15 percent shrubland, 7 percent forest, 2 percent open water, 1 percent wetlands, and less than 1 percent developed and barren. In 2001 (Homer and others, 2007) and 2006 (Fry and others, 2011), the only substantial change in land-use acreage from 1992 was an increase in developed land of approximately 5 percent. Area classified as shrubland decreased to 1 percent in 2001 and increased to 2 percent in 2006 (Homer and others, 2007; Fry and others, 2011).

Land use in Reach II was 64 percent cultivated crops in 1992, with 20 percent being grassland/herbaceous, 8 percent being forest, 3 percent being shrubland, and 1 percent being developed. In 2001, the proportion of the area classified as cultivated crops in Reach II decreased to 54 percent, grassland/herbaceous increased to 30 percent, developed land increased to 6 percent, and shrubland was virtually nonexistent (Homer and others, 2007). There were no appreciable changes in Reach II land use from 2001 to 2006 (Fry and others, 2011).

Review of the U.S. Census data for counties in the study area indicated that from 1980 to 2010 population remained relatively constant in the western counties of Harper and

Woodward (U.S. Census, 2013). Population of Blaine and Major Counties in the central part of the study area decreased slightly, and the population of Canadian County in the east almost doubled, most likely because of the proximity of that county to Oklahoma City.

Water Use and Management

Surface-water use for the Beaver and North Canadian Rivers and groundwater use for the Beaver-North Canadian River alluvial aquifer are managed by the OWRB on the basis of the 1978 water law and the OCWP (Oklahoma Water Resources Board, 2012). Surface-water use is a minor part of the Beaver and North Canadian Rivers water system budget (Oklahoma Water Resources Board, 2013). Surface-water features in the Beaver-North Canadian River alluvial aquifer hydrologic system include the Beaver and North Canadian Rivers, Fort Supply Lake, Canton Lake, and Lake Overholser (fig. 1). Reservoirs are primarily used to store streamflow that is later released and used downstream. The most substantial surface-water diversion is into the Lake Hefner Canal near the downstream end of Reach II (fig. 2). Because of the relatively small volumes of water diverted from ponds and intermittent streams, the study described in this report only considered diversions from the Beaver and North Canadian Rivers.

Long-term surface-water withdrawal permits have been issued by the OWRB, and the permitted volume was used in this report to estimate annual water use from the Beaver and North Canadian Rivers. During the study period, seven diversions (fig. 2) were issued to remove water from Reach I, with an annual mean of 2,000 acre-feet (acre-ft) being diverted (Oklahoma Water Resources Board, 2014). There were 14 diversions from Reach II during this period, with a mean annual permitted volume of approximately 81,000 acre-ft, which included a diversion into Lake Hefner Canal for the Oklahoma City public water supply.

Temporary, 3-month water-use permits have been issued by the OWRB for surface-water diversions, shown on figure 2 as temporary surface-water diversions. Temporary permits allow a specified volume to be diverted over a 3-month period (Oklahoma Water Resources Board, 2014). During the period of this study, 17 temporary surface-water diversions from the Beaver and North Canadian Rivers were active in Reach I, with a total permitted volume of 2,000 acre-ft, and 41 diversions were active in Reach II, with a total volume of 38,000 acre-ft.

As with surface water, selected groundwater users in Oklahoma are required to obtain a permit from the OWRB and have been required to report various aspects of their annual water use. A water-use permit allows a maximum annual water volume to be pumped from one or more wells. The actual volume of water pumped for a permit is estimated by the OWRB on the basis of other information provided by water users depending on the category of water use. The period of water use data analyzed for the study described in this report includes 1967–2011 with the exception of 1992, which did not have sufficient data.

Annual reporting of groundwater use has not been required for self-supplied domestic water wells, agricultural use that is less than 5 acre-feet per acre per year ([acre-ft/acre]/yr), or water pumped for irrigation and applied to less than 3 acres (Oklahoma Water Resources Board, 2014). For the OWRB to estimate irrigation usage for larger farms several parameters were required to be estimated by water users and reported. Before 1980, irrigators were required to report the crop type, the frequency of irrigation, and the number of irrigated acres (Oklahoma Water Resources Board, 2014). For 1980 and later, irrigators were required to include the number of applications and the inches of water per application or the number of applications (Oklahoma Water Resources Board, 2014), which reduced uncertainty by allowing irrigation volumes to be calculated directly. If only the number of applications were reported by an irrigator, the inches of application were estimated by using a sliding scale, where the first six applications were assumed to be 4 inches (in.) of water each. For applications 7–10, the amount of water was decreased to 3 in. each; applications 11–15 were assumed to be 2 in. each, and applications 16 and greater were each assumed to be 1 in. of water applied. The sum of all applications was then converted to feet and multiplied by the number of irrigated acres to determine acre-feet. Public water-supply use has been reported as the total annual volume pumped.

Other categories used by the OWRB to track water use include power, nonirrigated agriculture, recreation, mining, industrial, and commercial. Groundwater-use data were verified for 673 permits, and total annual groundwater use by category was determined for 1967–2011 for both reaches. Both reaches had a substantially higher water use from about 1970 to 1980 (fig. 3) than the rest of the period. Thus, water use in the periods 1970–80 and 1981–2011, which were selected because the first period represents a time of high water use and the second period includes recent population growth and modern irrigation methods, were selected for detailed analysis.

The mean annual total groundwater use in Reach I was 15,309 acre-feet per year (acre-ft/yr) during 1967–2011; 20,724 acre-ft/yr (range 11,867 to 27,799 acre-ft/yr) during 1970–80, and 13,739 acre-ft/yr (range 9,874 to 18,156 acre-ft/yr) during 1981–2011 (table 1). Mean annual water use in Reach II was slightly less than in Reach I. Mean annual use in Reach II was 14,098 acre-ft/yr during 1967–2011; 19,963 acre-ft/yr (range 12,520 to 28,046 acre-ft/yr) during 1970–80; and 12,285 acre-ft/yr (range 7,869 to 17,548 acre-ft/yr) during 1981–2011 (table 1).

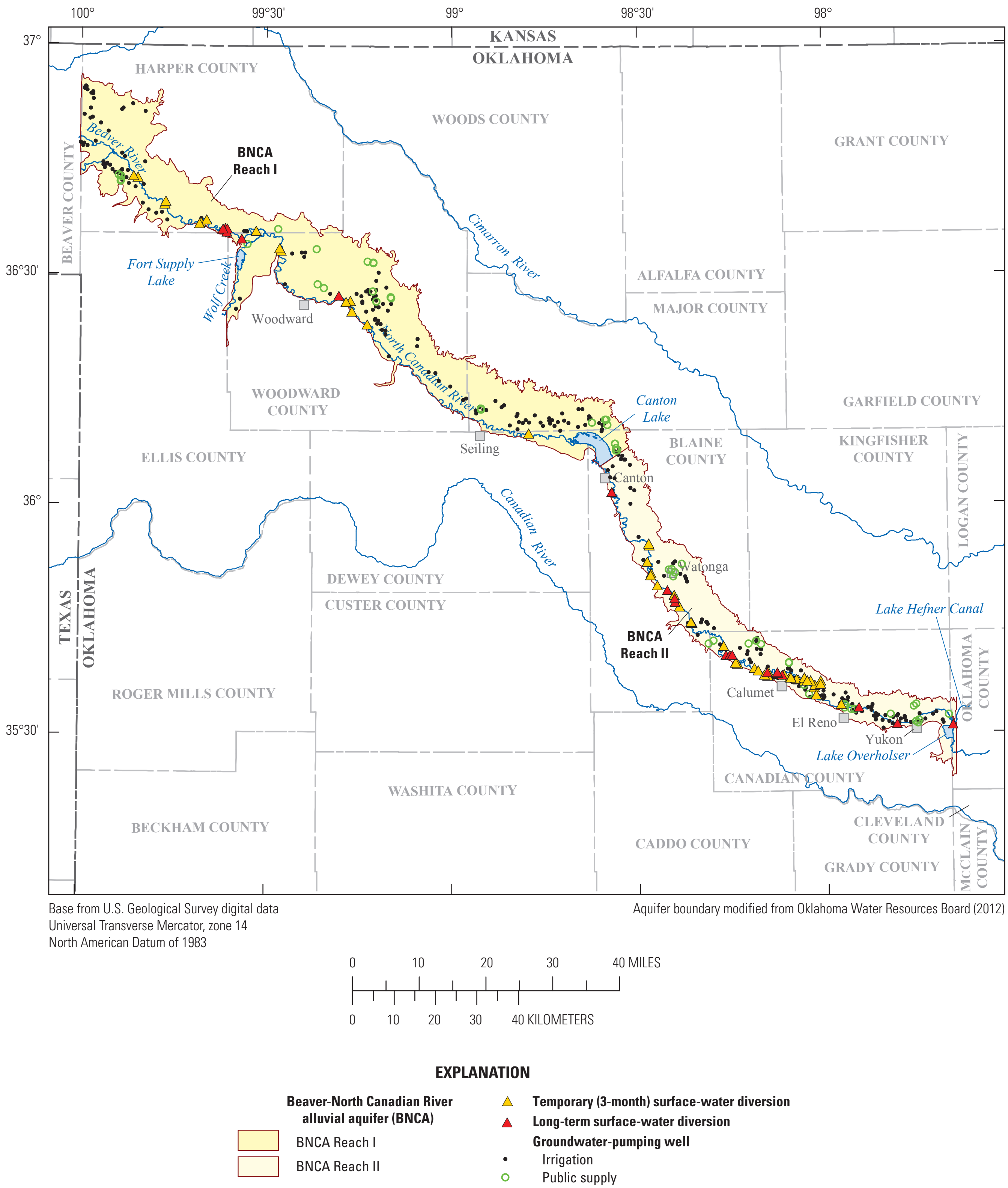


Figure 2. Irrigation and public water-supply wells and surface-water diversions active during 1980–2011 in areas overlying the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

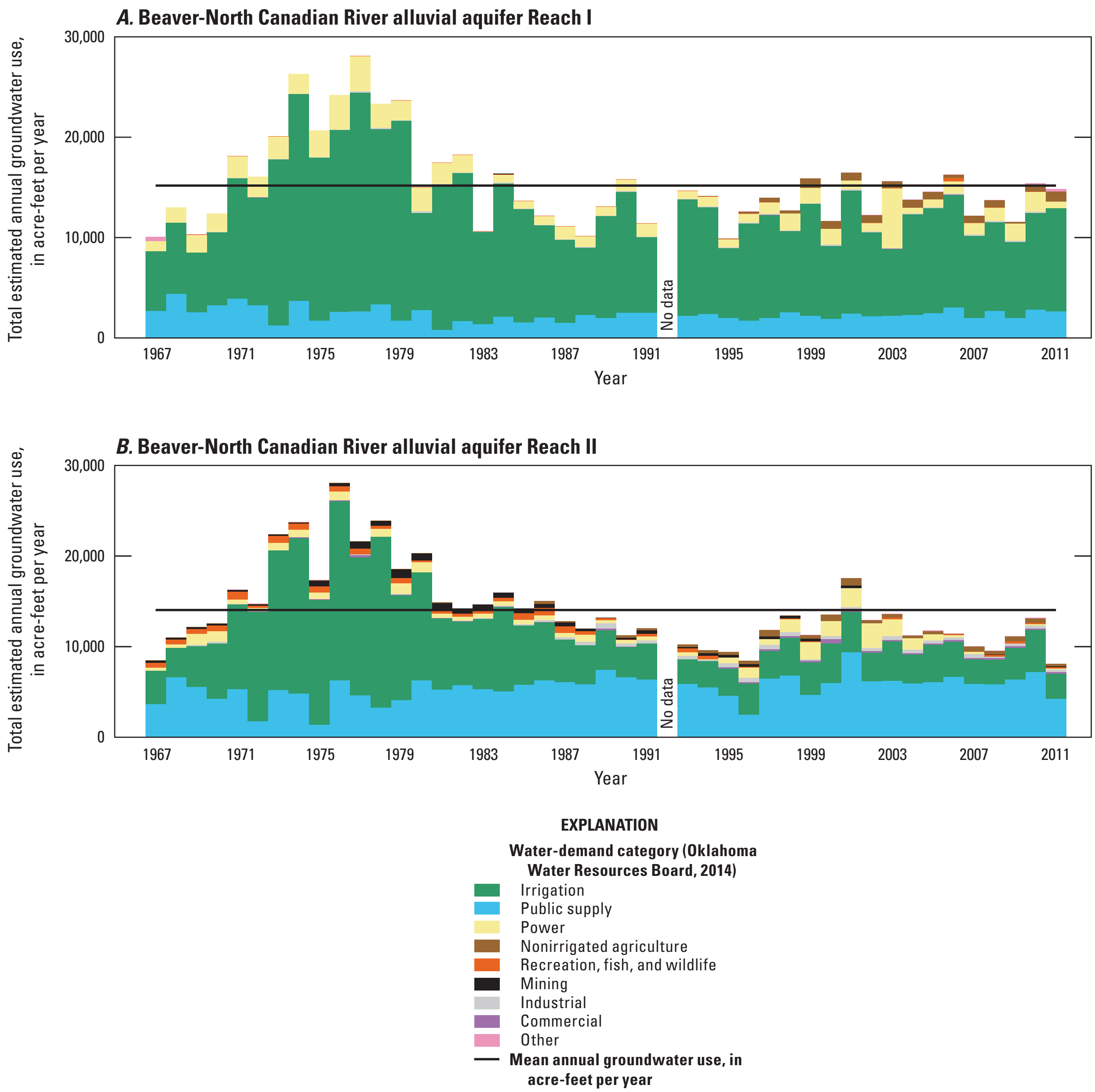


Figure 3. Total estimated annual groundwater use 1967–2011 by water demand category for *A*. Reach I and *B*. Reach II of the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

Table 1. Summary statistics of groundwater use for selected periods for the Beaver-North Canadian River alluvial aquifer.

[All units in acre-feet per year. The year 1992 was excluded from this analysis; data from Oklahoma Water Resources Board (2014)]

Period	1970–80		1981–2011		1967–2011	
	Reach I	Reach II	Reach I	Reach II	Reach I	Reach II
Mean	20,724	19,963	13,739	12,285	15,309	14,098
Minimum	11,867	12,520	9,874	7,869	9,874	7,869
Maximum	27,799	28,046	18,156	17,548	27,799	28,046

The largest mean annual groundwater use during 1967–2011 for both reaches was for irrigation, followed by public water supply (fig. 4; table 2), and in both reaches, the difference in groundwater use between the 1970–80 and 1981–2011 periods was greater for irrigation. The mean annual total groundwater use was similar in both reaches for all periods, though in Reach II, irrigation was less than in Reach I and decreased more during 1981–2011. Industrial groundwater use also increased substantially in Reach II after 1980 (Oklahoma Water Resources Board, 2013).

Irrigation composed 72 percent of groundwater use in Reach I (fig. 4*A*) and 48 percent of groundwater use in Reach II (fig. 4*B*) during 1967–2011. Public water supply was a much smaller proportion of total groundwater use in Reach I (15 percent) than in Reach II (39 percent). Groundwater use for power was 10 percent in Reach I (fig. 4*A*) and 5.2 percent in Reach II (fig. 4*B*). All other water-use categories only composed 2.2 percent of groundwater use in Reach I (fig. 4*A*). In Reach II, industrial, mining, and commercial categories composed 4.4 percent of groundwater use; recreation, fish, and wildlife was 2.3 percent; and nonirrigated agriculture and other was 1.5 percent (fig. 4*B*).

Mean annual estimated groundwater use during 1970–80 peaked in 1977 in Reach I (fig. 3*A*) and in 1976 in Reach II (fig. 3*B*). Total mean annual groundwater use for the period 1981–2011 in both reaches was more consistent, and the minimum groundwater use for Reach I was in 1995 and Reach II was in 1996 (fig. 3). The maximum annual pumping for the period 1981–2011 in Reach I occurred in 1982 and in Reach II occurred in 2001.

Mean annual groundwater use for public water supply was very similar between the two time periods, with a larger proportion of total groundwater use in Reach II than in Reach I (fig. 4; table 2). The mean annual groundwater use for power in 1981–2011 was about half that of 1970–80 in Reach I but was nearly the same during the same two periods in Reach II (table 2). Groundwater use for power was 10 percent of total groundwater use in Reach I (fig. 4*A*) but only approximately 5 percent in Reach II (fig. 4*B*). Groundwater use for mining decreased in Reach II during 1981–2011 compared to 1970–80 (fig. 3; table 2). In Reach I, recreation, mining, industrial, and commercial water uses were much less than in Reach II in all time periods (table 2). Groundwater use for nonirrigated agriculture was minimal before 1996 and similar in both reaches (fig. 3). There was much more recreational groundwater use in Reach II than in Reach I (table 2), and most of the recreational groundwater use occurred before 1989 in Reach II (fig. 3*B*).

Hydrology

The hydrology of the study area relates to water available for the Beaver-North Canadian River alluvial aquifer. Climate and streamflow characteristics are described in this section.

Climate

The climate of the Beaver-North Canadian River alluvial aquifer trends from warmer and drier semiarid in the northwest to wetter and slightly cooler humid-temperate in the southeast (Oklahoma Climatological Survey, 2011), which affects important components of the hydrologic system. The mean daily temperature across the Beaver-North Canadian River alluvial aquifer ranges from 58 to 60 degrees Fahrenheit (°F) and increases from the southeast to northwest (Oklahoma Climatological Survey, 2015a, b). The mean daily temperature for Harper County at the northwestern end of the study area (fig. 1) during the period 1960–2013 ranged from a high in July of 83.2 °F to a low in January of 35 °F (Oklahoma Climatological Survey, 2015a). During the same period in the southeastern end of the aquifer in Oklahoma County, mean daily temperature ranged from a high of 81.9 °F in July to a low of 36.6 °F in January (Oklahoma Climatological Survey, 2015b).

Precipitation measurements were obtained from the National Climatic Data Center for all available weather stations on and surrounding the study area for the period from 1980 to 2011 (National Climatic Data Center, 2013). Mean annual precipitation was interpolated across the study area as described in the “Groundwater Recharge” section of this report; the interpolated mean annual precipitation and most of the weather stations used in the interpolation are shown on figure 5. Interpolated mean annual precipitation for 1980–2011 trended gradationally from 23.5 in. of precipitation in the west to 35.7 in. of precipitation in the east, an increase of 52 percent (fig. 5).

Precipitation measurements from four weather stations distributed across the study area with long periods of record were used to describe general climatic conditions of the Beaver-North Canadian River alluvial aquifer. The weather stations included Gate, Woodward, Watonga, and Will Rogers World Airport (fig. 5). Years with less than 10 months of data were removed, and trace amounts of precipitation were not included. The earliest precipitation observations were recorded in 1908 at the Woodward weather station, which stopped recording observations after 2012; data collection continued at Gate, Watonga, and Will Rogers World Airport weather stations through 2013 (table 3). The station with the latest start year is Gate, at which data collection began in 1960. The period from 1960 to 2012, during which all of the stations were active, was used to describe precipitation across the study area.

The combined mean annual precipitation for all four of the weather stations during the period 1960–2012 was 27.6 in. (table 3) (Oklahoma Climatological Survey, 2014). As shown on figure 5, the mean annual precipitation increased from west to east: 21.7 in. at Gate, 24.5 in. at Woodward, 29.8 in. at Watonga, and 34.4 in. at Will Rogers World Airport (table 3).

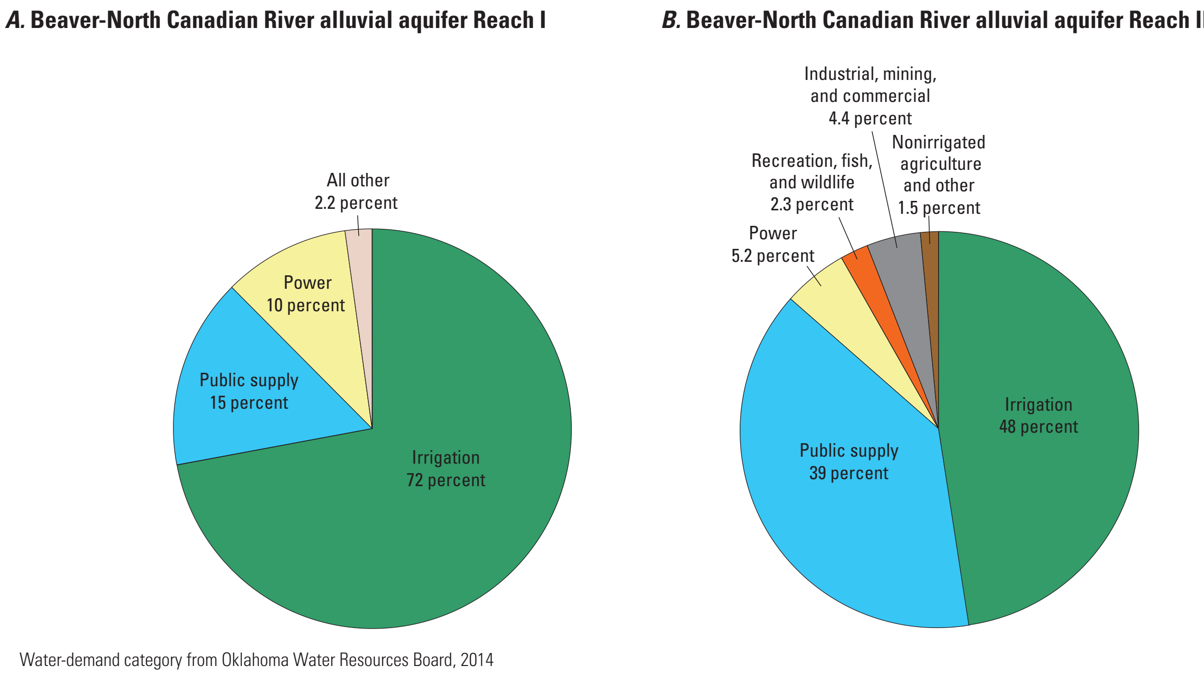


Figure 4. Distribution of mean annual groundwater use for 1967–2011 by percentage for water-use categories for *A*. Reach I and *B*. Reach II of the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

Table 2. Estimated mean annual groundwater use for selected periods by use category in acre-feet, Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

[All water use in mean acre-feet per year. The year 1992 was excluded because of missing data; IRR, irrigation; PWS, public water supply; AGR, nonirrigation agriculture; COM, commercial; NA, not available; data from Oklahoma Water Resources Board (2014)]

Period	Water-use category									
	IRR	PWS	Power	AGR	Recreation	Mining	Industrial	COM	Other	Total
					Reach I					
1970–80	15,493	2,746	2,418	NA	4	0	62	1	0	20,724
1981–2011	9,866	2,144	1,282	328	19	10	76	1	13	13,739
1967–2011	11,033	2,368	1,574	223	17	7	67	1	19	15,309
					Reach II					
1970–80	13,750	4,310	761	NA	547	453	41	61	3	19,963
1981–2011	4,415	5,952	742	283	217	254	301	112	9	12,285
1967–2011	6,708	5,496	738	214	320	303	219	92	8	14,098
Mean	**8,871**	**3,932**	**1,156**	**219**	**169**	**155**	**143**	**47**	**14**	**14,704**

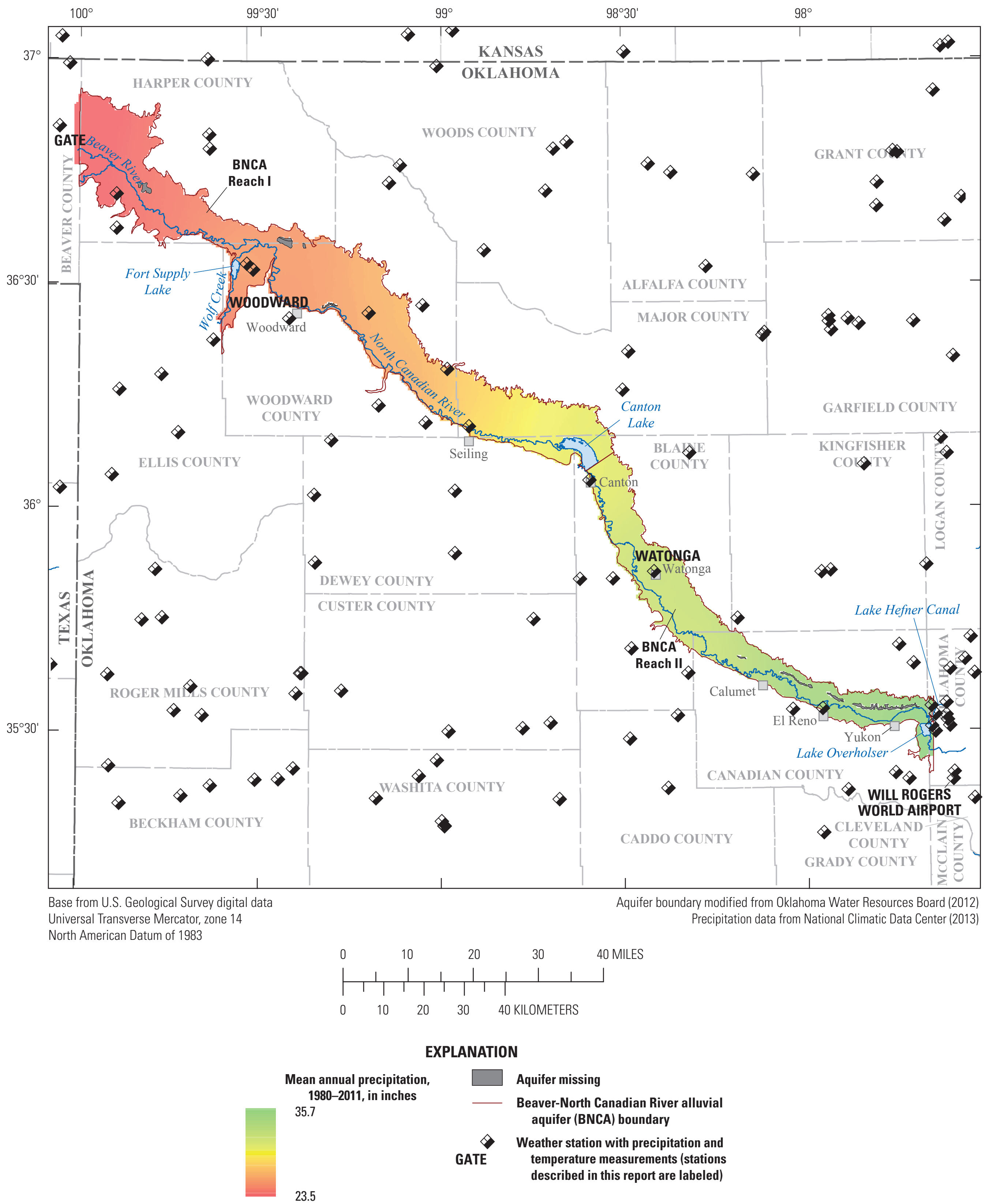


Figure 5. Interpolated mean annual precipitation and cooperative observer weather stations for the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma, from daily weather-station data over the period 1980–2011.

Table 3. Statistical summary of precipitation at selected weather stations for the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

[Data from National Climate Data Center (2013)]

Station name	Period of record	Number of years	Period of record mean annual precipitation (inches)	1960–2012 mean annual precipitation (inches)
Gate	1960–2013	54	21.7	21.7
Woodward	1908–2012	105	23.3	24.5
Watonga	1928–2013	86	27.6	29.8
Will Rogers World Airport	1948–2013	66	33.8	34.4
Mean of all stations			**26.6**	**27.6**

To describe seasonal precipitation and long-term wet and dry periods for the two reaches of the Beaver-North Canadian River alluvial aquifer, data from two weather stations centrally located in both reaches were used: the Woodward weather station in Reach I and the Watonga weather station in Reach II (fig. 5). Mean monthly precipitation for the period 1960–2012 showed similar seasonality at both stations and was consistently greater at the Watonga station (fig. 6). Mean monthly precipitation was greatest during May (3.8 in. at Woodward and 4.5 in. at Watonga), and the driest month at both stations was January (0.75 in. at Woodward and 1.0 in. at Watonga). Precipitation decreased from May to July, followed by typically wet falls, which were then followed by decreases in precipitation through January. At both weather stations mean monthly precipitation increased gradually from February to April, then increased substantially in May.

Long-term precipitation records from the Woodward and Watonga weather stations were used to delineate wet and dry periods by calculating the deviation of the 5-year weighted moving average of the total annual precipitation from the mean annual precipitation for the period of record. Wet and dry periods were compared to timing of regional hydrologic droughts that have affected the Beaver-North Canadian River alluvial aquifer during the period of record at each station. Dry periods were compared to periods of hydrological drought that have affected the region.

Since 1900, there have been five major hydrologic drought periods in the study area region: 1909–18, 1929–41 (the Dust Bowl), 1952–56, 1961–72, and 1976–81 (Oklahoma Climatological Survey, 2011). Precipitation at the Woodward weather station was below normal during the 1909–18 hydrologic drought (fig. 7). The Dust Bowl drought of the 1930s was of shorter duration in the study area than the regional drought, and decreases in precipitation during the 1952–56 and 1961–72 droughts were very pronounced at Woodward. The 1976–81 drought did not appear to affect the Woodward weather station, and there is a dry period during 1988–95 and a generally decreasing and below-normal period from 2002 to 2011 that do not correspond to a regional hydrologic drought.

There were extended below-normal precipitation periods at the Watonga weather station that coincided with the last four regional hydrologic droughts, and the droughts of the 1950s and 1960s were of longer duration at Watonga than the major regional droughts (fig. 8). Unlike at the Woodward weather station, above-normal precipitation periods were measured at the Watonga weather station from 1981 to 2001 and from 2005 to 2008; however, below-normal precipitation during 2009–11 was measured at the Watonga station.

Streamflow Characteristics

Median monthly streamflows in the Beaver River in and just upstream from the study area were highly variable from 1980 to 2011 (fig. 9). Streamflow in the North Canadian River is controlled by Canton Lake, and streamflow in Wolf Creek, which is the largest tributary to the North Canadian River in the study area, is controlled by Fort Supply Lake (fig. 1). Median monthly streamflow (U.S. Geological Survey, 2013d) in the Beaver and North Canadian Rivers at three streamflow-gaging stations on and near Reach I is shown in figure 9. Reach I stations include, in order from upstream to downstream, the streamflow-gaging station at Beaver, Okla. (07234000), which is approximately 30 mi upstream from the study area and shown on the figure 1 inset map, and the Woodward and Seiling streamflow-gaging stations (fig. 1). Periods of record at these three streamflow-gaging stations include the period from 1980 to 2011.

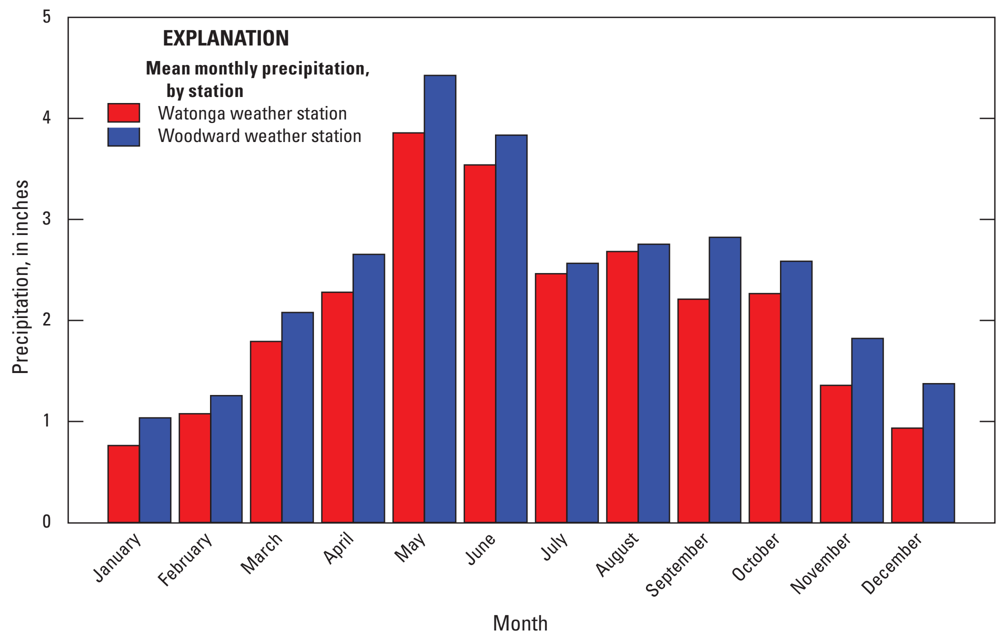


Figure 6. Mean monthly precipitation at Watonga and Woodward, Oklahoma, weather stations for the period 1960–2012.

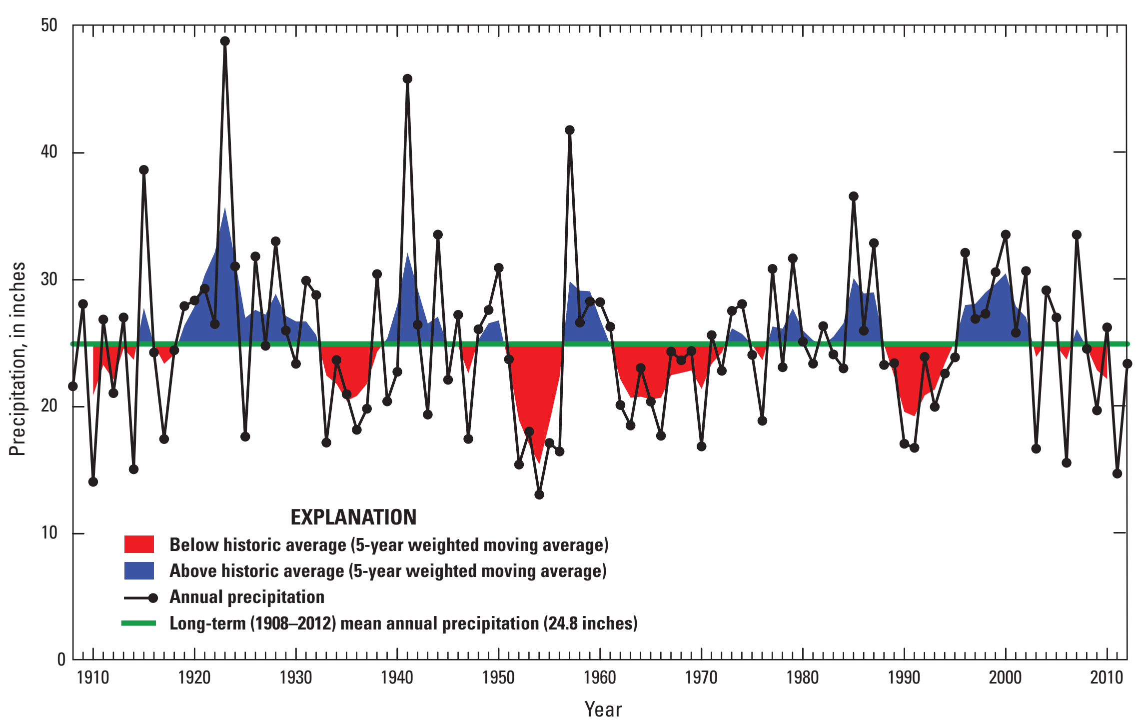


Figure 7. Annual departure from the mean annual precipitation from 1908 to 2012 and 5-year weighted moving average for the Woodward weather station, Beaver-North Canadian River alluvial aquifer Reach I, northwestern Oklahoma.

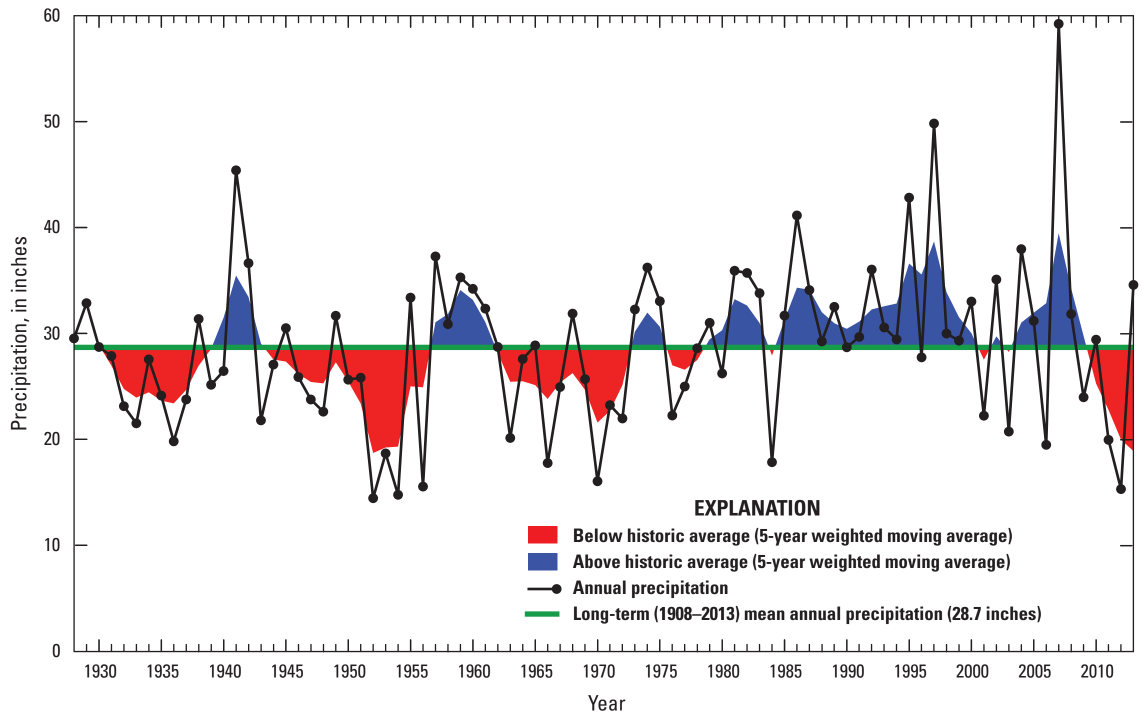


Figure 8. Annual departure from the mean annual precipitation from 1928 to 2013 and 5-year weighted moving average for the Watonga weather station, Beaver-North Canadian River alluvial aquifer Reach II, northwestern Oklahoma.

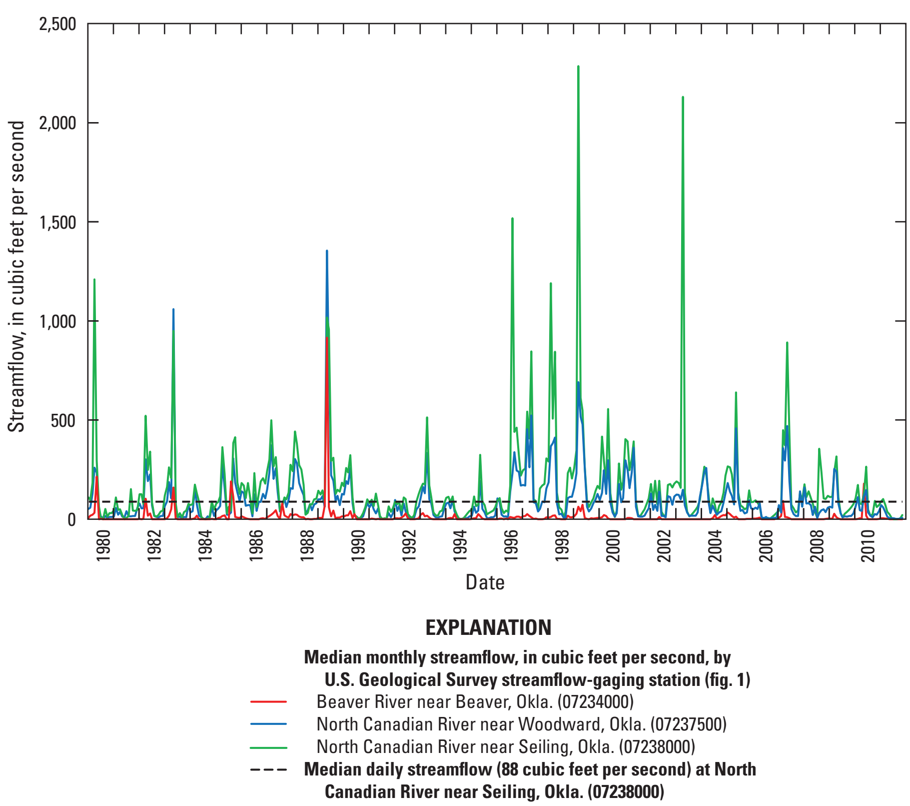


Figure 9. Median monthly streamflow for streamflow-gaging stations at Beaver River near Beaver, Oklahoma (07234000), at the North Canadian River at Woodward, Okla. (07237500), and at the North Canadian River near Seiling, Okla. (07238000), and the median monthly streamflow at the Seiling station for Reach I.

Streamflow in Reach I was highly variable with median daily streamflow at the Seiling streamflow-gaging station sometimes exceeding 2,000 cubic feet per second (ft^3/s) compared to a median of median daily streamflow of 88 ft^3/s (fig. 9). Streamflow also increased downstream, showed by the differences in streamflow among the Beaver, Woodward, and Seiling streamflow-gaging stations (fig. 9). The increase in streamflow was from a combination of base flow along the river channel and tributary inflows, including Wolf Creek via Fort Supply Lake, as described in the "Stream Base Flow" section of this report.

Median monthly streamflow for 1980–2011 is shown in figure 10 for North Canadian River streamflow-gaging stations in Reach II below Weavers Creek near Watonga, Okla. (07239300), and near El Reno, Okla. (07239500) (fig. 1). For the remainder of this report, these stations will be referred to as the "Watonga" and "El Reno" streamflow-gaging stations, respectively. Streamflow at the El Reno streamflow-gaging station typically was higher than the streamflow at the Watonga station, with the median streamflow at the El Reno streamflow-gaging station being 91 ft^3/s (fig. 10). Streamflow in Reach II increased progressively downstream similar to streamflow in Reach I, although streamflow in Reach II was controlled by Canton Lake and the median streamflow was very similar to Reach I. In both reaches, the streamflow time-series graphs in figures 9 and 10 show a relatively wet period from 1986 to 1990, a relatively dry period from 1991 to 1996, and a relatively wet period from 1996 to 2002.

Streamflow entering the Beaver-North Canadian River alluvial aquifer system in the study area from the Beaver River at Beaver, Okla., streamflow-gaging station (07234000) decreased from 1978 to 1994, primarily related to groundwater depletion in the High Plains aquifer and a resulting decrease in base flow to streams upstream from the study area (Wahl and Tortorelli, 1997). Wolf Creek drains the High Plains aquifer and contributes flow to the North Canadian River through Fort Supply Lake, but it is not known how much depletion of groundwater in the High Plains aquifer has affected Wolf Creek streamflow.

Hydrogeological Framework

The hydrogeological framework of the Beaver-North Canadian River alluvial aquifer describes the physical characteristics of the aquifer, including the geological setting, the characteristics and hydraulic properties of hydrogeological units, the potentiometric surface, and groundwater-flow directions. The hydrogeological framework was used to construct the numerical groundwater-flow models.

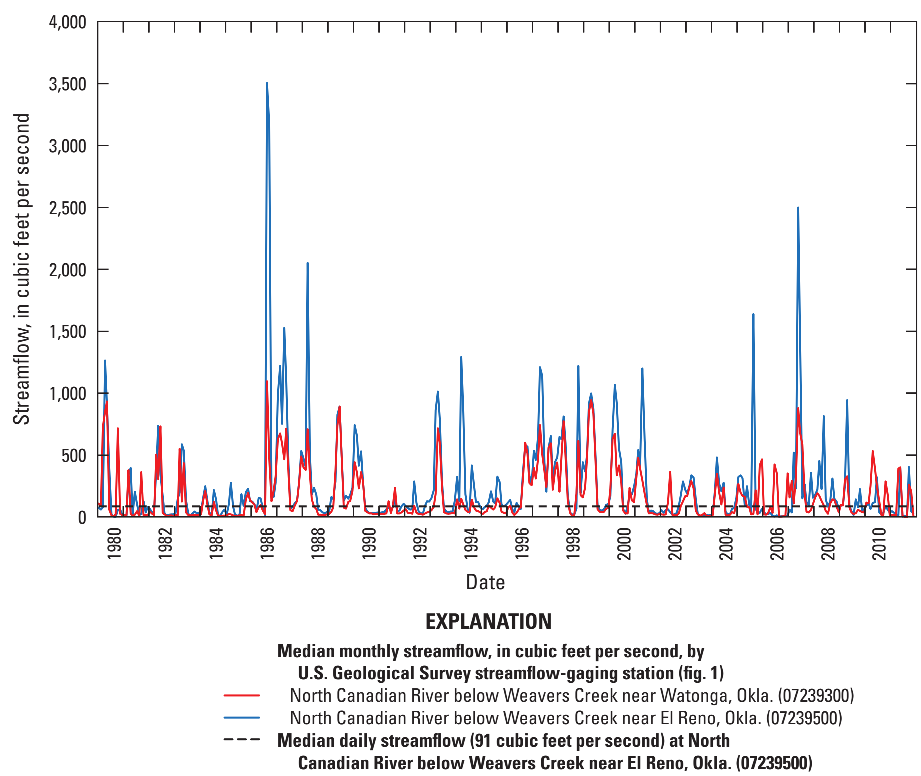


Figure 10. Median monthly streamflow at the North Canadian River below Weavers Creek near Watonga, Oklahoma (07239300), and near El Reno, Okla. (07239500), streamflow-gaging stations and the median daily streamflow at the El Reno station for Reach II.

Geology

The Beaver-North Canadian River alluvial aquifer is composed of alluvium and terrace, two Quaternary-age unconsolidated alluvial deposits that unconformably overlie bedrock units that range in age from the Permian to Tertiary (fig. 11). For most of the aquifer area, the alluvium and terrace deposits are physically and hydraulically connected, although in the lower parts of Reach II Permian units outcrop in an elongated band between alluvium and terrace deposits where both are missing. Only two of the underlying bedrock units are used as water sources, and no other Permian-age units are considered to contribute groundwater to the Beaver-North Canadian River alluvial aquifer groundwater-flow system.

Quaternary-age geologic units in the study area (fig. 11) consist of unconsolidated alluvium, dune sand, and terrace deposits. Dune sand is not differentiated in the geologic map of the study area from Heran and others (2003) but is described in Wood and Stacy (1965) as overlying the alluvium and terrace deposits throughout much of study area, and in some areas in Reach I, the landscape includes relic dunes and hummocky topography. The dune sand is 20–30 feet (ft) thick, well-sorted, medium- to fine-grained quartz sand in Woodward County (Myers, 1959; Wood and Stacy, 1965). Dune sand is typically above the water table and not a separate zone or unit of the aquifer, but because of the high permeability, dune sand can facilitate infiltration of precipitation and thus increase recharge to the aquifer.

Alluvium is delineated along the active channel of the Beaver and North Canadian Rivers and Wolf Creek as shown in figure 11, consisting of gravel, sand, silt, and clay (Myers, 1959) with an estimated mean thickness along the river channel of 30–40 ft and a maximum thickness of approximately 100 ft (Morton, 1980; Davis and Christenson, 1981; Christenson, 1983). The alluvium is only a few hundred feet wide in parts of the northwestern parts of Reach I and widens to the southeast such that it is wider than terrace deposits in Canadian County (fig. 11). Terrace deposits were deposited by the Beaver and North Canadian Rivers as they migrated to the southwest in the approximate direction of the regional dip of the underlying Permian-age geologic units. The terrace deposits are topographically higher than the alluvium and consist of gravel, sand, silt, clay, and minor amounts of volcanic ash, bentonite, and soft caliche (Myers, 1959; Morton, 1980; Davis and Christenson, 1981; Christenson, 1983). The terrace deposits are reported to have a mean thickness of between 60 and 70 ft and have been determined to be as thick as 150 ft (Morton, 1980). The terrace deposits on the northeastern margin of the aquifer have been eroded by widening of the adjacent Cimarron River Valley (fig. 1) and in places form the topographic drainage divide.

The Tertiary-age Ogallala Formation (To on fig. 11) consists of beds of moderately well sorted to poorly sorted sand and gravel, some of which are partially cemented by calcium carbonate (Myers, 1959). The mean thickness of the Ogallala Formation in the study area is 150 ft, and the maximum thickness is approximately 400 ft (Morton, 1980). Because the Ogallala Formation is difficult to differentiate from the alluvial and terrace deposits in borehole lithologic logs, Davis and Christenson (1981) included the Ogallala Formation as part of the Beaver-North Canadian River alluvial aquifer in the northwestern end of the study area where the alluvial deposits overlie the Ogallala Formation. For this report, the only location where the Beaver-North Canadian River alluvial aquifer is differentiated from the underlying Ogallala Formation is part of the terrace deposits in the Wolf Creek drainage (fig. 11). Where the Ogallala Formation is included, horizontal hydraulic conductivity (Kh) of the Beaver-North Canadian River alluvial aquifer is much lower because the Ogallala Formation is consolidated and includes beds of caliche and clay. The combined alluvium and Ogallala Formation makes the northwestern end of the Beaver-North Canadian River alluvial aquifer the thickest part of the aquifer.

Permian-age bedrock units exposed adjacent to and subcropping below the Beaver-North Canadian River alluvial aquifer are predominantly composed of fine-grained sandstone, siltstone, shale, dolomite, and gypsum (Heran and others, 2003). Permian-age rocks have a general regional dip to the south-southwest of approximately 17 ft per mile (Morton, 1980). In parts of the study area, Permian-age geologic units crop out in isolated areas within the alluvium and the terrace deposits because of protruding high spots on the irregular bedrock surface (Christenson, 1983). No notable geologic structures in bedrock units have been identified in the study area, although local-scale sinkhole development caused by groundwater dissolution of halite and gypsum in the Blaine Formation has resulted in minor folding in the area that includes Reach II (Morton, 1980).

Permian-age units underlying the Beaver-North Canadian River alluvial aquifer from youngest to oldest, and moving from northwest to southeast include the Cloud Chief, Rush Springs, and Marlow Formations, Dog Creek Shale, Blaine Formation, Bison Shale, Chickasha Formation, and Duncan Sandstone. Where these units are present at the land surface and the approximate areas where they subcrop below the Beaver-North Canadian River alluvial aquifer are shown on figure 11.

Most of Reach I is underlain by the Rush Springs and Marlow Formations (Pr and Pm in red on fig. 11, respectively) with two narrow areas along the northeastern margin of the aquifer upstream from Wolf Creek being underlain by the Cloud Chief Formation (Pcc in red on fig. 11). The Cloud Chief Formation is composed of shale and siltstone, with minor amounts of fine sandstone. The Rush Springs Formation consists of orange-brown fine-grained sandstone and siltstone, with interbedded red-brown shale, silty shale, and gypsum (Wood and Stacy, 1965). The Rush Springs Formation is the most permeable of the bedrock units in the area and is delineated by the OWRB as an aquifer southeast of the study area (Oklahoma Water Resources Board, 2012); it is considered to be hydraulically connected to the Beaver-North Canadian River alluvial aquifer. The Marlow Formation has texture similar to the Rush Springs Formation but with more silt and yields small quantities of water to domestic and stock wells (Wood and Stacy, 1965).

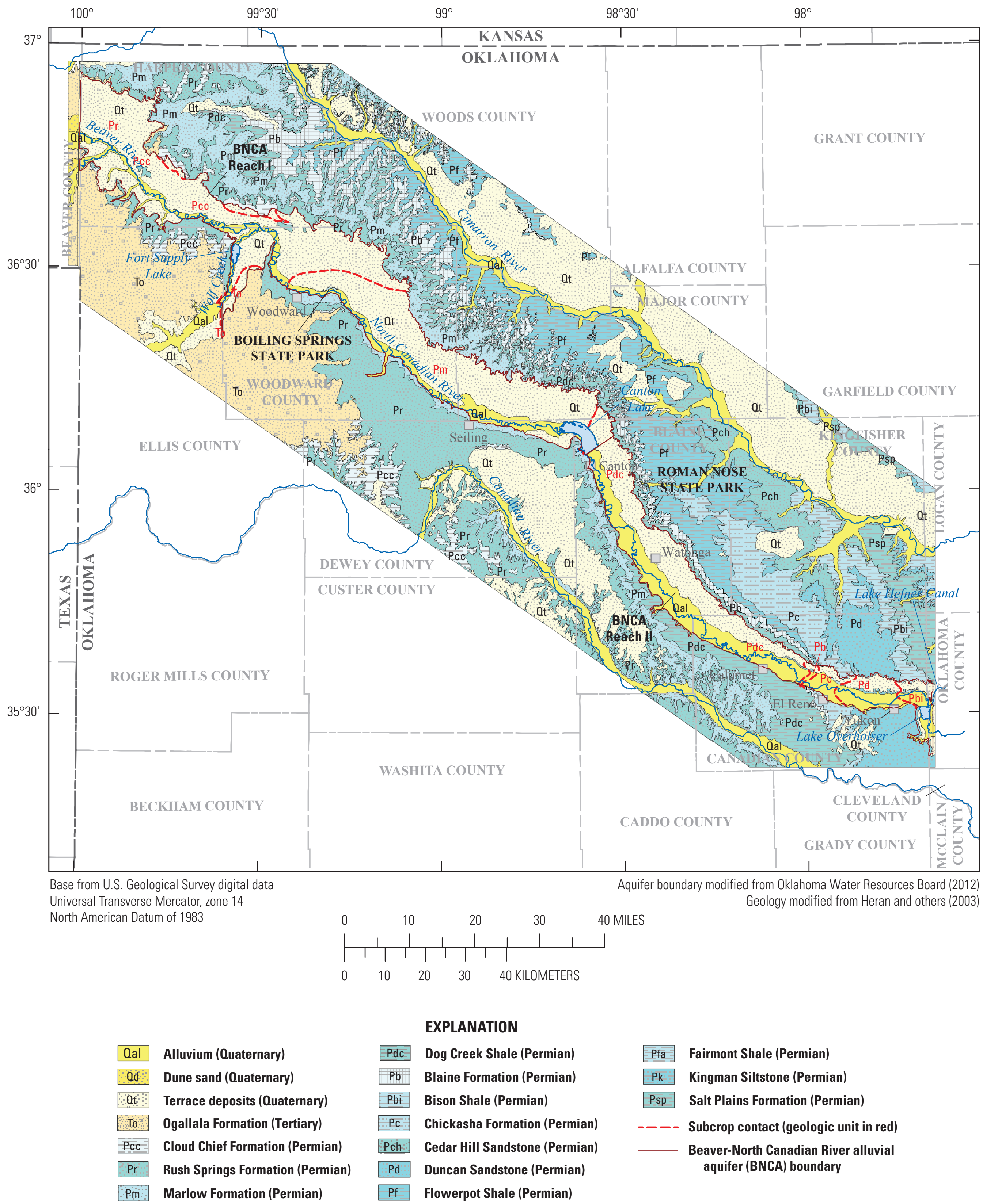


Figure 11. The geology of the Beaver-North Canadian River alluvial aquifer area showing approximate delineation of bedrock units that underlie the aquifer.

The Dog Creek Shale (Pdc on fig. 11) is red-brown shale with discontinuous bands of silt and thin layers of dolomite that underlie a substantial part of the Beaver-North Canadian River alluvial aquifer in Reach II (Morton, 1980). The Dog Creek Shale has very low permeability and is not a source of water (Mogg and others, 1960; Wood and Stacy, 1965).

The Blaine Formation, Chickasha Formation, and Duncan Sandstone (Pb, Pc, and Pd on fig. 11, respectively) underlie the eastern extent of the Beaver-North Canadian River alluvial aquifer in Canadian County. The Blaine Formation consists of thin gypsum beds with thin beds of dolomite below each gypsum layer interbedded with red-brown shale (Fay, 1962; Bingham and Moore, 1975). The gypsum is highly soluble and forms dissolution features that provide conduits for springs to form just east of the Beaver-North Canadian River alluvial aquifer such as those at Roman Nose State Park (fig. 11).

The Chickasha Formation (Pc on fig. 11), Duncan Sandstone (Pd on fig. 11), and Bison Shale (Pbi on fig. 11) underlie the southeastern-most parts of the Beaver-North Canadian River alluvial aquifer. The Chickasha Formation consists of mudstone conglomerate and red-brown to orange-brown silty shale and siltstone with minor amounts of orange-brown fine-grained sandstone (Bingham and Moore, 1975) that underlies the Beaver-North Canadian River alluvial aquifer in the area of the city of El Reno. The Duncan Sandstone is a red-brown to orange-brown fine-grained sandstone with some mudstone conglomerate and shale (Bingham and Moore, 1975) that underlies the Beaver-North Canadian River alluvial aquifer near the city of Yukon. The Bison Formation is a reddish-brown fine-grained sandstone and shale unit (Bingham and Moore, 1975).

Hydrogeological Units

A hydrogeological unit is a continuous unit with consistent hydraulic properties that may or may not coincide with a single stratigraphic unit and is hydraulically distinct from vertically or laterally adjacent hydrogeological units in the same hydrogeological system. Each hydrogeological unit may include zones or distinct vertical intervals that are unique but are discontinuous and not considered to be distinct hydrogeological units.

Though two units—the alluvial and terrace units—compose the Beaver-North Canadian River alluvial aquifer, both are included in the one hydrogeological unit because they have similar hydraulic properties, are typically laterally connected, and are not vertically juxtaposed. Dune sand is not mapped as a separate geologic unit in the study area.

In the northwestern part of Reach I, the Ogallala Formation is in contact with the terrace and alluvium both laterally and vertically, and the alluvium and terrace are mostly unsaturated. Thus, the Ogallala Formation is included in the Beaver-North Canadian River alluvial aquifer hydrogeological unit where it is overlain by alluvium, and the base of the unit is defined as the top of the Rush Springs Formation.

By using lithological borehole logs and modifying maps from Davis and Christenson (1981) and Christenson (1983), the altitude of the base of the Beaver-North Canadian River alluvial aquifer was mapped and is shown on figure 12 with the estimated aquifer thickness. The aquifer base is approximate in the northwestern end where there are few borehole logs that distinguish the base of the Ogallala Formation from the Rush Springs Formation.

The base of the Beaver-North Canadian River alluvial aquifer is an erosional surface scoured by the Beaver and North Canadian Rivers. The bedrock surface was constructed by using lithologic borehole logs with sufficient detail to provide the altitude of the bedrock contact. Because the base is an erosional surface, it was contoured so that all points on the surface drain down the valley to the southwest. Because of numerous wells drilled since 1980, the base of the Beaver-North Canadian River alluvial aquifer in this study is updated in this report by using additional well logs.

The thickness of the Beaver-North Canadian River alluvial aquifer as estimated in this report with the Ogallala Formation varies from nonexistent to 329 ft, and where the aquifer does not include the Ogallala Formation, it is typically less than 150 ft thick. There are elongated areas between the terrace and alluvium where the Beaver-North Canadian River alluvial aquifer is missing and the Duncan Sandstone outcrops.

Potentiometric Surface and Water-Level Fluctuations

Groundwater in the Beaver-North Canadian River alluvial aquifer generally flows downstream to the southeast and locally flows toward and discharges to the Beaver and North Canadian Rivers in most areas (fig. 13). The Beaver and North Canadian Rivers flow along the southwestern side of the valley, and recharge on the eastern upland areas creates a head gradient to the southwest across the valley. There are locations where upland recharge creates a groundwater divide and a gradient toward the eroded northeastern boundary. In these areas, some of the groundwater discharges to springs along slopes and small bluffs. The Beaver and North Canadian Rivers are generally gaining streams based on the potentiometric-surface contours, and base flow is described in more detail in the "Conceptual Hydrological Model" section of this report.

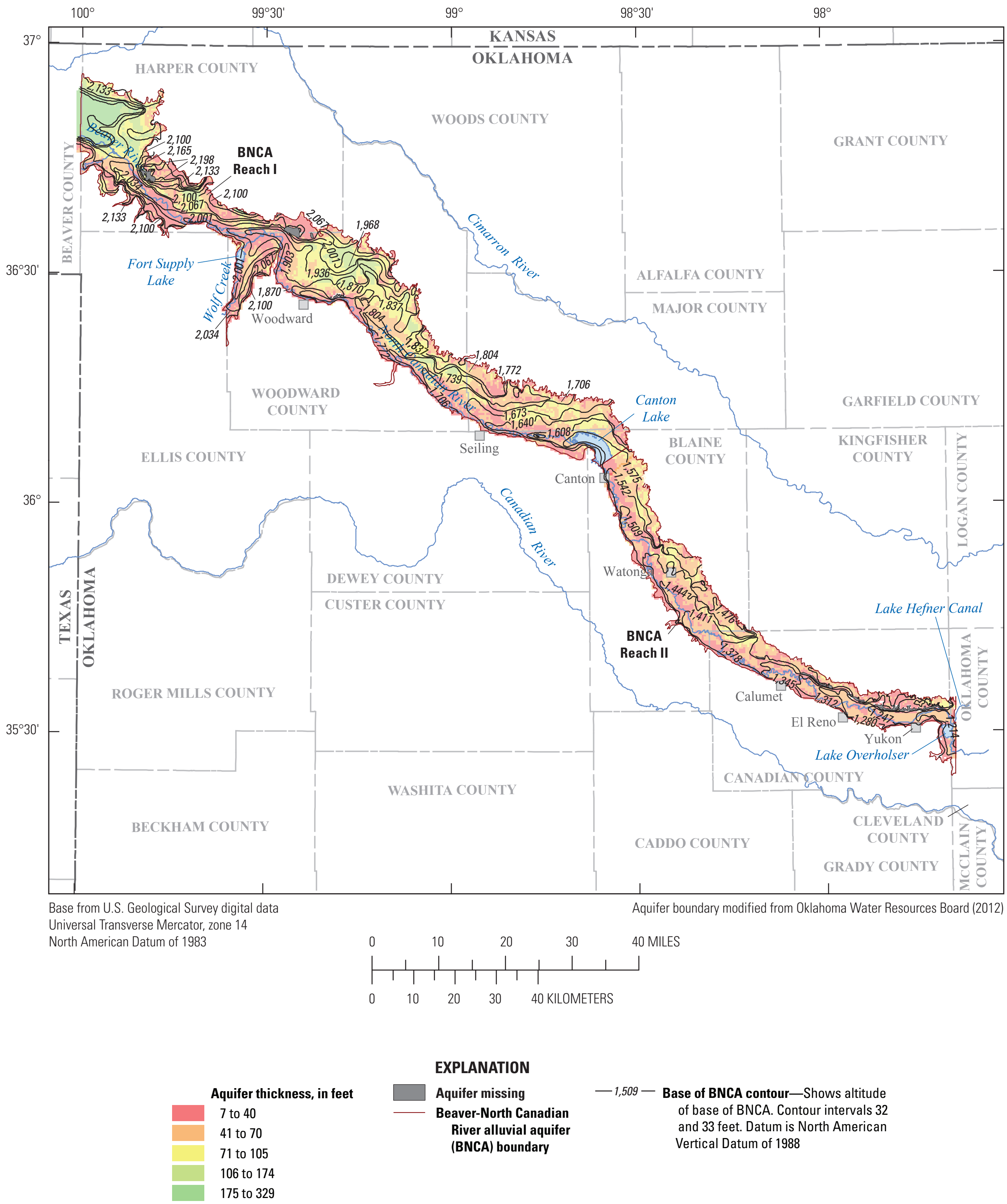


Figure 12. The approximate thickness and altitude of the base of the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

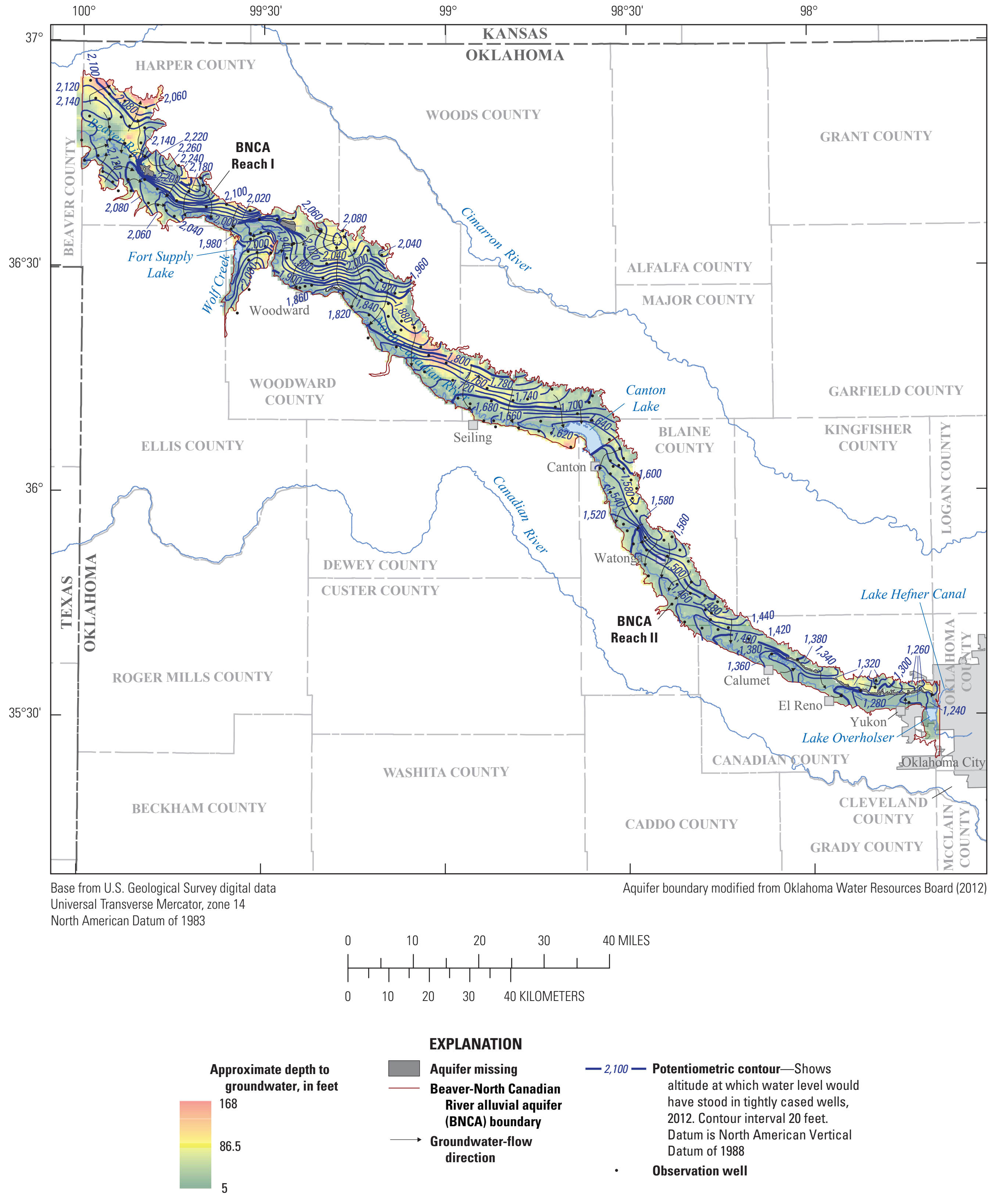


Figure 13. The Beaver-North Canadian River alluvial aquifer potentiometric surface, direction of groundwater flow, and approximate depth to groundwater from observations in 2012 (water-level data from 160 wells completed in the alluvial aquifer; U.S. Geological Survey, 2013c).

Water levels in the Beaver-North Canadian River alluvial aquifer measured at observation wells not located close enough to groundwater-pumping wells to be affected by drawdown and with long-term records with at least 25 observations were used to describe groundwater fluctuations and trends (U.S. Geological Survey, 2013c). Observation well water data are listed in table 4 with the number of readings, dates of first and last reading, mean depth to water, the change in water level from first to last reading, and the name used for the well on figures 1 and 14. Locations of six selected wells listed on table 4 are shown on figure 1, and time-series hydrographs of depth-to-water readings are shown in figure 14. The six wells with hydrographs in figure 14 are distributed across both reaches. Water levels in most wells with long-term records became shallower from 1980 to 2012, and some rose by more than 10 ft during that period (U.S. Geological Survey, 2013c). Linear trend lines on figure 14 show that water levels generally trended upward from 1980 to 2012, though all of the water levels dropped after 2008.

Aquifer Hydraulic Properties

Because the Beaver-North Canadian River alluvial aquifer is unconsolidated alluvium deposited in a fluvial environment, the Kh and specific yield (Sy) of this aquifer can be highly variable. Ryder (1996) reported that the Beaver-North Canadian River alluvial aquifer had a mean Kh of 59 feet per day (ft/d) and a maximum Kh of 160 ft/d. Water wells completed in the alluvium and terrace deposits typically yield 100–300 gallons per minute (gal/min), and yields range from less than 25 gal/min to more than 1,000 gal/min in some high-capacity irrigation and municipal wells (Davis and Christenson, 1981; Christenson, 1983).

Table 4. Water-level depth statistics and water-level change from observation wells with multiple readings for the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

[Source: U.S. Geological Survey (2013c); water-level change is the difference between the first reading and the last reading; mm, month; dd, day; yyyy, year; NA, not applicable; OW, observation well]

Site number	Number of readings	Date of first reading (mm/dd/yyyy)	Date of last reading (mm/dd/yyyy)	Reach	Mean depth to water (feet)	Standard deviation of depth to water (feet)	Water-level change (feet)	Name on figures 1 and 14
353107097453701	48	04/14/1980	10/11/1995	2	8.8	2.0	4.1	NA
355724098283501	41	02/19/1980	01/14/2010	2	47.3	2.4	6.8	OW-7
360927098354701	39	02/19/1980	01/14/2010	1	16.1	2.9	8.5	NA
360600098324701	36	01/26/1981	01/16/2008	1	25.1	3.0	5.8	NA
355151098215101	34	05/28/1981	01/18/2006	2	26.0	3.3	8.1	NA
353315097521001	30	02/22/1980	01/26/2010	2	8.7	2.9	6.0	OW-8
355045098243101	30	02/19/1980	01/14/2010	2	14.1	3.6	5.8	NA
362942099320301	30	01/29/1980	01/06/2011	1	28.1	4.2	9.8	NA
353236097551801	29	02/22/1980	03/06/2009	2	18.4	2.8	-0.1	NA
361155098360801	29	03/17/1980	01/20/2010	1	15.8	3.1	9.4	OW-6
362818099103001	29	01/28/1980	01/20/2010	1	59.4	4.4	10.0	OW-3
363300099232001	29	01/31/1980	01/20/2010	1	37.0	4.8	11.0	OW-2
364118099444701	29	03/25/1980	01/14/2010	1	10.4	3.4	3.2	NA
363827099485001	28	03/25/1980	01/14/2010	1	7.3	1.3	-0.6	OW-1
364923099570301	26	03/26/1980	01/24/2006	1	21.9	2.4	3.3	NA
362728099220201	26	02/03/1981	01/17/2008	1	10.4	1.6	-5.7	NA
362325099091901	26	01/28/1980	01/11/2008	1	26.3	2.4	-1.1	NA
363844099442301	25	01/20/1982	01/14/2010	1	26.2	7.5	4.6	NA

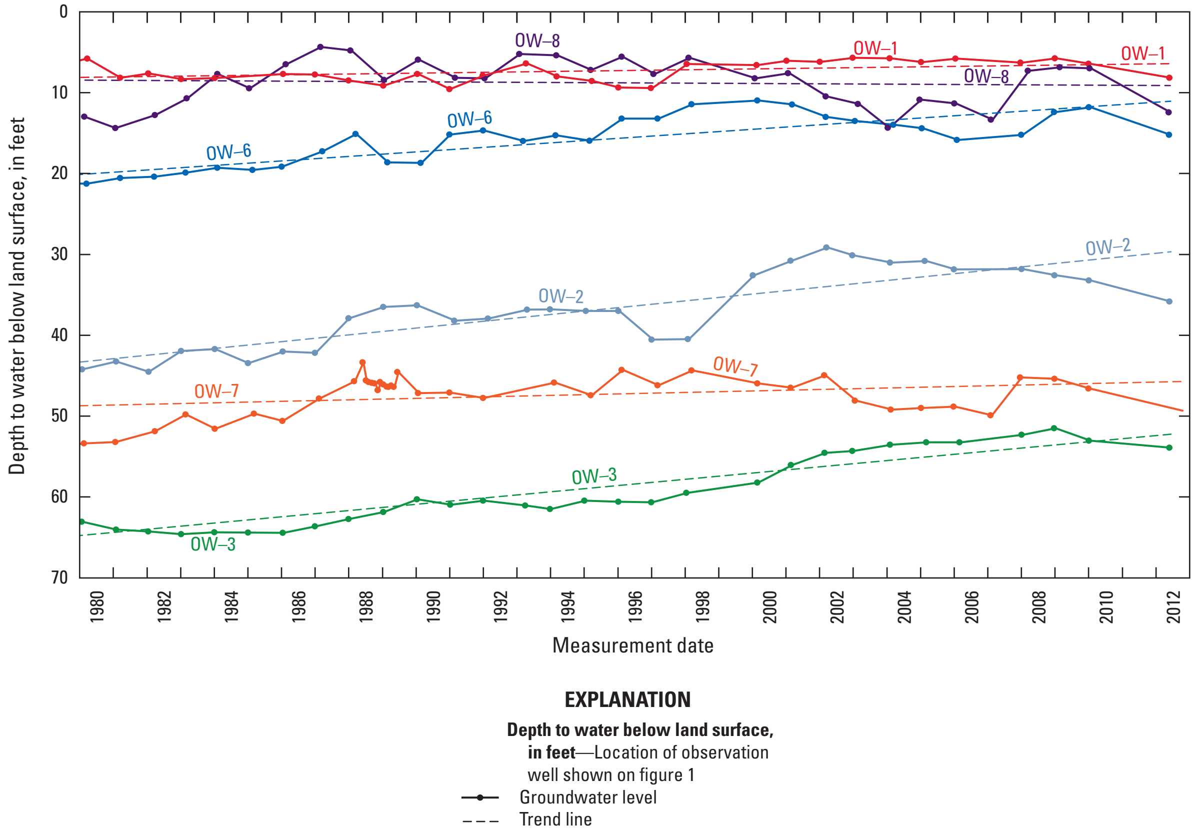


Figure 14. Long-term groundwater levels and trends from selected observation wells completed in the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma, 1980–2012.

Aquifer tests were reported at 10 sites on the Beaver-North Canadian River alluvial aquifer by Mogg and others (1960), Wood and Stacy (1965), and Fox and Kizer (2009) (fig. 15). Tests reported by Mogg and others (1960) were located in the far eastern end of Reach II. The test reported in Fox and Kizer (2009) was an investigation into stream depletion due to groundwater pumping wells along the riverbank and was located just north of the city of El Reno in Reach II. Aquifer tests reported in Wood and Stacy (1965) were from Woodward County clustered just south of Fort Supply Lake in Reach I. Values of Kh from published aquifer tests conducted in the study area ranged from 51 to 223 ft/d, and Sy ranged from 0.10 to 0.24, as listed in table 5.

Estimated mean Kh from lithologic borehole logs provided an initial distribution of Kh to be adjusted during calibration of the numerical groundwater-flow models. The mean Kh was estimated by assigning a Kh value to lithologic classes described for intervals in borehole logs, and calculating the mean, weighted by the thickness of each interval. To assign Kh values to intervals, the Kh for lithologic texture classes of the Beaver-North Canadian River alluvial aquifer was estimated by using published values.

The greatest number of aquifer-test results for the Beaver-North Canadian River alluvial aquifer was compiled in Mogg and others (1960), which included a sieve analysis of 189 sediment samples from 34 boreholes in Canadian County. Mogg and others (1960) reported the measured coefficient of permeability in gallons per day per square foot for each of the sieve samples. The coefficient of permeability was converted to Kh in feet per day by multiplying by 0.134 (Fetter, 1994). An approximate linear relation between Kh and texture was then calculated and used to assign a Kh value to various categories of lithology (table 6). For this report, lithologic descriptions in borehole logs (Oklahoma Water Resources Board, 2013) were categorized to a textural class and assigned the associated Kh from table 6. Thickness-weighted mean Kh at each borehole location and locations where an aquifer test had been performed were interpolated across the Beaver-North Canadian River alluvial aquifer by using the inverse distance weighted method (Esri, Inc., 2015). Because the alluvial aquifer contains beds of silt and clay, the vertical hydraulic conductivity was estimated to be one-tenth of the Kh.

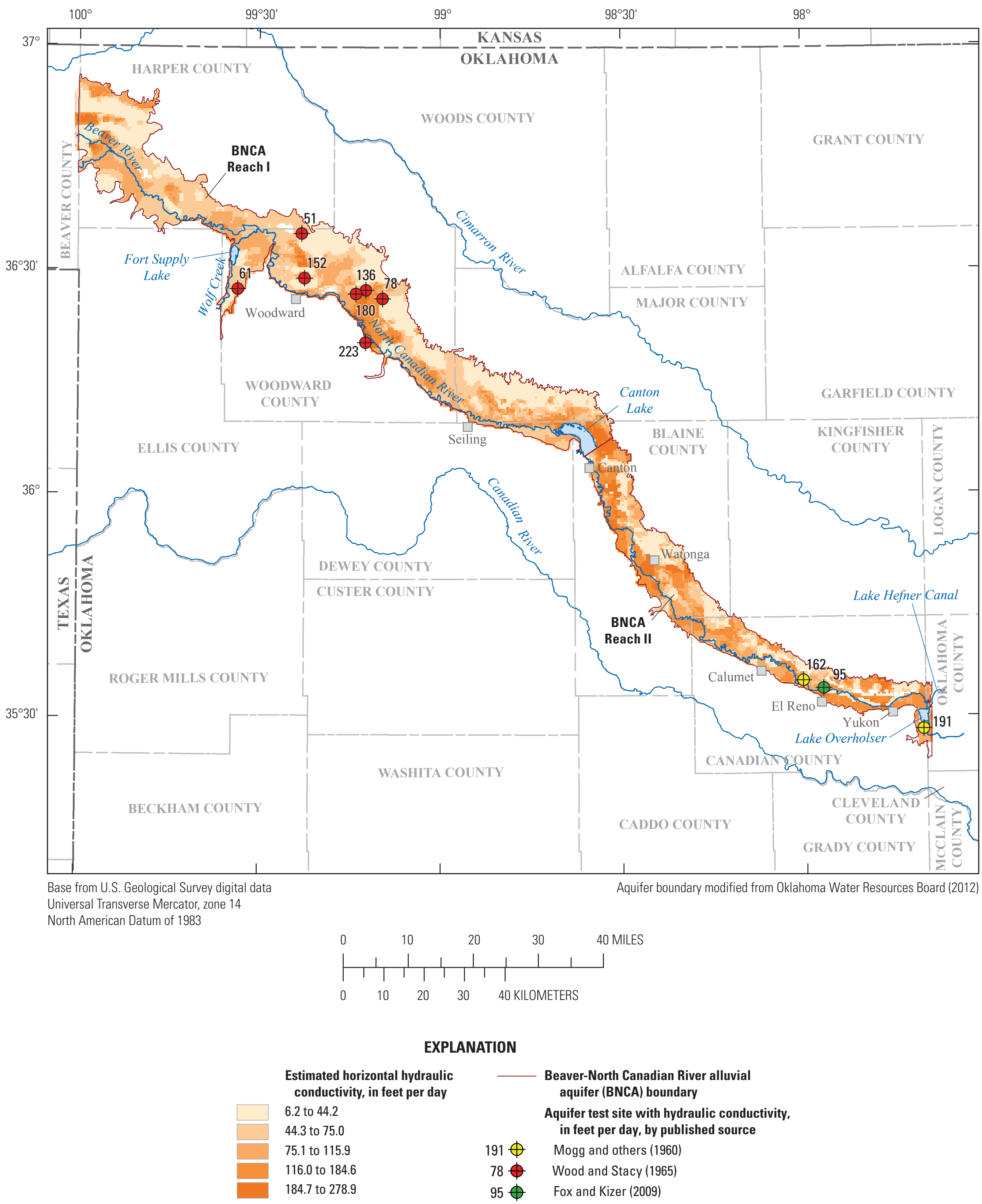


Figure 15. Locations of published aquifer tests and calibrated horizontal hydraulic conductivity from numerical flow models for the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

Table 5. Estimated hydraulic conductivity and specific yield of the Beaver-North Canadian River alluvial aquifer from published aquifer tests.

[NA, not available]

Site number	Unit	Hydraulic conductivity (feet per day)	Specific yield	Source
NA	Alluvium	95	0.24	Fox and Kizer (2009)
13N-08W-24 CCD	Alluvium	162	0.10	Mogg and others (1960)
12N-05W-36 DBB	Alluvium	191	0.14	Mogg and others (1960)
22N-19W-35 CCA 4	Alluvium	223	NA	Wood and Stacy (1965)
23N-22W-22 DCD1	Alluvium	61	NA	Wood and Stacy (1965)
23N-18W-30 DDC 1	Terrace	78	NA	Wood and Stacy (1965)
23N-19W-23 CBD 1	Terrace	136	NA	Wood and Stacy (1965)
23N-19W-28 ACA 1	Terrace	180	NA	Wood and Stacy (1965)
23N-20W-07 DBD 5	Terrace	152	NA	Wood and Stacy (1965)
24N-20W-06 CDB 1	Terrace	51	NA	Wood and Stacy (1965)

Table 6. Horizontal hydraulic conductivity assigned to textural classes of sediments in the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

[Data from Fetter (1994)]

Textural class	Hydraulic conductivity (feet per day)
Gravel	280
Very coarse sand	175
Coarse sand	90
Medium sand	20
Fine sand and silt	0.01
Clay	0.00001

Because little information was available on Sy from published aquifer tests in the Beaver-North Canadian River alluvial aquifer, Sy for each borehole location was calculated from estimated mean Kh. Horizontal hydraulic conductivity and Sy for textural classes were taken from ranges published in Fetter (1994) and used to caculate a logarithmic regression to estimate Sy for other values of Kh. The coarsest sediment in the Beaver-North Canadian alluvial aquifer was assumed to be medium-grained gravel with a Kh of 280 ft/d and was assigned an Sy of 0.27. The finest grained texture likely found in the aquifer was assumed to be clay with a Kh of 0.00001 ft/d and was assigned an Sy of 0.07. Medium-grained sand with a Kh of 50 ft/d was assigned an Sy of 0.26. A logarithmic (ln) regression with a correlation coefficient of 0.998 was determined by using the three textural classes using equation 1.

$$Sy = a \ln(Kh) + b \qquad (1)$$

where

a and *b* are calculated regression coefficients.

The best-fit logarithmic regression coefficients were found, and the regression was determined to be

$$Sy = 0.0119 \ln(Kh) + 0.2078 \qquad (2)$$

By using this method, the mean Sy in Reach I was 0.16, and the mean Sy in Reach II was 0.2. As with Kh, the derived Sy at each location was an estimate and an initial value that was adjusted during numerical-model calibration.

The Kh of the bedrock underlying the Beaver-North Canadian River alluvial aquifer was estimated by using lithologic descriptions of geological units from Heran and others (2003) and approximate Kh values from Fetter (1994) for the lithologic type (table 7). Bedrock Kh values were generalized and assumed to be homogeneous within each geologic unit. No direct measurements of the bedrock Kh have been made. Storage parameters for Permian bedrock units were generalized to 0.1 for Sy and 0.0001 for specific storage. Specific storage is a parameter that is used in confined conditions and is required for the numerical groundwater-flow model.

Table 7. Texture and horizontal hydraulic conductivity assigned to bedrock units underlying the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

Unit	Lithology (Heran and others, 2003)	Hydraulic conductivity from Fetter (1994) (feet per day)
Ogallala Formation	Sandstone, clay, and caliche	3.5
Cloud Chief Formation	Shale, siltstone	0.0001
Rush Springs Formation	Fine-grained sandstone with siltstone, gypsum	0.9
Marlow Formation	Fine-grained sandstone and siltstone, gypsum	0.2
Dog Creek Shale	Shale and siltstone	0.0001
Blaine Formation	Gypsum and dolomite	0.01
Chickasha Formation	Mudstone, conglomerate, and silty shale	0.001
Duncan Sandstone	Fine-grained sandstone with mudstone	0.1
Bison Formation	Shale	0.0001

Conceptual Flow Model

The conceptual flow model of the Beaver-North Canadian River alluvial aquifer hydrologic system is a schematic description of the boundary conditions and related flows that compose the aquifer flow budget. The conceptual flow model with the hydrogeologic framework was used to conceptualize, design, and construct the numerical groundwater-flow models.

Flow volumes for the major boundaries of the Beaver-North Canadian River alluvial aquifer hydrologic system were estimated to produce an approximate mean annual budget for the Beaver-North Canadian River alluvial aquifer during the period 1980–2011. Boundary categories estimated for the aquifer included surface recharge, stream and lake interactions with the aquifer, human water use, discharge to springs and seeps, and ET in each reach. This flow budget is generalized because of available data, and a more detailed estimate of the flow budget is quantified by the numerical groundwater-flow models.

Hydrological Boundaries

Hydrological boundaries are defined as locations through which a substantial amount of water moves—or is not able to move in the case of a no-flow boundary—to or from the groundwater system and are used to quantify and categorize groundwater flows. Flow boundaries are of three types: specified-flow boundaries, head-dependent boundaries, and constant-head boundaries. Specified-flow boundaries include wells and recharge through which a continuous flow passes during a simulation stress period. Flow through head-dependent boundaries is a function of the relative head at the boundary and the adjacent aquifer and the conductance of the boundary. Head-dependent boundaries in the Beaver-North Canadian River alluvial aquifer include streams, lakes, lateral flow from adjacent units, and springs. Constant-head boundaries, through which a flow passes based on an assigned head, are not used in the models for this report.

The most areally extensive boundary in the Beaver-North Canadian River alluvial aquifer is the specified-flow boundary at the land surface, through which a portion of precipitation flows to the aquifer as groundwater recharge and water that is taken up and transpired to the atmosphere from groundwater by vegetation if the water table intersects the root zone. The second most extensive boundary is the base of the alluvial aquifer through which water can move to or from the underlying bedrock. The channel of the Beaver and North Canadian Rivers is a head-dependent flow boundary where groundwater and streamflow interact and are governed by the conductance of the streambed. Flow through the head-dependent flow boundary consisting of lakebeds was estimated to be much less than flow to the Beaver and North Canadian Rivers and was included in the budget for streams. Point location specified-flow boundaries included groundwater-pumping wells shown in figure 2 and springs along the eastern margin of the aquifer.

Lake seepage in the study area has not been studied or measured. Although the U.S. Army Corps of Engineers has collected and calculated daily flows for Canton and Fort Supply Lakes (U.S. Army Corps of Engineers, 2013), groundwater flow was not separated from runoff or stream inflow. As shown in the potentiometric surface in figure 13, there was a groundwater gradient toward the lakes and it was assumed that groundwater flowed into the lakes, but groundwater flows to the lakes were not estimated for the conceptual flow model.

The groundwater flow between the Beaver-North Canadian River alluvial aquifer and bedrock is not estimated for the conceptual flow model. In the northwestern part of Reach I, the aquifer is connected to the Ogallala Formation of the High Plains aquifer both in the Beaver and North Canadian River Valleys and along the western margin (fig. 11). Because of a lack of local hydrogeologic data, groundwater flow from the Ogallala Formation or underlying units could not be estimated for the conceptual model.

In the northwestern parts of the study area, the Beaver-North Canadian River alluvial aquifer overlies the Rush Springs Formation, although in the absence of local groundwater pumping, groundwater flow to the Beaver-North Canadian River alluvial aquifer would require a vertical, upward head gradient and is assumed to be unsubstantial, as reported in Christenson (1983). There is the potential for water loss from the Beaver-North Canadian River alluvial aquifer to the Blaine Formation in the southeastern parts of the aquifer because of saline and gypsum karst features in the bedrock (Morton, 1980); however, these features have not been mapped, nor have any estimates of flow in that area been made.

Stream Base Flow

Stream base flow is defined in Barlow and Leake (2012) as the flow of groundwater into streams through the streambed. A gaining stream receives base flow, and a losing stream loses streamflow through infiltration to an aquifer. Base flow and local runoff are the sources of most of the Beaver and North Canadian Rivers streamflow, with inflows from sources outside the aquifer from the west including Wolf Creek (fig. 1) and streamflow from the Beaver River upstream from the Beaver-North Canadian River alluvial aquifer. There are no known tributaries that flow over the Beaver-North Canadian River alluvial aquifer from the east. A substantial amount of the flow in Reach II of the North Canadian River was composed of streamflow released from Canton Lake (U.S. Army Corps of Engineers, 2013).

To quantify the stream base flow, seepage-run measurements and hydrograph (base flow)-separation methods were used. Base-flow separation uses streamflow hydrographs to estimate the total base flow and base-flow index (BFI), or the ratio of base flow to total streamflow. Seepage runs were used to characterize streamflow and estimate base flow at one point in time. A seepage run isolates base flow by measuring streamflow approximately simultaneously at different locations in a drainage basin at a time when streams are at low flow, ET is at a minimum because plants are dormant, and recent precipitation is minimal, so runoff is very low, if not zero. Base flow is estimated during a seepage run by calculating the difference between the streamflow measurement at the upstream end of a reach (inflow) and the streamflow measurement at the downstream end of a reach (outflow). Inflow from tributaries is accounted for so that only the gain or loss of streamflow along the stream reach is measured.

Base-flow separation was performed by using the BFI computer program (Wahl and Wahl, 2007) that uses hydrograph-recession records. The BFI computer program uses a specified window of days that covers the duration of storm-runoff peaks to separate base flow from runoff by using hydrograph-recession analysis. Because of streamflow control by Canton Lake, base-flow separation was not performed for Reach II.

Reach I Seepage Runs

A seepage run reported in Davis and Christenson (1981) was conducted from March 12 to 14, 1979, with 18 synoptic streamflow measurements along the Beaver and North Canadian Rivers and 13 tributaries (fig. 16). The first upstream reach was considered to be losing because the total inflow of 11.8 ft^3/s (9.5 ft^3/s from Kiowa Creek and 2.3 ft^3/s from upstream) was much greater than the outflow of 2.8 ft^3/s. The net difference was a loss of 9.0 ft^3/s over about 1 mi of channel between Kiowa Creek and the next measurement (fig. 16). Beaver and North Canadian Rivers reaches between Kiowa Creek and Persimmon Creek were generally gaining except for the reaches at Clear and Otter Creeks. The only other losing reach was at Bent and Deep Creeks, which lost 2.0 ft^3/s over about 10 mi. Wolf Creek below Fort Supply Lake was considered to be gaining, although it was not known whether the flow measured near the confluence with the Beaver River was base flow or included flow released from Fort Supply Lake because release data were not available for the time the seepage run took place.

The streamflow in the Beaver and North Canadian Rivers during the 1979 seepage run by stream reach with distance downstream is shown on figure 17 as the total observed streamflow including tributaries (solid red line) and the cumulative streamflow gain with tributary input subtracted (dashed red line). The slope of the dashed line indicates whether it is gaining (positive slope) or losing (negative slope). The cumulative base flow for the 1979 seepage run alternated between losing and gaining, reflecting flows in the reaches shown in figure 16 until just past 40 mi where the river became a gaining stream. At approximately 70 mi downstream from the northwestern aquifer boundary, the accumulated base flow surpassed the streamflow that was lost, and at the end of Reach I, the accumulated streamflow gain was 31 ft^3/s as shown at the downstream end of the red dashed line in figure 17.

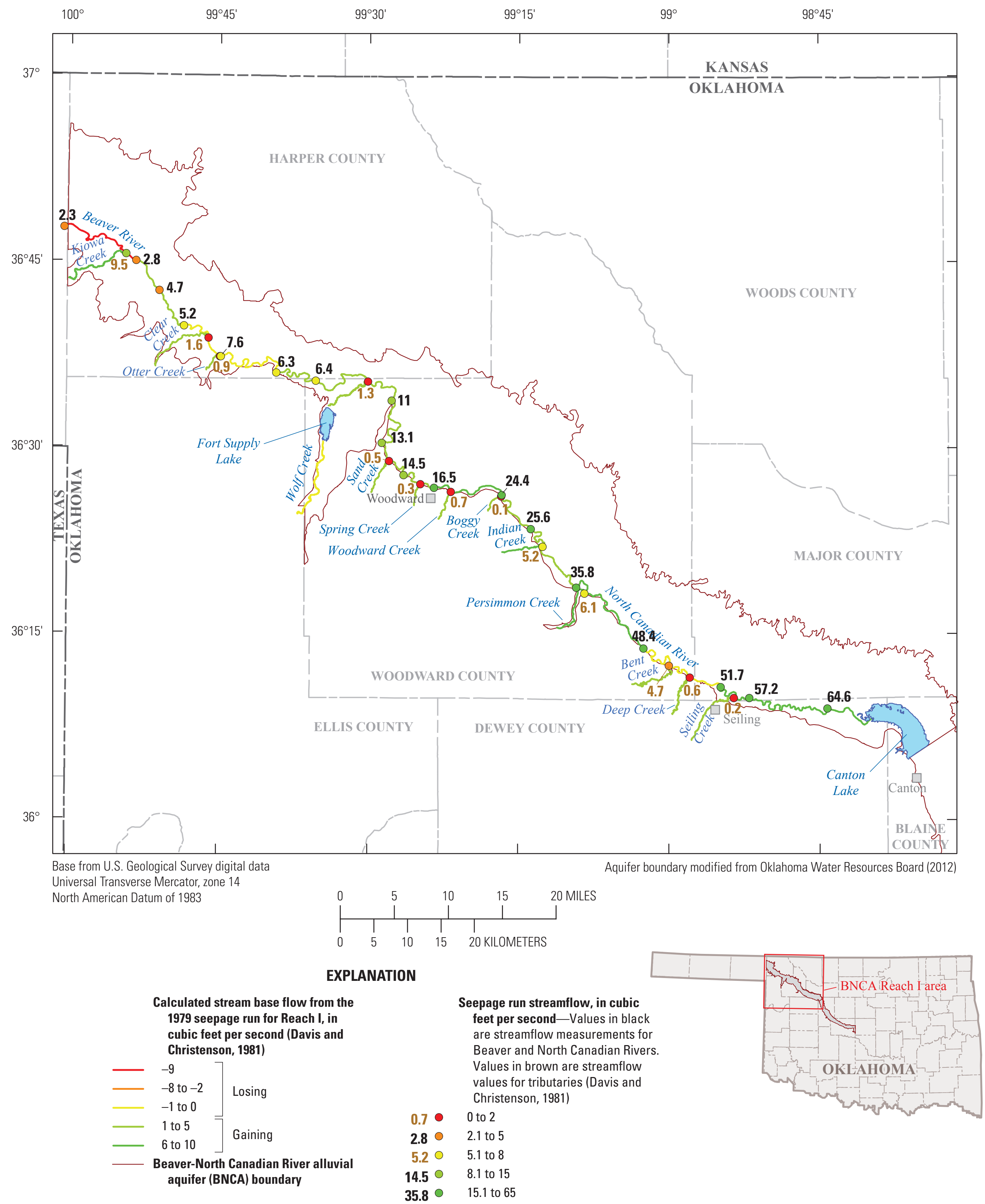


Figure 16. Streamflow measurements and calculated base flow from the 1979 seepage run in Davis and Christenson (1981) for Reach I of the Beaver and North Canadian Rivers, northwestern Oklahoma.

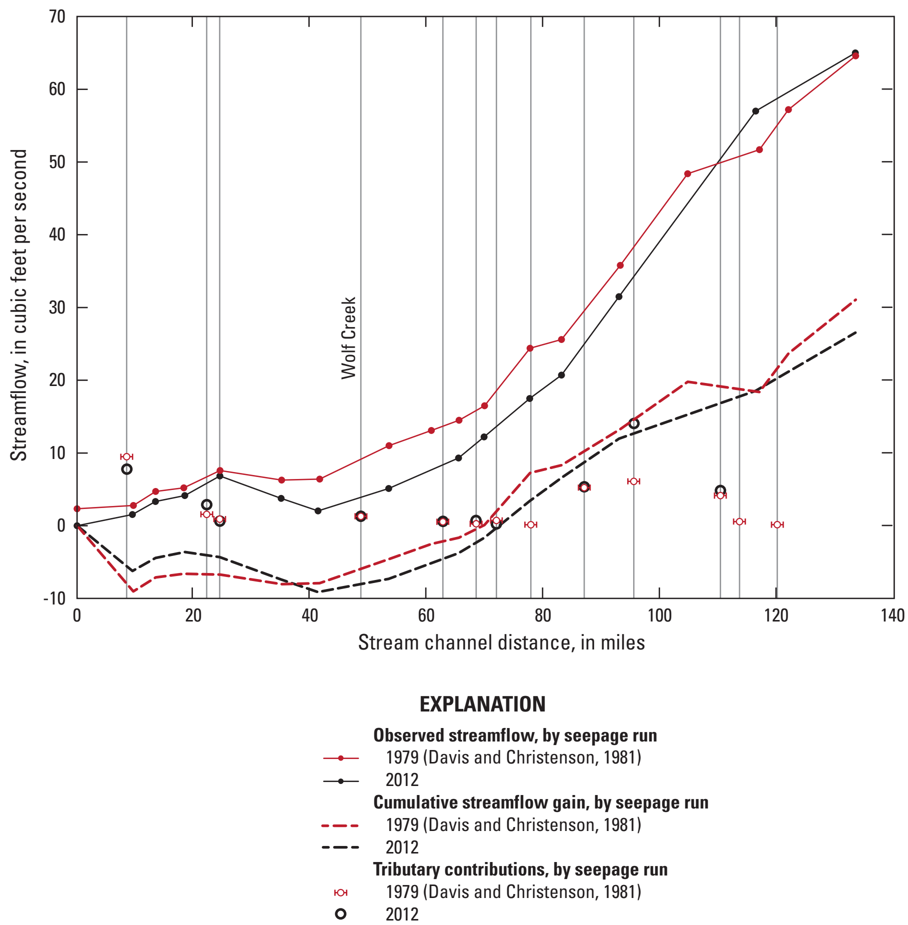


Figure 17. Cumulative streamflow and streamflow corrected for tributary inflow with distance downstream from the upstream limit of the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma, by stream reach in the Beaver and North Canadian Rivers, from the 1979 (Davis and Christenson, 1981) and 2012 seepage runs.

On February 21–22, 2012, a series of streamflow measurements were made for a seepage run along the Beaver and North Canadian Rivers and contributing tributaries in Reach I similar to the measurements described in Davis and Christenson (1981). Influence from surface runoff was estimated to be minimal because the highest precipitation amount recorded during the 10 days preceding the seepage run was less than 0.20 in. at the Seiling streamflow-gaging station (07238000), and streamflows during that period were constant or very slightly declining. Comparative statistics in table 8 show that streamflow measurements for this seepage run were made when streamflows were less than the minimum 7-day, 2-year recurrence interval at the Woodward streamflow-gaging station and were slightly less than the minimum 7-day, 2-year recurrence interval flow conditions at the Seiling streamflow-gaging station. At both stations, the daily mean streamflows during the seepage run were substantially less than the historical median February streamflow. For these reasons, streamflow in the Beaver and North Canadian Rivers and all contributing tributaries was considered to be mostly, if not entirely, composed of base flow at the time of the seepage run.

There were 14 streamflow measurements made along the Beaver and North Canadian Rivers and 11 measurements made on 10 tributaries, including 2 on Wolf Creek for the 2012 seepage run (fig. 18). Tributary streamflow was measured a short distance upstream from the confluence with the Beaver or North Canadian Rivers, and in these instances, river-mile distances were reported relative to the confluence. The two measurements on Wolf Creek were separated by Fort Supply Lake and were not used for base-flow calculations for Wolf Creek.

Table 8. Comparative streamflow statistics for selected U.S. Geological Survey streamflow-gaging stations during the 2012 seepage run, North Canadian River, northwestern Oklahoma.

[All flow in cubic feet per second]

Streamflow-gaging station	+Daily mean flow Feb. 21–22, 2012	*February flow statistics			*Minimum 7-day, 2-year flow Nov. 1–Mar. 31
		Maximum	Median	Minimum	
07237500	17, 17	246	79.7	12.6	19.8
07238000	60, 57	360	118	36.7	43.5

+U.S. Geological Survey (2013d).

*Lewis and Esralew (2009).

At the northwestern edge of the Beaver-North Canadian River alluvial aquifer, the Beaver River was dry at the time of the seepage run and received 7.8 ft^3/s of streamflow from Kiowa Creek (fig. 18). The first stream reach had an outflow of 1.5 ft^3/s and thus lost 6.3 ft^3/s over that reach. The next two downstream streamflow measurements gained streamflow, but after removing the inflow from Clear and Otter Creeks, the downstream reaches were losing until just upstream from the confluence of Wolf Creek. All of the reaches from Wolf Creek to Canton Lake were gaining base flow, even when corrected for substantial inflow from tributaries (figs. 17 and 18). The total base flow determined from the total downstream increase in flow measured during the 2012 seepage run adjusted for tributary inflow was 28.0 ft^3/s. Streamflow measured at the Seiling streamflow-gaging station, including tributary input, was 65.0 ft^3/s.

Comparison of streamflow data collected during the 1979 and 2012 seepage runs indicates similar streamflow characteristics (fig. 17). The seepage runs indicate that the Beaver and North Canadian Rivers and Wolf Creek were generally gaining streams with losing sections upstream from Wolf Creek. Tributary streamflows were comparable between the two seepage runs with the exception of streamflow in Persimmon Creek, which in 2012 was nearly twice that measured in 1979. At least half of the total downstream increase in streamflow measured in the Beaver and North Canadian Rivers in Reach I during both seepage runs was from tributaries, with 33.5 ft^3/s in 1979 and 38.5 ft^3/s in 2012. The total base flow calculated for Reach I was 31.1 ft^3/s in 1979 and 26.6 ft^3/s in 2012; the mean total base flow for Reach I from seepage runs was 28.8 ft^3/s. The streamflow at the Seiling streamflow-gaging station was nearly identical in both seepage run measurements, 64.6 ft^3/s in 1979 and 65.0 ft^3/s in 2012.

Reach I Base-Flow Separation

Daily streamflow data were available for the entire period of study at the Seiling streamflow-gaging station, which is located just upstream from Canton Lake (fig. 1). These data were used in the BFI computer program (Wahl and Wahl, 2007) to calculate an annual BFI (total streamflow/total base flow) and total base-flow volume. The window for storm hydrograph duration—the mean length of a runoff peak from a precipitation event—was estimated at 6 days. The mean BFI, or the proportion of streamflow that originates as base flow for 1980–2011, was calculated to be 0.63, which was similar to estimates in Esralew and Lewis (2010). The mean annual base flow for Reach I was calculated to be approximately 69,000 acre-ft (table 9).

Reach II Seepage Run

Christenson (1983) described a seepage run in the North Canadian River south of Canton Lake conducted during January 1981 that measured flow at various locations including near USGS streamflow-gaging stations (fig. 19). Tributary flow was not considered a substantial component in Reach II and was not measured (Christenson, 1983). An additional seepage run was not conducted for the study described in this report.

During the seepage run, Canton Lake was releasing 6.1 ft^3/s in streamflow into the North Canadian River, and in nearly every reach, streamflow measurements increased downstream, although base flow was variable among reaches. In total, the streamflow in the North Canadian River in Reach II increased from 6.1 to 20.3 ft^3/s (fig. 19) and thus gained 14.2 ft^3/s in streamflow between Canton Dam and the Lake Hefner Canal diversion; only one segment between Watonga and Calumet lost streamflow (0.4 ft^3/s) to the Beaver-North Canadian River alluvial aquifer (fig. 19). The greatest gains were 4.8 ft^3/s in streamflow measured in the first reach below Canton Lake and 3.0 ft^3/s of streamflow measured between the streamflow-gaging station near Calumet (07239450) and the streamflow-gaging station near El Reno (07239500).

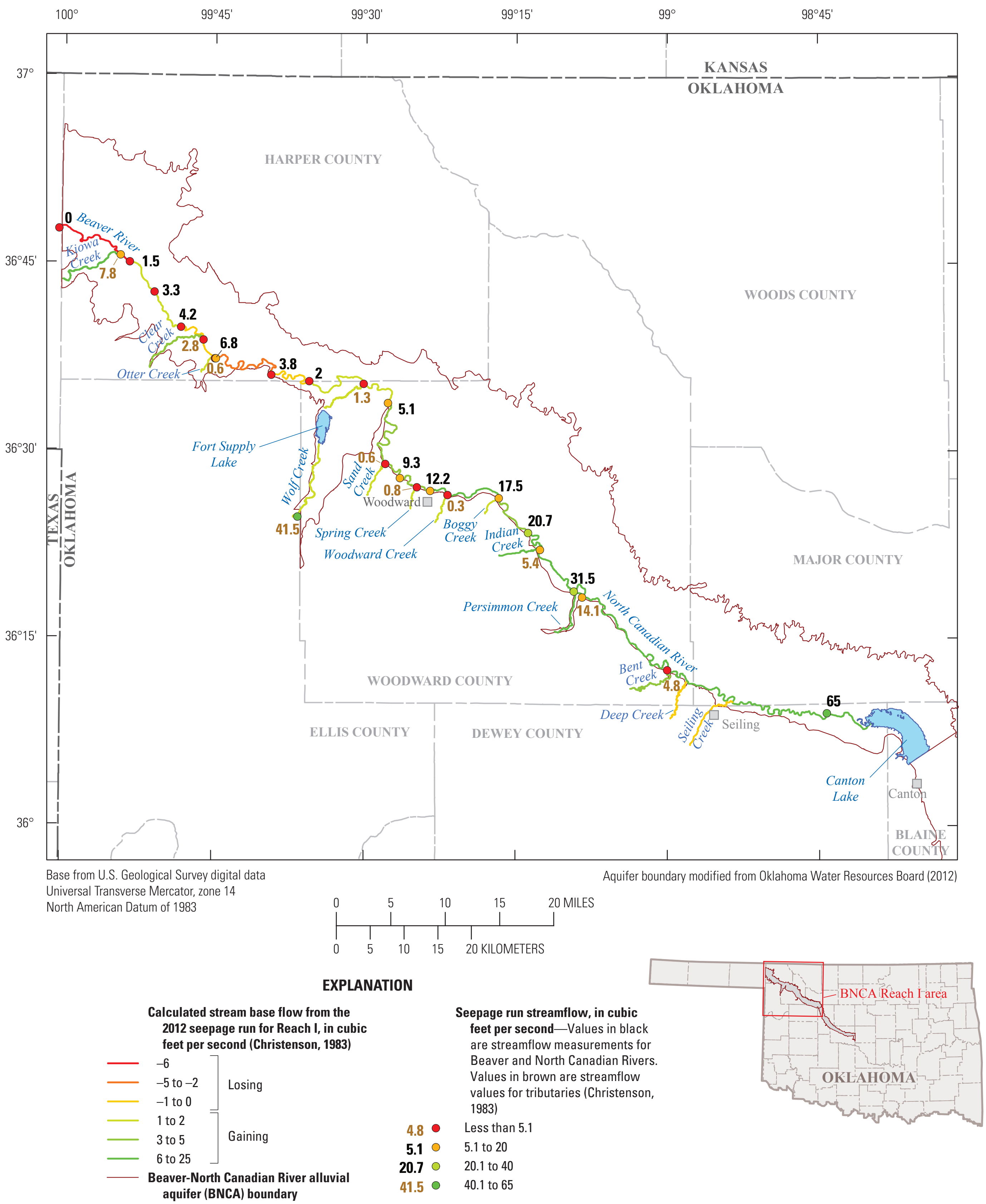


Figure 18. Streamflow measurements and calculated base flow from the 2012 seepage run, Reach I of the Beaver and North Canadian Rivers, northwestern Oklahoma.

Table 9. Conceptual flow model estimated annual hydrological budget for the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

[All units in acre-feet per year; positive values are volumes to the aquifer, and negative values are leaving the aquifer; NA, not applicable]

Budget category	Reach I	Reach II	Total
Inflow			
Recharge	136,400	82,400	218,800
Outflow			
Evapotranspiration and springs	53,400	NA	NA
Base flow to streams	69,000	NA	NA
Groundwater pumping	14,000	12,000	26,000
Total outflow	**136,400**	**82,400**	**218,800**

Groundwater Recharge

Groundwater recharge is the primary source of inflow to the Beaver-North Canadian River alluvial aquifer. Recharge was estimated both areally across the aquifer by using a soil-water-balance (SWB) model and at two locations by using a water-level fluctuation (WTF) method. The methods used provided spatially distributed transient recharge estimates on the basis of physical and climatologic variables, and the point measurements provided estimates of the ratio of precipitation that enters the groundwater system as recharge.

Soil-Water-Balance Model

To estimate transient groundwater recharge across the Beaver-North Canadian River alluvial aquifer, the SWB code of Westenbroek and others (2010) was used. The SWB code used grids of landscape and climate data with grid cells 1,640 ft by 1,640 ft to provide estimates of spatially distributed deep percolation through the soil profile. Deep percolation could become groundwater recharge and is referred to in this report as “recharge” because the aquifer is unconfined. The SWB-calculated recharge consists of recharge arrays that are a starting point for calibrating groundwater-flow models, as shown in Stanton and others (2012).

The SWB code tracks soil-water content within the soil root zone and inflows (percolation from the land surface due to precipitation and runoff from adjacent areas) and outflows (plant interception and ET) on daily time steps. Plant ET was calculated in the SWB code by using the Hargreaves and Samani (1985) method based on the land-cover vegetation. Recharge is the surplus soil water that infiltrates into the soil profile when the soil in the root zone is fully saturated.

A simple runoff model is used in the SWB code to route runoff between cells by using a grid of land-surface flow direction derived from a digital elevation model (DEM) (U.S. Geological Survey, 2013a). The amount of water that infiltrates into the soil profile is calculated by using the soil runoff curve number and hydrologic soil group from soil survey geospatial data (Natural Resource Conservation Service, 2013). The total soil-water storage capacity is calculated by using the available water capacity from soil data (Natural Resource Conservation Service, 2013) and the root-zone depth determined from the land-cover vegetation and soil type in each cell (Thornthwaite and Mather, 1957).

The SWB code used grids of daily precipitation and maximum and minimum temperature interpolated from 173 weather stations located on and in the general area of the Beaver-North Canadian River alluvial aquifer (National Climatic Data Center, 2013). Weather stations within a rectangle bounded by 35.1–37.2 degrees latitude and 100.4–97.3 degrees west longitude were used, and most are shown in figure 5. Because the period of record varies for the stations used, the number of stations with temperature and precipitation data on any particular day varied during the period of study. In 1980, the mean number of stations with readings on a given day was 42, and in 2011, the mean number of stations with readings was 115. Daily grids of precipitation and high and low temperature were interpolated from point data by using the inverse distance weighted method (Esri, Inc., 2015).

Recharge estimated by the SWB model is spatially variable because soil properties, flow direction, land cover, precipitation, and temperature are spatially variable. Important assumptions of the SWB code are that the root zone is above the water table and that the only source of water for the soil profile is water percolating from the land surface. In parts of the Beaver-North Canadian River alluvial aquifer, particularly near lakes and streams, plant roots may reach the water table. The SWB model calculates the potential ET and then limits the actual ET to the available water in the soil on the basis of soil moisture content; however, if groundwater is shallow enough to intersect the root zone such that plants can access it, the actual ET calculated by the SWB model is underestimated, and though the recharge may be accurate, there is an additional sink to the groundwater system. Thus, there may be an additional loss via ET that is not accounted for—as much as the difference between the actual ET and the potential ET calculated by the SWB model, which causes recharge to be overestimated. This topic is described further in the “Numerical Groundwater-Flow Model” section of this report.

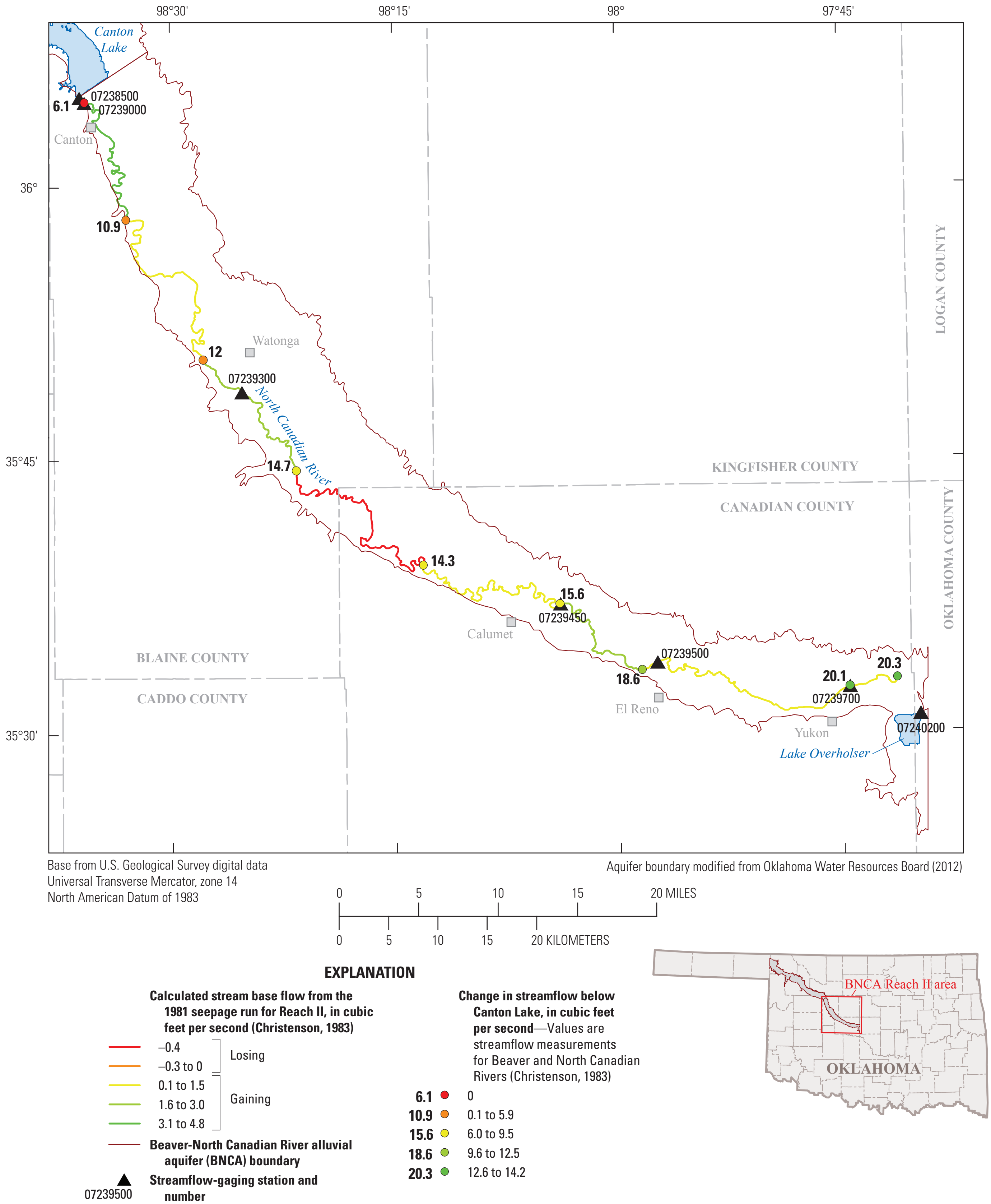


Figure 19. Streamflow measurements and calculated base flow from the 1981 seepage run for Reach II of the North Canadian River, from Christenson (1983).

The SWB recharge calculated for the Beaver-North Canadian River alluvial aquifer over the period of study was summed to produce an estimate for total recharge over the study period and for each year. Grids of recharge for each month of the model period were used for numerical groundwater-flow model inputs. A map of the spatially distributed mean annual recharge in inches calculated by the SWB code is shown in figure 20. Mean annual recharge was less in the northwestern part of the aquifer and is concentrated where runoff causes additional water to collect.

Recharge is highly temporally variable as precipitation changes season to season and year to year. Particularly in the drier western Reach I, recharge is sensitive to changes in precipitation because the soil profile must become fully saturated before excess infiltration can become recharge. A graph of the total annual recharge and mean annual recharge (218,800 acre-ft) to the Beaver-North Canadian River alluvial aquifer for the period of study as estimated by using the SWB code is shown in figure 21. There were no prolonged periods of hydrologic drought with unusually low precipitation and recharge during this time period, although 1980–81 were the last 2 years of the 1976–81 drought, and 2011 was the ninth driest year statewide in Oklahoma since 1925 (Shivers and Andrews, 2013). The lowest calculated recharge years were 2003 and 2006, which were 28 and 30 percent of the mean annual SWB recharge, respectively. The longest period of negative departure from the mean recharge was 1988–91, during which no year reached the study period mean recharge. The years with the greatest recharge were 1985, 2004, and 2007, in which 165, 160, and 195 percent of the mean annual SWB recharge were estimated to reach the water table, respectively. There were two periods with consistently positive departures from the mean recharge, 1985–87 and 1997–2001 (fig. 21).

A sensitivity analysis was performed by varying the two parameters that the analysis is most sensitive to, precipitation and root-zone depth (Westenbroek and others, 2010; Stanton and others, 2011), independently by 10 percent. Available water capacity was not used in the sensitivity analysis because it directly correlates with root-zone depth. A 10-percent increase in daily precipitation applied during the model run resulted in a 26-percent increase in total recharge, and a 10-percent decrease in precipitation caused a 23-percent decrease in recharge (fig. 22). Recharge was sensitive to root-zone depth as well. Recharge decreased 9 percent with a 10-percent increase in root-zone depth and increased 8 percent with a 10-percent decrease in root-zone depth.

The importance of the sensitivity analysis is that the precipitation and root-zone depth are generalized and interpolated across the model area. Precipitation measurements have measurement and the interpolation error. Root-zone depth is estimated for each land-use type and soil type, and although the land-use types and soils are not highly variable, with most of the area covered by grassland and sandy soil, local small-scale variation is not represented in 1,640-ft square grid cells.

The estimated mean annual recharge from the SWB model was 136,400 acre-ft in Reach I and 82,400 acre-ft in Reach II, for a total of 218,800 acre-ft. The total estimated recharge from 1980 to 2011 was approximately 4,350 thousand acre-ft for Reach I and 2,600 thousand acre-ft for Reach II. It should be noted that Reach I typically receives less precipitation than Reach II, and the mean annual recharge was 0.25 acre-feet per acre (acre-ft/acre) in Reach I and 0.34 acre-ft/acre in Reach II. The total recharge flow in Reach I was greater than in Reach II because the area of Reach I is substantially larger.

Local Recharge Estimation

Groundwater recharge from precipitation was estimated at two locations in Reach I by using the WTF method from Healy and Cook (2002). Concurrent readings of water levels from observation wells and precipitation from the Woodward and Seiling streamflow-gaging stations (fig. 1) were analyzed (U.S. Geological Survey, 2013c, d). Observation wells closest to streamflow-gaging stations were selected and continuous readings of groundwater head recorded. Observation wells at these sites included observation well OW-4 (USGS site number 362726099230401) near the Woodward streamflow-gaging station and observation well OW-5 (361145098560401) near the Seiling streamflow-gaging station (fig. 1). The two observation well locations are subsequently referred to as the “Woodward” and “Seiling” sites. Instruments in OW-4 and OW-5 recorded the groundwater level every 30 minutes for parts of 2012 and 2013, and the mean daily water level at both sites was compared with daily precipitation measured at respective streamflow-gaging stations.

The WTF method uses the change in the groundwater head related to a precipitation event in shallow, unconfined aquifers, multiplied by the Sy of the aquifer to calculate the amount of water from that precipitation event that became groundwater recharge. If the groundwater head was rising or dropping previous to the precipitation event, that trend was extrapolated below the groundwater-head peak to estimate the rise in groundwater head as a peak superimposed on the trend.

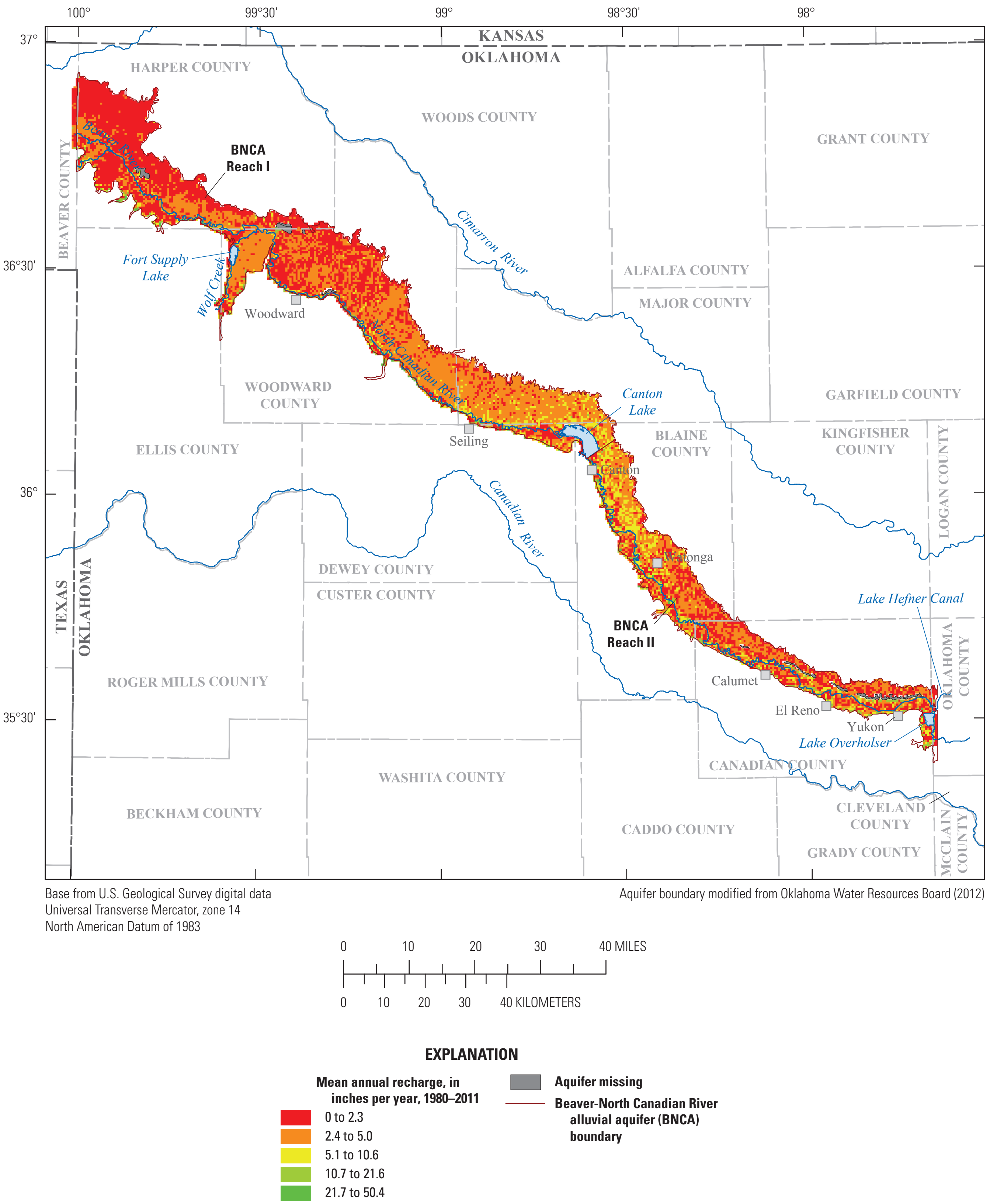


Figure 20. Mean annual groundwater recharge from 1980 to 2011 calculated by using the soil-water-balance code of Westenbroek and others (2010) for the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

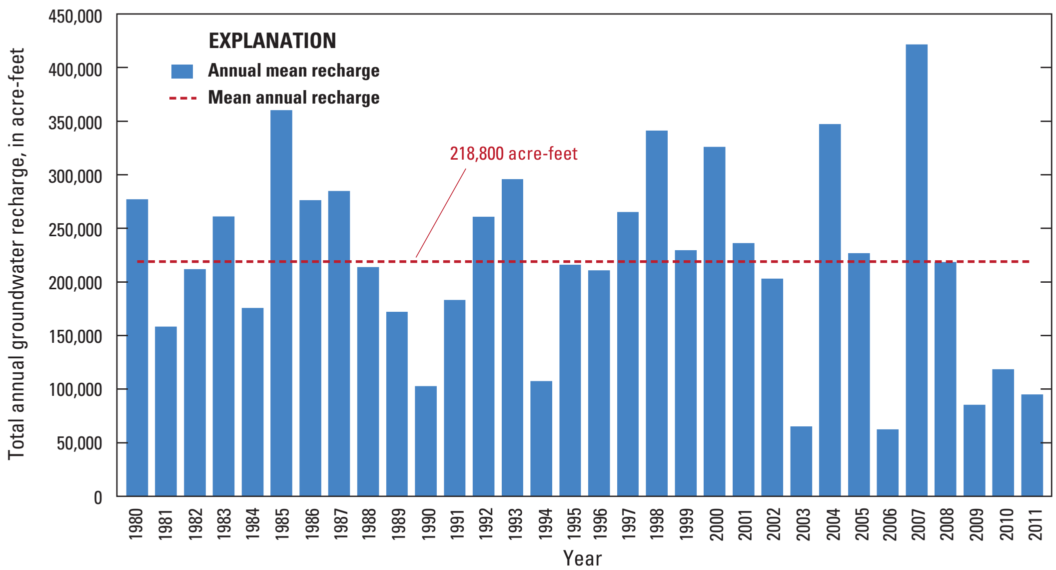


Figure 21. Total annual groundwater recharge 1980–2011 calculated by using the soil-water-balance model for the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

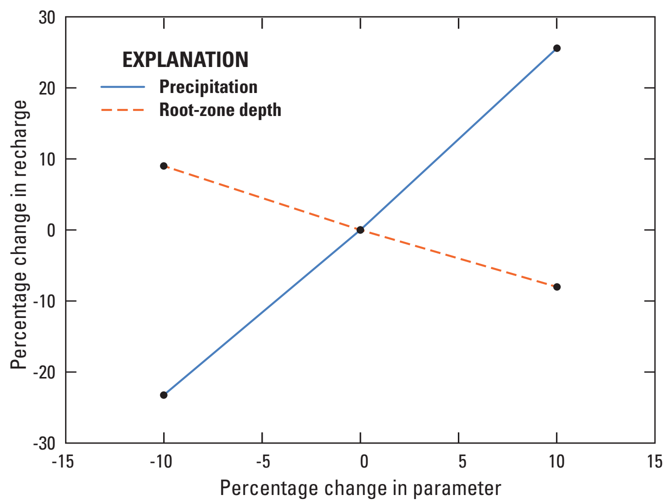


Figure 22. Sensitivity of recharge calculated by the soil-water-balance model (Westenbroek and others, 2010) for the Beaver-North Canadian alluvial aquifer to changes in precipitation and root-zone depth.

The WTF method is approximate and relies on infiltration of precipitation reaching the water table within several days, and the water level is not affected by other processes such as plant uptake, pumping wells, surface runoff, or infiltration from surface water. After precipitation takes place, infiltration that becomes groundwater causes the water level in a well to rise. The water level then drops as groundwater is redistributed or is removed from the aquifer by other processes. Thus, the aquifer must be unconfined, the water table must be within a few feet of the land surface, and the topsoil and aquifer material must be permeable enough so that the infiltration flow rate is greater than the rate at which the groundwater dissipates or flows to groundwater sinks for this analysis. Because the records of water-level observations did not include a full calendar year, the WTF analyses included the water year 2013 (October 2012 through September 2013). Recharge estimated by using the WTF method could not be directly compared to the SWB model because the SWB model was only run through 2011, but the mean percentage of precipitation that was estimated to become recharge in the SWB model was compared to percentages estimated for the Woodward and Seiling sites.

Woodward Site

The Woodward site is located at observation well OW-4 (fig. 1), which was 0.7 mi east of the North Canadian River and just over 6 mi upstream from the Woodward streamflow-gaging station. The period of detailed water-level records for OW-4 was from June 26, 2012, through December 8, 2013. The altitude of the land surface at OW-4 is 1,874.87 ft as measured with the Global Positioning System (GPS). Land use at the Woodward site in 2006 was classified as grassland (Fry and others, 2011), and the site is located on the valley bottom with little slope. During the period of data collection, the water table was between 6 and 7 ft below land surface and 104 of the 527 days had measurable precipitation totaling 17.4 in.

The Sy of the aquifer at the Woodward site had not been measured but was estimated on the basis of the general aquifer characteristics. Three wells with borehole logs used in the estimation of Kh in the “Hydrogeological Framework” section are located within 1 mi of observation well OW-4. All three borehole logs listed only sand (assumed to refer to medium sand) and fine sand in the upper 20 ft of the aquifer. The Sy of fine to medium sand ranges from 0.15 to 0.20 (Fetter, 1994). The mean of the two Sy values (0.18) was used for the Beaver-North Canadian alluvial aquifer at the Woodward site.

A water-level time series graph for well OW-4 (fig. 23) shows a decline of approximately 1.39 ft from June through September 2012, most likely due to plant uptake and little precipitation. There were 49 precipitation events, many lasting more than 1 day, during the period of data collection, and all were used to calculate recharge; the five largest peaks are described.

The first water-level peak associated with precipitation was a 0.04-ft (0.5 in.) rise on October 16, 2012, most likely related to 0.48 in. of precipitation on September 27 (fig. 23). Assuming an Sy of 0.18, the first precipitation event resulted in 0.1 in. of recharge. Water level then rose gradually 0.29 ft (3.5 in.) from the end of October through most of February 2013. As shown on figure 23, from October 13 through December 30 the water level rose 0.12 ft (1.5 in.) with only 0.22 in. of precipitation. During this period, there may have been more water moving into the area from another source because the water-level rise was approximately linear and indicates recharge of 0.26 in., which was more than the precipitation during that time. It was expected that plant uptake was minimal during October through December, which likely contributed to the water-level rise.

A sustained precipitation event from February 20 to March 9, 2013, with a total of 4.47 in. of precipitation, caused the water level to rise 1.39 ft (16.7 in.) above the projected water-level trend on March 4, 2013 (fig. 23); total estimated recharge was 3.0 in. The water level remained high because of several minor precipitation events until June 2013 when the water level declined rapidly. On June 11, 2013, the declining water-level trend was interrupted by a peak that rose 0.10 ft (1.2 in.) above the declining trend, related to 0.92 in. of precipitation on June 4; recharge was 0.2 in (fig. 23).

The water level continued to decline until a small peak of 0.08 ft (1.0 in.) related to 0.53 in. of precipitation on July 17, 2013, (0.2 in. of recharge) and a 0.53 ft (6.3 in.) peak on August 8, 2013, for 1.1 in. of recharge. The August 8 peak was interpreted to be attributed to several precipitation events with a total of 2.36 in. that ended on July 19, 2013. Water levels continued to decline through October and then began to rise similar to November of 2012.

The total precipitation recorded was 17.44 in., and 14.18 in. occurred during the 2013 water year—October 2012–September 2013 (fig. 23). With the WTF method using all rainfall events, approximately 6.3 in. of recharge (44 percent of precipitation) was calculated. For the SWB model, during the period 1980–2011 the mean annual precipitation at the location of OW-4 was 26.2 in., and the mean annual recharge was 2.4 in., which was 9.2 percent of precipitation and much lower than the percentage calculated by the WTF method. The difference between these estimates may be related to discretization of soil and land-use parameters for the SWB model. Recharge in SWB cells adjacent to the cell containing OW-4 ranged from 0.12 to 5.2 in. of recharge per year, which was 1–20 percent of precipitation.

Seiling Site

Observation well OW-5 (fig. 1) at the Seiling site was approximately 1 mi from the Seiling streamflow-gaging station. The period of detailed water-level records for OW-5 was from June 22, 2012, through December 3, 2013. The altitude of the land surface at OW-5 was measured with the GPS at 1,696.1 ft, and the altitude of the streamflow-gaging station at Seiling is 1,675.5 ft (U.S. Geological Survey, 2013d). The groundwater head at the observation well was

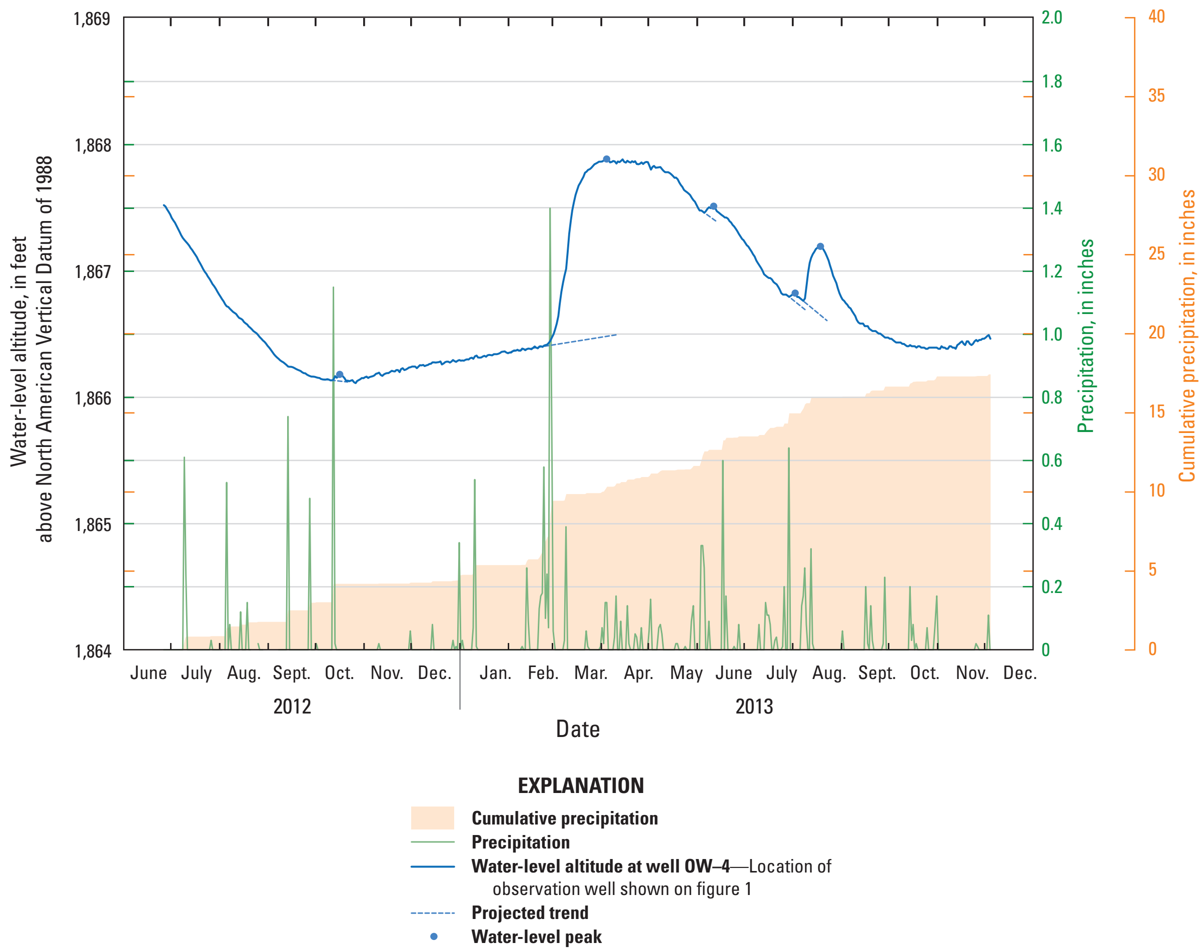


Figure 23. Water-level fluctuation at observation well OW-4 and adjusted stream stage and precipitation at the North Canadian River at Woodward, Oklahoma (07237500), streamflow-gaging station.

approximately 9 ft higher than the stream stage, suggesting that the stream reach was generally gaining, as determined in both seepage runs reported in the "Stream Base Flow" section of this report (figs. 16 and 18). Land use at the Seiling site in 2006 was classified as a mix of grassland and cultivated cropland (Fry and others, 2011).

The Sy has not been measured and no borehole lithologic log was available for OW-5 or other wells near the Seiling site, so the published Sy for the range of textures found in the Beaver-North Canadian River alluvial aquifer (silty sand to fine gravel) was used to estimate Sy at the Seiling site. The Sy of silty sand is approximately 0.12, and a sand and gravel mixture has an Sy of approximately 0.22 (Fetter, 1994). A mean value of the two textures (0.17) was used for the aquifer at the Seiling site.

The depth to water in OW-5 fluctuated between approximately 6 and 8 ft below land surface during the period of measurement (1,687.8–1,689.5 ft altitude) and was sensitive to most precipitation events (fig. 24). All precipitation events were used in the WTF analysis, and several of the most substantial precipitation events are described.

As at the Woodward site, the water level dropped from June through September 2012, most likely related to plant uptake and minimal precipitation (fig. 24). The water level then reached a minimum in November and rose gradually with very little precipitation into February 2013. Precipitation of 4.21 in. that ended on February 26 caused a 0.86 ft (10.3 in.) rise in water level that peaked on March 21 (fig. 24) for approximately 1.8 in. of recharge. Seven more peaks were included in the analysis during a wet period that lasted from March through July of 2013, after which the water level dropped rapidly. Precipitation of 1.35 in. on July 15 caused a 0.21-ft (2.5 in.) water-level peak on August 3 above the declining trend (fig. 24), for approximately 0.4 in. of recharge. The water level declined until two substantial precipitation events on July 26 and 29, 2013, combined for 5.69 in. and caused the water level to peak 0.58 ft (6.9 in.) above the declining trend on August 15 for approximately 1.2 in. of recharge.

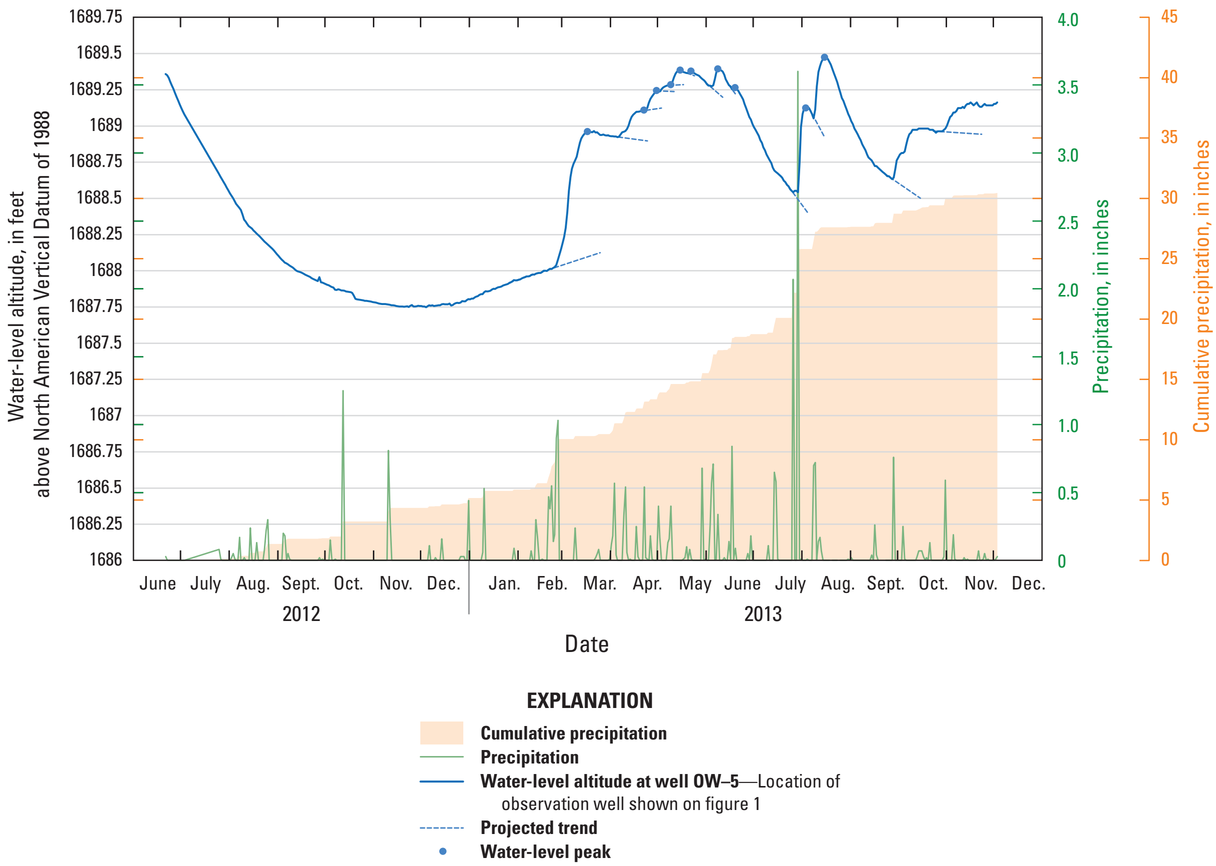


Figure 24. Water-level fluctuation at observation well OW-5 and stream stage and precipitation at the North Canadian River near Seiling, Oklahoma (07238000), streamflow-gaging station.

Total recorded precipitation was 30.45 in., and 26.84 in. was during the 2013 water year at the Seiling site (fig. 24). The WTF method estimated a total of 6.9 in. of recharge related to this precipitation, which was 25.9 percent of precipitation. The SWB model calculated a mean annual precipitation at OW-5 of 28.75 in. per year and recharge of 6.6 in. per year. The SWB model calculated that 23.0 percent of precipitation became recharge, which was very similar to the percentage from the WTF method.

Water Use

The OWRB-permitted water use described in the “Water Use and Management” section of this report was simplified for the conceptual flow model to the largest water-use categories and surface-water diversions from the Beaver and North Canadian Rivers. Groundwater use in the numerical groundwater-flow model was limited to irrigation and public water-supply wells pumping from the Beaver-North Canadian River alluvial aquifer. Irrigation and public water supply made up almost 90 percent of the long-term water use from both reaches (fig. 4).

There were 58 temporary and permanent surface-water diversions used in the model, with a total of approximately 1,240 acre-ft/yr; 70 acre-ft/yr from Reach I and 1,170 acre-ft/yr from Reach II. Because surface-water diversions were not from the Beaver-North Canadian River alluvial aquifer, these flow rates are not included in the conceptual flow model budget.

The mean annual volume of water pumped for irrigation and public water supply during the study period of 1980–2011 was 14,500 acre-ft/yr in Reach I and 10,100 acre-ft/yr in Reach II, for a total of 24,600 acre-ft/yr. These volumes are greater than volumes in table 2 because the conceptual flow model includes 1980.

Evapotranspiration and Springs

The only published report that addressed ET on the Beaver-North Canadian River alluvial aquifer was Mogg and others (1960), which included estimated plant ET for phreatic plants present in Canadian County, Okla., at the southeastern end of Reach II. Mogg and others (1960) estimated that cottonwoods and willows consumed on average 64.5 in. of water per year and that the part of the Beaver-North Canadian River alluvial aquifer in Canadian County was 16.25 mi^2. The mean annual ET for the Beaver-North Canadian River alluvial aquifer in Canadian County was approximately 56,000 acre-ft/yr. As shown in figure 5, the mean annual precipitation in the eastern part of the Beaver-North Canadian River alluvial aquifer was approximately 35 in. Thus, adjusted for precipitation, the mean annual ET rate from groundwater where cottonwood and willows are present in Canadian County was approximately 30 in. per year. In the 1992 land-use classification, there were approximately 17,000 acres of deciduous forest, or 2 percent of the area of the Beaver-North Canadian River alluvial aquifer.

The SWB model calculated ET from plant consumptive use in the soil-water system but did not provide an estimate for the uptake from groundwater. Because estimation of groundwater ET flow was beyond the scope of this study, the ET flow for the conceptual flow model was not estimated directly for the aquifer water budget. Instead, ET was assumed to be equal to the balance of estimated groundwater recharge that was not discharged to streams or pumped by wells in Reach I; ET was not available for Reach II because base flow to streams was not calculated. The ET process was simulated in the numerical flow model, and an estimate for the flow is provided in the "Numerical Groundwater-Flow Model" section of this report.

There are numerous springs along the western boundary of the Beaver-North Canadian River alluvial aquifer where it is eroded, and the groundwater divide is inside the aquifer boundary (fig. 13). The flow from these areas has not been measured or estimated, and such analysis was beyond the scope of this study. In comparison to other budget categories, the water discharged from the Beaver-North Canadian River alluvial aquifer to springs appeared to be small because there were no apparent spring-fed perennial streams emanating directly from the boundary of the Beaver-North Canadian River alluvial aquifer, and the main evidence of springs was increased vegetation in draws observed in summer aerial orthophotographs (U.S. Department of Agriculture, 2013). No field observations or measurements of spring flow were made.

Continuously flowing springs are present at Boiling Springs and Roman Nose State Parks (fig. 11). The springs at Boiling Springs State Park are located where the terrace deposit thins and is missing toward the North Canadian River, exposing the Doe Creek Lentil of the Marlow Formation, which discharges groundwater through dissolution channels in the sandy limestone (Suneson, 1998). Groundwater in the Doe Creek Lentil originates in the terrace alluvium to the north and percolates into the limestone. Boiling Springs flow was estimated to be about 0.1 ft^3/s in 1998, although flow may have decreased during the years preceeding 1998 because of local irrigation groundwater use (Suneson, 1998). Discharge from the springs is collected in a small reservoir used for recreation, which releases streamflow to a small drainage on the alluvium in the Beaver and North Canadian River flood plains. Most if not all of this water percolates into the alluvium before reaching the river.

Streamflow from springs at Roman Nose State Park emanates from dissolution features in salt and gypsum of the Blaine Formation beneath the northern part of Reach II, which is separated from the Beaver-North Canadian River alluvial aquifer in that area by 100 ft of the overlying Dog Creek Shale (Fay, 1959). There are three springs in the State park that have a combined discharge of 1.5–1.8 ft^3/s (Fay, 1959). It is not known how thick the Dog Creek Shale is below the Beaver-North Canadian River alluvial aquifer in all areas, but it is likely that the discharge from springs in Roman Nose State Park originates in the aquifer where the Dog Creek Shale is thin or absent, eroded by the North Canadian Rivers. Discharge from the springs at Boiling Springs and Roman Nose State Parks was estimated to be no more than 1,500 acre-ft/yr, and some of the discharge at Boiling Springs returns to the aquifer.

Flow to springs in the Beaver-North Canadian River alluvial aquifer was not estimated as part of the conceptual flow model but was included with ET as the balance of recharge not discharged to streams and lakes or pumped by wells in Reach I. The amount of ET in Reach II as a balance of flow was not available because the base flow to streams was not calculated.

Conceptual Flow Model Water Budget

Estimates of the total flow into and out of the Beaver-North Canadian River alluvial aquifer by reach and category are listed in table 9. This water budget is approximate and generalized, and a more detailed budget with annual flow is calculated by the numerical groundwater-flow model in the "Numerical Groundwater-Flow Model" section of this report. The only inflow to the Beaver-North Canadian River alluvial aquifer was determined to be recharge, and the two largest discharges from the aquifer were determined to be base flow to streams and lakes and ET to plants. In many aquifers, recharge is assumed to be equal to stream base flow, but in this case recharge estimated by using the SWB model was approximately 136,400 acre-ft/yr in Reach I, and flow to streams and lakes was estimated to be only 69,000 acre-ft/yr; only 14,000 acre-ft/yr is estimated to be discharged to pumping wells (fig. 24; table 9). It was assumed that in Reach I inflow was equal to outflow, and ET and discharge to springs were responsible for the balance of groundwater discharge, which was approximately 53,400 acre-ft/yr (table 9). It is also assumed that the majority of water is lost to ET and a very small amount of water is lost to springs.

In Reach II, the SWB model recharge was estimated at 82,400 acre-ft/yr, and discharge to pumping wells was 12,000 acre-ft/yr (table 9). Discharge to stream base flow and the balance that may represent ET and spring discharge were not calculated.

Numerical Groundwater-Flow Model

The primary objective of the numerical groundwater-flow model was to provide a model of the flow system to run transient simulations for water management and forecast the effects of water use and drought on available water. The model objective required a separate transient numerical model for Reach I and Reach II, hydrological boundaries, and flows to be constructed, calibrated, and run with various predictive scenarios. Separate models were constructed because the two reaches require independent calculations of EPS and separate water budgets.

Finite-difference numerical groundwater-flow models were constructed by using MODFLOW-2005 (Harbaugh, 2005) for each of the two reaches of the Beaver-North Canadian River alluvial aquifer. Several modular packages were used to simulate flow and boundary conditions with the Newton formulation solver for MODFLOW-2005 (Niswonger and others, 2011). Steady-state and transient models were constructed for each reach, and the models used the same grid cell dimensions as those used for the SWB recharge analysis.

Assumptions

The use of the MODFLOW finite-difference flow model to simulate groundwater flow requires several assumptions about the system being modeled. Assumptions pertinent to this study include that the groundwater in the Beaver-North Canadian River alluvial aquifer flows according to Darcian flow principles, is incompressible, and can be simulated by using 1,640-ft by 1,640-ft cells and two layers of variable thickness. Many parameters such as Kh and Sy are known to change on a spatial scale smaller than 1,640 ft. The average value of measured or interpolated parameters in cells was assumed to adequately model the average flow conditions in the Beaver-North Canadian River alluvial aquifer. Also, though the parameters change on a local scale, they are not sampled on the scale of their spatial variance. The hydrogeologic framework is assumed to be a suitable basis to capture the textures of the Beaver-North Canadian River alluvial aquifer and represent the distribution of Kh of the aquifer for the groundwater-flow system. Model layers represent hydrogeological units that have spatially consistent hydraulic properties. It is assumed that the grid used and the aquifer samples were adequate to simulate varying hydraulic parameters and that the groundwater-flow system was at an approximate equilibrium during the initial model period of 1980. Because hydrologic data were not available for a period before groundwater resources were developed, a period when recharge and reported total groundwater pumping were similar was identified so that the flow system was not in a state of great change in flow. The year 1980 had similar stresses in comparison with 1979 and 1981 and is assumed to be sufficiently stable to avoid having to calibrate a model to a system that is undergoing change on a time scale smaller than the model time steps.

Model Extents and Discretization

The numerical groundwater-flow models for Reach I and Reach II took advantage of the most current packages and processes available for MODFLOW at the time this study was conducted to simulate the major hydrological processes operating on the Beaver-North Canadian River alluvial aquifer. Discretization of the aquifer was performed to best simulate these processes and capture the spatial variability in model parameters and flows. Starting values for hydraulic properties Sy and Kh were taken from the estimates described in the “Hydrogeological Framework” section of this report and were adjusted during calibration.

Two separate models were constructed for the two reaches of the Beaver-North Canadian River alluvial aquifer. The boundary between Reach I and Reach II as defined by the OWRB is at the Canton Dam (fig. 1). To avoid having the model active area boundary near several pumping wells (fig. 2), which could cause the boundary to affect flow to wells, the transition from Reach I to Reach II was moved just south of Canton Lake, near the town of Canton, along a line approximately perpendicular to the general trend of the Beaver-North Canadian River alluvial aquifer (fig. 25). Groundwater and surface water were allowed to leave the Reach I model and enter the Reach II model through boundary cells as described in the “Boundary Conditions” section of this report. The two models were not linked and were calibrated independently.

Because the Beaver-North Canadian River alluvial aquifer is thin and unconfined, the Newton formulation solver for MODFLOW (MOFLOW-NWT v. 1.0.8; Niswonger and others, 2011) was used. This solver is built on the MODFLOW-2005 version (Harbaugh, 2005) and allows cells to be rewetted if they become dry, which is likely to occur in a transient simulation of groundwater in a thin alluvial aquifer with varying climatic conditions.

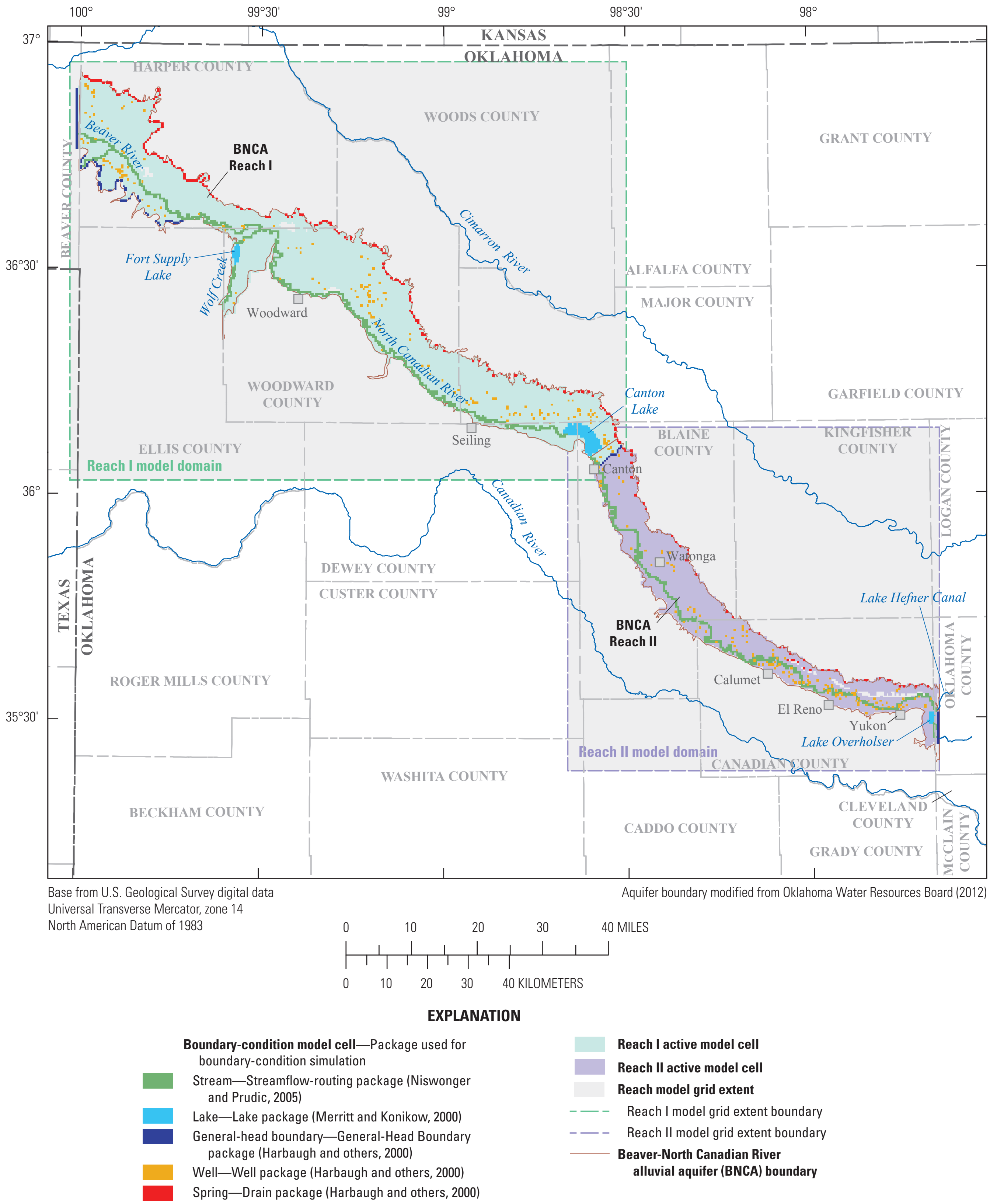


Figure 25. Reach I and Reach II numerical groundwater-flow model layouts, active areas, and boundary condition cells excluding wells, Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

Discretization is the process of converting continuous variables in space or time to discrete partitions, which results in some measure of generalization and uncertainty. The aquifer top and bottom and hydraulic properties are continuous variables that must be represented in a finite-difference grid and layer structure for the MODFLOW groundwater-flow model software. Thus, the size of grid cells and their thicknesses must be chosen so that the spatial variations in parameters, such as aquifer thickness, Kh, and Sy and interactions between boundary conditions such as streams and wells, are adequately captured without having more than one boundary condition in a single cell. Cell dimensions also affect the computational requirements to solve the groundwater-flow equation between cells for each stress period. Thus, cells were chosen to be small enough to characterize the flow system and variability in aquifer properties but not so small that solving the model with available computers would be unmanageable. The cell size adequate to simulate the Beaver-North Canadian River alluvial aquifer properties and flow system in both models was determined to be 1,640 ft on all sides. Because the Beaver-North Canadian River alluvial aquifer consists of a single hydrogeological unit, each cell used one layer for the Beaver-North Canadian River alluvial aquifer. Where the aquifer was missing, cells were made inactive in layer 1 and were considered no-flow boundaries within the active grid. Starting Kh and Sy parameters were estimated in the “Hydrogeological Framework” section and were assigned to the cells. In some areas, the cell size was too large to discretize the thin aquifer on steep slopes, and the aquifer thickness was increased slightly, which caused some uncertainty.

Underlying bedrock was included as an underlying layer (layer 2) to simulate the exchange of water between bedrock and the Beaver-North Canadian River alluvial aquifer. Layer 2 was not a single hydrogeological unit; each cell was assigned the general hydraulic properties of the bedrock lithology. All calibration, budget, and flow analyses were performed on layer 1.

For the steady-state models, one stress period and time step that used annual mean flow values was simulated for 1980. The MODFLOW stress period was 366 days long to calculate model budget flows. Because the Beaver-North Canadian River alluvial aquifer is directly connected to surface water and precipitation, plant demands, and groundwater pumping—all of which have strong seasonal fluctuations—stress periods in the transient models were set at 1 month each. Four time steps were solved in each stress period to capture changes in head and stress-period flows caused by monthly changes in stress. Both model simulations started with a steady-state stress period for 1980, which was the last year of analyses reported in Davis and Christenson (1981) and Christenson (1983). From 1981 through 2011, the models used transient monthly stress periods.

The initial potentiometric surface is the groundwater head in the aquifer when the simulation began. The initial head was modified from the maps produced by Davis and Christenson (1981) and Christenson (1983) and all available water-level measurements from 1980. Head observations used in the model calibration were taken from wells screened only in the Beaver-North Canadian River alluvial aquifer and measured during the model period, 1980–2011 (U.S. Geological Survey, 2013c). No head observations from the bedrock units were used, and no calibration of bedrock properties was performed. Head observations were not used if the well was in the same cell as a boundary control such as a stream or river or if a head observation was within two cells of a groundwater-pumping well.

Boundary Conditions

Boundaries defined in the “Conceptual Flow Model” section of this report were incorporated into the model by assigning boundary conditions to the appropriate cells (such as wells, streams, and lakes) or by assigning flows to areas (such as recharge or ET). Cells with boundary conditions are shown on figure 25. Mean daily recharge from the SWB model was included in the models by using the Recharge package (Harbaugh and others, 2000). A recharge flow rate for each stress period was applied to layer 1. Where the Beaver-North Canadian River alluvial aquifer is missing and bedrock is exposed, no recharge was assumed to occur. Output arrays from the SWB model were used as model input for the steady-state and transient models. The steady-state models used an array of the mean daily recharge for 1980, and the mean daily recharge for each month in the transient models was used for each transient stress period.

The ET from groundwater was simulated by using the Evapotranspiration package (Harbaugh and others, 2000). This package sets the extinction depth or the vegetation root-zone depth at each cell. If the groundwater head rises above the extinction depth, the Evapotranspiration package calculates the flow because of plant consumptive use and limits ET to the supplied maximum ET flow. The extinction depth was set at the root-zone depth used by the SWB model. The maximum ET flow rate was equivalent to the SWB model potential ET calculated for each stress period. The SWB model assumed that the vegetation could not access groundwater and limited actual ET by the available soil moisture, but if the water table was as shallow as the root zone, the actual ET could equal the potential ET. Because the SWB model already reduced recharge by the actual ET, the maximum ET in the Evapotranspiration package was set equal to the difference between the SWB model potential and actual ET. Both the maximum ET and extinction depth were parameters that were adjusted during model calibration.

Streams were simulated in the models by using the Streamflow-Routing package version 2 (SFR2) (Niswonger and Prudic, 2005), and lakes were simulated by using the Lake package (Merritt and Konikow, 2000). The SFR2 and Lake package work together, routing water between lakes and streams and simulating flow between surface water and groundwater. Both packages track the surface-water stage by stress period and calculate interactions with the aquifer on the basis of the groundwater head in the aquifer relative to the stream or lake stage. Flow between surface water and groundwater is controlled by the hydraulic conductivities of the aquifer and stream or lakebed. The SFR2 allows streamflow to be input to reaches to simulate inflow from outside the model or removed from reaches to simulate surface-water diversions. Because most of the channels of the Beaver and North Canadian Rivers are sandy, initial streambed hydraulic conductivity for all stream segments was set at 13 ft/d, the approximate hydraulic conductivity of fine sand, and lakebed hydraulic conductivity was set equal to that of clay, 0.7 ft/d (Fetter, 1994). Streambed and lakebed hydraulic conductivity were adjusted during model calibration.

Streamflow measurements from USGS streamflow-gaging stations (U.S. Geological Survey, 2013d) and releases from lakes in the study area (U.S. Army Corps of Engineers, 2013) were used to assign the flow into and out of lakes and streams. Streamflow from the Beaver River at Beaver, Okla. (07234000), streamflow-gaging station was routed into the upstream segment of the Beaver River in Reach I. Streamflow entering the model in Wolf Creek was taken from the Wolf Creek near Gage, Okla. (07235600), streamflow-gaging station (fig. 1) and the Wolf Creek at Lipscomb, Texas (07235000), streamflow-gaging station. The Lipscomb streamflow-gaging station was located approximately 30 mi upstream to the west from the Gage streamflow-gaging station and is shown on the figure 1 inset map; streamflow data from this station were used to fill in gaps in the streamflow record from Wolf Creek near Gage. Lake releases from Fort Supply Lake and Canton Lake (U.S. Army Corps of Engineers, 2013) were routed into the nearest downstream SFR2 stream segment. Streamflow released from Canton Lake was routed into the short stream segment below the lake in the Reach I model and into the first stream segment in the Reach II model (fig. 25).

Long-term and temporary Beaver and North Canadian Rivers diversion volumes (Oklahoma Water Resources Board, 2014) were simulated as being from the SFR2 stream segment nearest to the location of the permitted diversion during the stress periods that the permit was active. Because the monthly diversion rates for temporary diversions were not recorded, the total permitted diversion volume was set at a constant rate over the 3-month period that each permit covered.

Lateral groundwater flow into or out of the models from the Ogallala Formation or upstream or downstream alluvium was simulated by using the General-Head Boundary (GHB) package (Harbaugh and others, 2000) (fig. 25). A GHB occupies a single model cell with specified head for each stress period. Groundwater can enter or leave the model through GHBs regulated by the relative head between the aquifer and GHB and the specified boundary conductance.

The groundwater head in each GHB was set at the estimated head from the initial potentiometric surface in the Beaver-North Canadian River alluvial aquifer at the start of the simulation, and the hydraulic properties were set at the estimated hydraulic properties of the Ogallala Formation (3.5 ft/d; table 7). Flow into the Beaver-North Canadian River alluvial aquifer along the upstream extent of Reach I, across the boundary between the two reaches, and out of the model at the downstream extent of Reach II were all simulated by using GHB cells with the estimated starting head and Kh of the aquifer. Conductivity and groundwater head in GHB cells were adjusted during model calibration.

Groundwater pumped from the Beaver-North Canadian River alluvial aquifer was simulated by using the Well package (Harbaugh and others, 2000). Every model cell with a well was assigned a flow for each stress period, and if multiple wells were located in one cell, pumping was set at the sum of discharge for all wells. The annual withdrawal rates from groundwater-pumping wells used in the “Conceptual Flow Model” section were input into the steady-state and transient periods by using the model cell in which each permitted well fell on the basis of the location provided by the OWRB. If more than one well shared the permitted pumping for a single permit, the reported flow for that permit was divided equally among all wells. Withdrawal was assigned to the stress periods in which the permit was active.

The steady-state models used the 1980 pumping rate for each well, but the transient models used monthly stress periods so the withdrawal rates had to be distributed across months. The Oklahoma Water Resources Board (2012) includes estimates for the monthly percentage of the annual water discharge that different categories of wells pump by county. This percentage was used for each county in the study area to approximate the monthly fraction of annual pumping rates for transient stress periods. There were 301 irrigation and 57 public water-supply well boundary conditions that were tied to groundwater permits active during the period of study (fig. 2). Well boundary conditions consolidated some wells that were in the same model cell.

Springs that discharge water along the eastern margin of the Beaver-North Canadian River alluvial aquifer were simulated with the Drain package (Harbaugh and others, 2000). The Drain package functions independently of other boundaries and only allows groundwater to leave the model. Because no springs have been mapped by previous studies and no flow has been measured along the eastern margin, drains were placed where a possible spring was located based on where thick vegetation visible on aerial orthophotographs indicated that a seep or small spring may exist. Discharge at drains was expected to be small relative to other boundaries. The altitude of each drain was set at the approximate land surface altitude derived from DEMs (U.S. Geological Survey, 2013a). Groundwater flow through drains is controlled by aquifer head relative to the altitude of a spring and the conductance of the drain. The initial conductance was set equal to the aquifer hydraulic properties at each drain location, and the drain altitude and conductance were adjusted to improve model calibration and limit spring flow to 0.1 ft^3/s or less. Not all drains had flow because the groundwater head was not always higher than the drain altitude.

Model Calibration Methods

The steady-state and transient models for each reach were calibrated to groundwater-head observations. Because the primary model objective was to estimate EPS, the saturated thickness and changes in head in response to pumping were the main characteristics of interest; stream base-flow readings were not included as model observations.

To determine the accuracy and confidence in the model simulations, the steady-state and transient head fields were observed at various points in time and compared to observed head values retrieved from the National Water Information System (U.S. Geological Survey, 2013a) by using the Head-Observation package (Hill and others, 2000). Head residuals were calculated by the Head-Observation package by subtracting the simulated head from the observed head. Groundwater-head measurements were assumed to have 5–10 percent error combined in the land-surface altitude measurement and the measurement of the depth to groundwater.

Model parameters including recharge, Kh, and Sy for layer 1, maximum ET, and altitude and conductance of selected streams, lakes, GHBs, and drains were adjusted within reasonable limits to reduce residuals and increase the confidence of the models. Because there were no observations or boundary controls in layer 2 (bedrock) and head observations in layer 1 were not sensitive to parameter changes in layer 2, parameters in layer 2 were not adjusted during model calibration.

Recharge was adjusted with multiplier arrays, and other parameters were adjusted directly. For both models, one recharge multiplier array was used for the steady-state stress period, and another was used for all transient stress periods. Parameters were adjusted until the residual improvement was only marginal and it was apparent that the residuals could not be improved further without using unrealistic parameter values.

For both reaches, a separate steady-state model was calibrated for conditions in 1980 by changing Kh, ET, and boundary-control parameters and scaling recharge on a cell-by-cell basis within reasonable parameter limits to minimize head residuals. The results of this calibration were used in the transient models for the starting potentiometric surface and Kh. The transient models were calibrated by adjusting the recharge by scaling the SWB recharge arrays with one multiplier for all stress periods. The Kh and Sy were adjusted on a cell-by-cell basis in the transient model in areas where there were head targets from the transient period but no steady-state period targets. The ET extinction depth and maximum ET rate were adjusted on a cell-by-cell basis in limited areas where groundwater was shallow. The GHB conductance and groundwater head were adjusted to improve calibration in local areas directly affected by GHBs.

Reach I Calibration Results

The Reach I model calibration used 47 observation wells, with a total of 515 groundwater-head observations during the model period; 28 observations were used during the steady-state period, and 487 were used during the transient period. Groundwater-head observations were from both the terrace and alluvial deposits. Reach I model calibration resulted in a good correlation between measured and simulated heads for both the steady-state and transient stress periods, with a coefficient of determination (R^2) of 0.9996 (fig. 26). Of the residuals from the steady-state and transient stress periods,

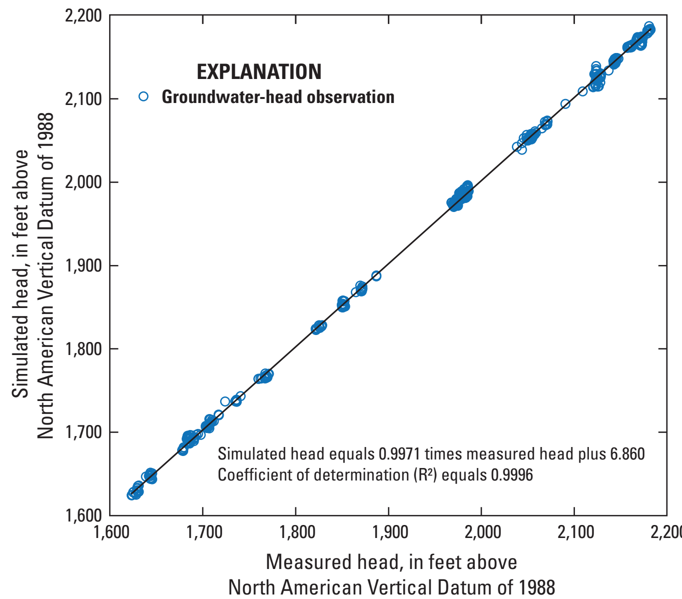


Figure 26. Observed groundwater heads plotted with simulated heads combined for the steady-state and transient models for Reach I of the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

83 percent were between -5 and 5 ft (fig. 27). Residual distribution skewed to the positive, indicating that the simulated heads were more commonly lower than observed values. The final simulated potentiometric surface and locations of observation wells symbolized by mean residuals for observation wells with multiple readings for each well during the transient and steady-state periods are shown in figure 28.

Residual statistics show that the Reach I numerical groundwater-flow model provides a reasonable simulation of the aquifer head observations. Steady-state period residuals ranged from -5.61 to 3.46 ft with a mean of -0.64 ft and from -12.14 to 15.01 ft with a mean of 0.87 ft for the transient period (table 10). The mean for all residuals was 0.79 ft. The mean of the absolute value of residuals and the root-mean-square error (RMSE), which is the square root of the mean of squared model residuals, provide a measure of error without negative and positive residuals canceling each other out. The mean of residual absolute values was 1.67 ft for the steady state period, 2.82 ft for the transient period, and 2.76 ft for all residuals. The RMSE was 2.31 ft for the steady-state period, 3.93 ft for the transient period, and 3.86 for all observations. The RMSE as a percentage of the total head relief in the model, or the difference between highest head and lowest head in the model (731 ft from fig. 28), provides the error in the context of the model head variability. The RMSE as a percentage of head relief was 0.3 percent for the steady-state period and 0.5 percent for the transient period and all observations.

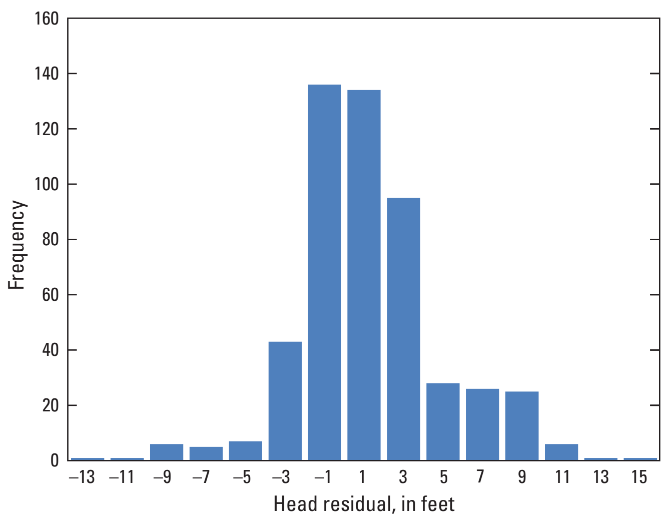


Figure 27. Head residual values combined for the steady-state and transient models for Reach I, Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

The final calibrated Reach I numerical groundwater-flow model provides estimates of the model groundwater heads, input parameters, and stream base flow in the groundwater system. Reach I Kh ranged from 6 to 279 ft/d, with a mean of 70 ft/d (table 11), and is shown in figure 15. The simulated head at the end of the transient model period—December of 2011—was compared to the base of the aquifer to calculate the saturated thickness. Reach I mean saturated thickness was 36 ft, and the maximum aquifer thickness was 308 ft (table 11).

Table 12 lists the Reach I model mean annual flow budget for recharge, lateral groundwater flow, flow into and out of storage, ET, base flow to lakes and streams, groundwater pumping, and flow to springs; figure 29 shows the relative mean annual flows for recharge, combined flow for ET and springs, combined base flow to streams and lakes, and groundwater pumping. Calibrated Reach I recharge was slightly higher than the estimated SWB-model recharge for the conceptual flow model in table 9. Estimated base flow for the conceptual flow model in Reach I was much higher than in the numerical groundwater-flow model, possibly because of the large volume of ET calculated by the model (fig. 29; table 9). In table 12 the sum of the inflow categories does not match the sum of the outflow categories exactly because of round-off errors after converting flow from model units of cubic meters to acre-feet.

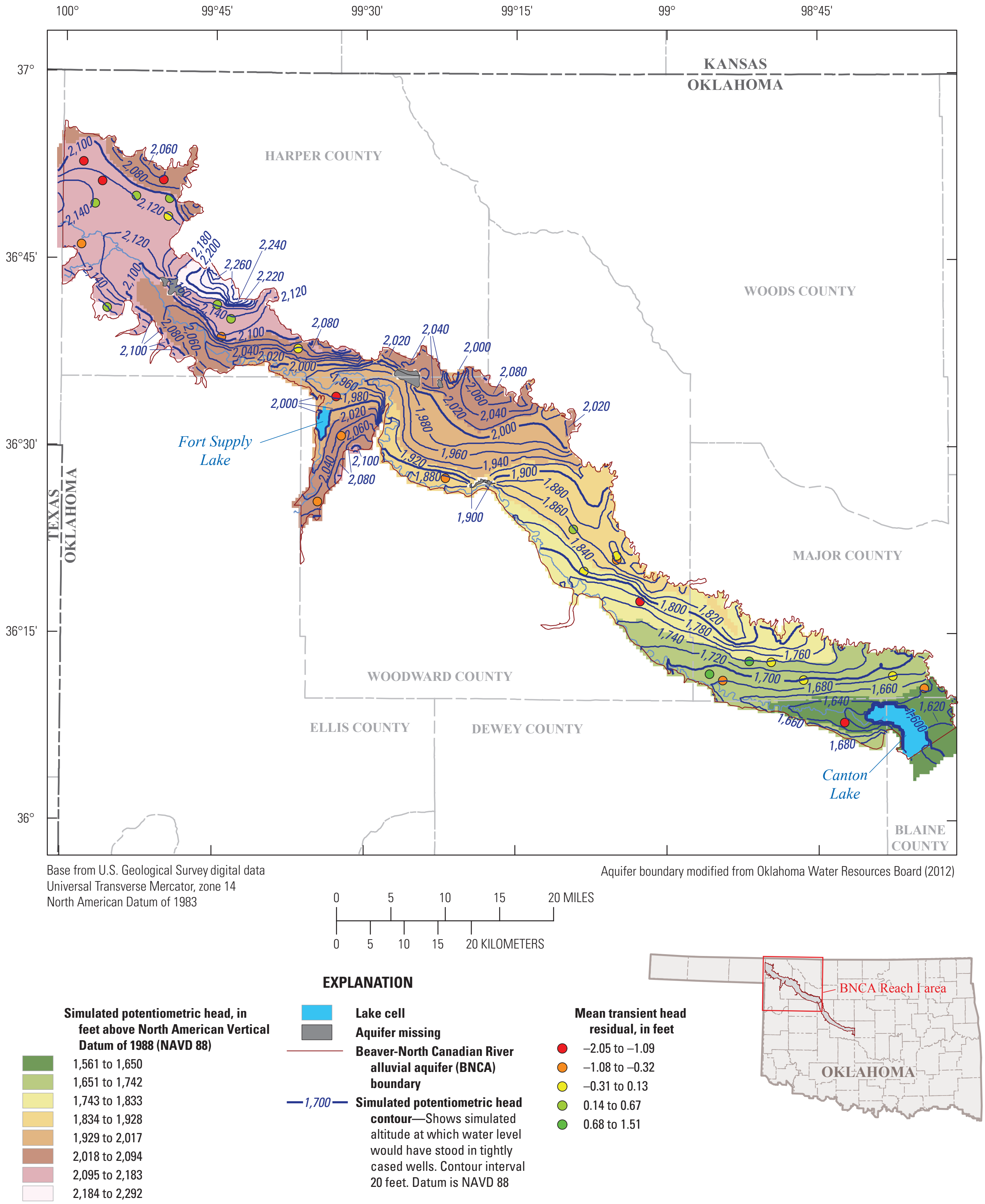


Figure 28. Simulated potentiometric surface at the end of the transient simulation and head targets in Reach I symbolized by mean residual for the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

Table 10. Statistical comparison of measured and simulated groundwater heads, numerical groundwater-flow model for the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

[Residual is calculated as the measured value minus the simulated value; thus, a negative residual for water levels indicates that simulated values are larger than measured values; all units except percentage of head relief are feet]

Model	Reach I			Reach II		
Observation group	**Steady state**	**Transient**	**All**	**Steady state**	**Transient**	**All**
Observation count	28	487	515	75	134	209
Minimum residual	-5.61	-12.14	-12.14	-3.79	-10.02	-10.02
Mean residual	-0.64	0.87	0.79	-0.69	-0.23	-0.39
Maximum residual	3.46	15.01	15.01	9.83	10.57	10.57
Mean absolute residual	1.67	2.82	2.76	1.71	3.26	2.66
Root-mean-square error (RMSE)	2.31	3.93	3.86	2.40	4.15	3.58
RMSE percentage of head relief	0.3	0.5	0.5	0.6	1.0	0.8

Table 11. Statistical summary for calibrated hydraulic conductivity and saturated thickness for the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

[Saturated thickness represents conditions during December 2011 at the end of the transient model period; mi^2, square mile; Kh, horizontal hydraulic conductivity]

Reach	Cell count	Area (mi^2)	Mean saturated thickness (feet)	Maximum thickness (feet)	Minimum Kh (feet per day)	Mean Kh (feet per day)	Maximum Kh (feet per day)
Reach I	8,894	858	36	308	6	70	279
Reach II	3,843	371	29	86	4	92	279
Aquifer total	**12,737**	**1,229**	**34**	**308**	**4**	**77**	**279**

Table 12. Numerical groundwater-flow model mean annual flow budget, Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

[All units are acre-feet; ET, plant evapotranspiration; positive values are flow to aquifer; negative values are discharge]

	Reach I	Reach II	Total
	Inflow		
Recharge	143,990	60,950	204,940
Flow from storage	114,580	48,610	163,190
Flow from streams	37,570	36,460	74,030
Lateral inflow	14,630	930	15,560
Flow from lakes	170	20	190
Total inflow	**310,940**	**146,970**	**457,910**
	Outflow		
Evapotranspiration	101,100	33,610	134,710
Storage	115,470	50,910	166,380
Streams	61,830	50,020	111,850
	Outflow—Continued		
Groundwater pumping	12,490	8,620	21,110
Lateral outflow	10,800	880	11,680
Springs	8,270	2,920	11,190
Flow to lakes	990	10	1,000
Total outflow	**310,950**	**146,970**	**457,920**
	Net flow		
Streams	-24,260	-13,560	-37,820
Lateral flow	3,830	50	3,880
Net change in storage	890	2,300	3,190
Lakes	-820	10	-810

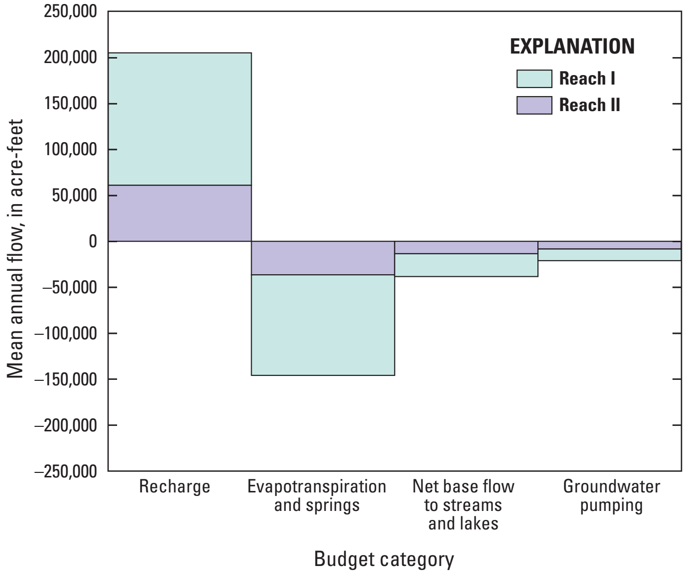


Figure 29. Numerical groundwater-flow model mean annual flow budget for the period 1980–2011, Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

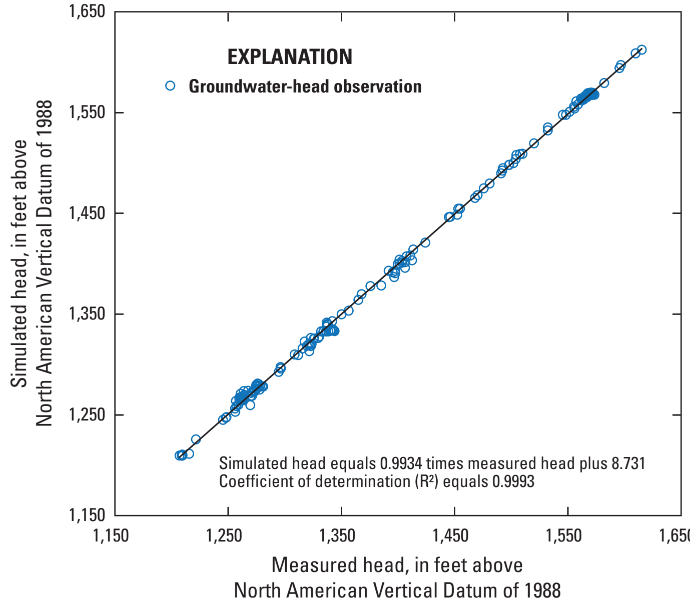


Figure 30. Observed groundwater heads and simulated heads for Reach II of the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

Reach II Calibration Results

A total of 209 groundwater-head measurements were used in calibration of the Reach II model, 75 of which were from the steady-state period of 1980, and 134 of which were from 31 wells used during the transient stress periods (table 10). The groundwater head observed at each observation well was compared to the simulated heads in figure 30. The correlation between observed and simulated groundwater heads was nearly 1:1, with a R^2 of 0.9993. The distribution of Reach II head residuals shows that the model error was evenly distributed between simulating head greater than observed and less than observed (fig. 31). For Reach II, 85 percent of residuals from the steady-state and transient stress periods were between -5 and 5 ft (fig. 31). Residuals ranged from -3.79 to 9.83 ft for the steady-state period, with a mean of -0.69 ft, and -10.02 to 10.57 ft, with a mean of -0.23 ft during the transient period (table 10). The mean of all residuals was -0.39 ft. The mean of residual absolute values was 1.71 ft for the steady state period, 3.26 ft for the transient period, and 2.66 ft for all residuals. The RMSE was 2.40 ft for the steady-state period, 4.15 ft for the transient, and 3.58 ft for all observations. The RMSE as a percentage of the total head relief in the model (437 ft from fig. 32) provides the error in the context of the model head change. The RMSE as a percentage of head relief was 0.6 percent for the steady-state period, 1.0 percent for the transient period, and 0.8 for all observations.

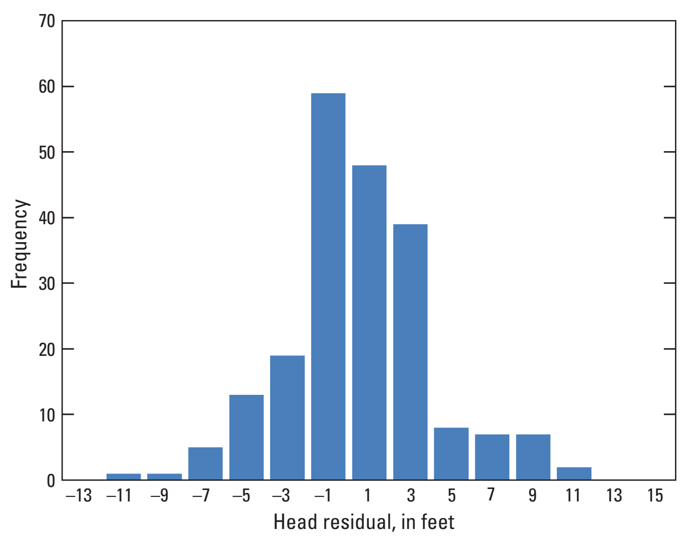


Figure 31. Distribution of head residuals combined for the steady-state and transient models for Reach II, Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

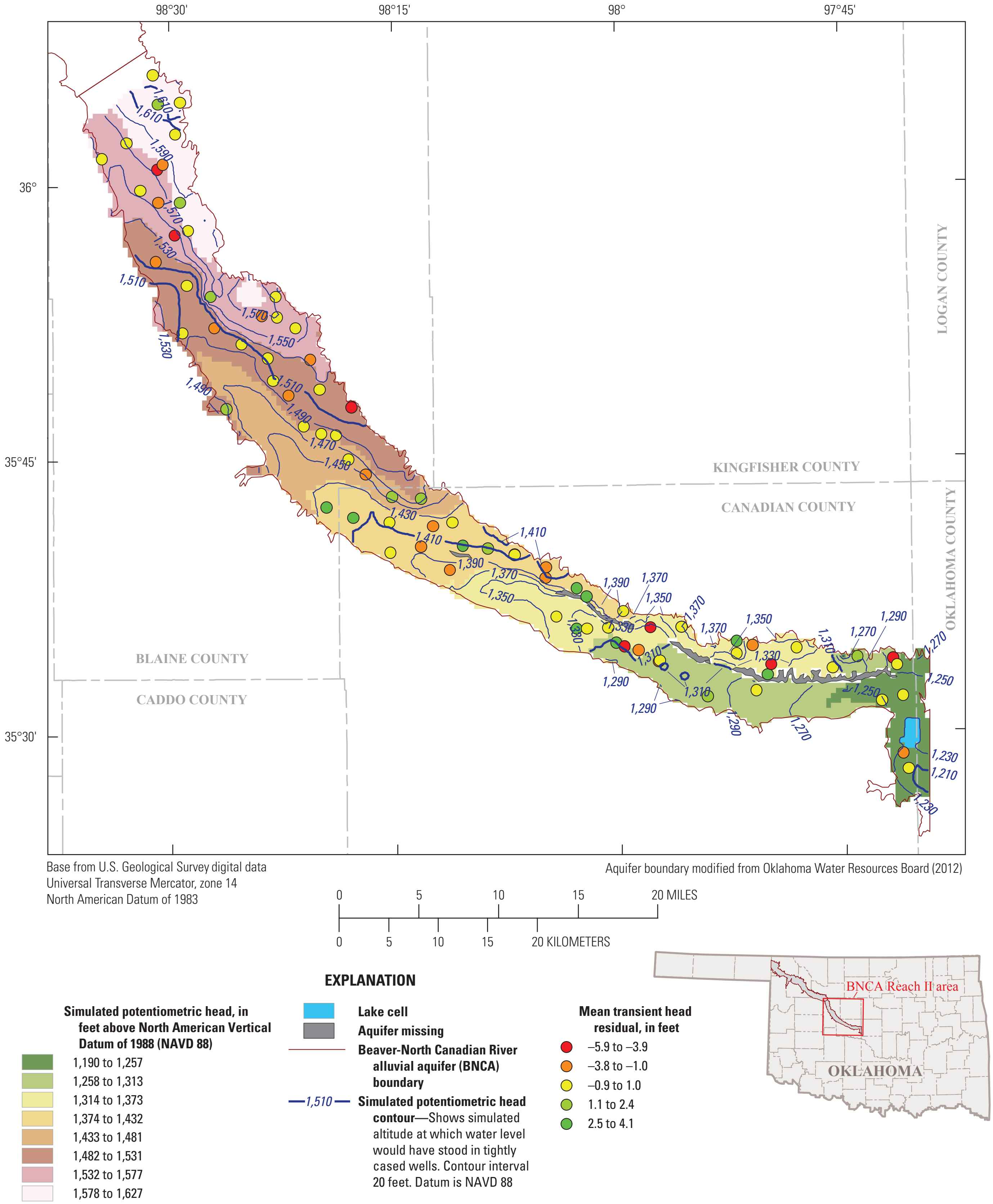


Figure 32. Simulated groundwater head and head targets symbolized by mean residual combined for the steady-state and transient models for Reach II of the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

The final calibrated numerical groundwater-flow model for Reach II provided estimates of the heads, model input parameters, and stream base flow in the groundwater system. Reach II Kh ranged from 4 to 279 ft/d, with a mean of 92 ft/d (table 11). The simulated head at the end of the transient model period—December of 2011—was compared to the base of the aquifer to calculate the saturated thickness. Reach II mean saturated thickness was 29 ft, and the maximum was 86 ft.

The Reach II model mean annual flow budget (fig. 29; table 12) shows the simulated flow for several categories to be much different than the flows estimated in the conceptual flow model (table 9). Recharge scaled during calibration was about 74 percent of the total SWB-model annual recharge volume for Reach II. The SWB-model recharge was most likely overestimated, but the amount of plant ET calculated by the model may have been less than the volume that was actually discharged. Thus, the lower volume of recharge in the Reach II model may have compensated for ET that was not simulated.

Model Sensitivity

The sensitivity of simulated heads in both models to changes in hydraulic parameters, maximum ET, and recharge was determined. Sensitivity was measured by varying the final calibrated arrays for recharge, Kh, Sy, and maximum ET equally across the model by 10 percent independently and calculating the resulting change in simulated heads at observation points. Changes in head at each observation point were then scaled by the number of observations to determine the mean model sensitivity. The model sensitivity helps to identify which parameters contribute most to the model solution and thus estimate the model confidence.

The Reach I model simulated head was most sensitive to changes in recharge and much less sensitive to changes in Kh, Sy, and maximum ET (fig. 33). Simulated head observations were nearly three times as sensitive to recharge as they were to Kh, which was nearly double that of Sy. The Reach II model simulated head was much less sensitive to recharge, and the recharge and Kh sensitivities were almost an order of magnitude higher than those of Sy and maximum ET.

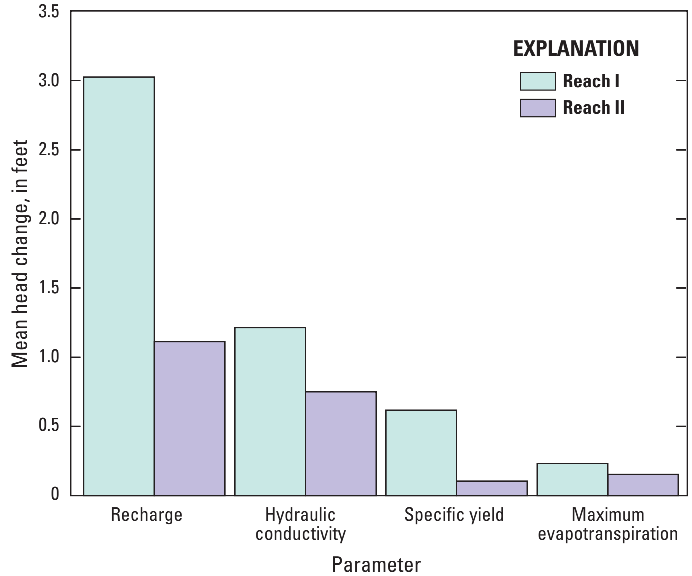


Figure 33. Reach I and Reach II numerical groundwater-flow model groundwater-head sensitivity to changes in selected parameters, Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

Equal-Proportionate-Share Estimation

The EPS pumping rate of groundwater for alluvial aquifers is defined by the State of Oklahoma as the hypothetical constant rate of groundwater pumping per acre of land that results in half of the aquifer having saturated thickness of 5 ft or less after a period of 20 years (Oklahoma Statutes Title 82 Section 1020.5, 2011). For the Beaver-North Canadian River alluvial aquifer, the EPS estimation also included periods of 40 and 50 years. To determine the EPS pumping rate, the reach models were modified to include one hypothetical groundwater-pumping well in each active model cell. Each well pumped the same EPS rate, and this rate was held constant throughout the transient model period. At the end of the transient model run, the number of model cells with 5 ft or less of saturated thickness was counted, and the percentage of the basin was calculated in a geographic information system (Esri, Inc., 2015). This process was repeated with incremental increases in pumping for all wells until half of the cells had a saturated thickness of 5 ft or less. This discharge was determined to be the approximate EPS pumping rate. To provide a range of EPS pumping rates, the process was repeated with recharge, to which heads were most sensitive, and increased and decreased by 10 percent.

All of the model EPS runs began with the simulated head and model inputs of 2011. To include climatic and water-use variations of the model period without causing perturbations to the system outside of normal fluctuations, the transient model was then reconfigured to step back through the 31-year transient model period. The 20-year EPS calculation stepped backward through model data for 1991–2011. For the 40- and 50-year periods, the model inputs included the entire 31-year transient model period stepping backward (2011–1981), then stepping forward again for nine years (1981–89) for the 40-year period, and 19 years (1981–99) for the 50-year period. Model inputs for recharge, surface-water releases and diversions, and ET rates were the same as those used in each stress period of the calibrated models.

The EPS pumping rates are approximate and affected by several factors. Because the EPS rate is determined by the changes in saturated thickness of the Beaver-North Canadian River alluvial aquifer under pumping stresses, the irregular nature of the aquifer base, discretization of an irregular surface, and error in the model used introduce uncertainty. Seasonal fluctuations in recharge and ET introduce uncertainty, particularly in the longer runs of 40 and 50 years because the aquifer saturated thickness changes on a seasonal time scale. In some cases, the EPS pumping rate may not be distinguishable or is only separated by 0.1 (acre-ft/acre)/yr. Because of the uncertainty associated with the EPS analysis, the pumping rates were rounded to the nearest 0.01 (acre-ft/acre)/yr. Furthermore, the model period of 1980–2011 used to estimate EPS was relatively wet, and thus EPS may be overestimated for future dry periods.

Estimated Equal-Proportionate-Share Pumping in Reach I

The initial annual groundwater-pumping rate for the EPS analysis was 0.38 (acre-ft/acre)/yr pumped continuously from every acre of the aquifer and increased incrementally by 0.05 (acre-ft/acre)/yr. The results for the 20-year period are shown in figure 34, and the EPS rates calculated for all three time periods are listed in table 13. For a 20-year period, 50 percent of the basin with less than or equal to 5 ft of saturated thickness was reached at a groundwater-pumping rate of 0.57 (acre-ft/acre)/yr. Note that the EPS rate is rounded to 0.01 (acre-ft/acre)/yr on the x-axis. Decreasing recharge 10 percent resulted in an annual rate of 0.53 (acre-ft/acre)/yr, and increasing the recharge 10 percent resulted in a rate of 0.60 (acre-ft/acre)/yr. The final result of the EPS analysis for Reach I was an annual EPS groundwater-pumping rate between 0.53 and 0.60 (acre-ft/acre)/yr as shown in figure 34.

Increasing the time period to 40 and 50 years caused the EPS pumping rate to decrease slightly to 0.54 and 0.53 (acre-ft/acre)/yr, respectively (table 13). Both rates varied by approximately 0.05 (acre-ft/acre)/yr with a 10-percent change in recharge. Including all time periods and changes in recharge, the EPS pumping rate for Reach I varied between 0.48 and 0.60 (acre-ft/acre)/yr.

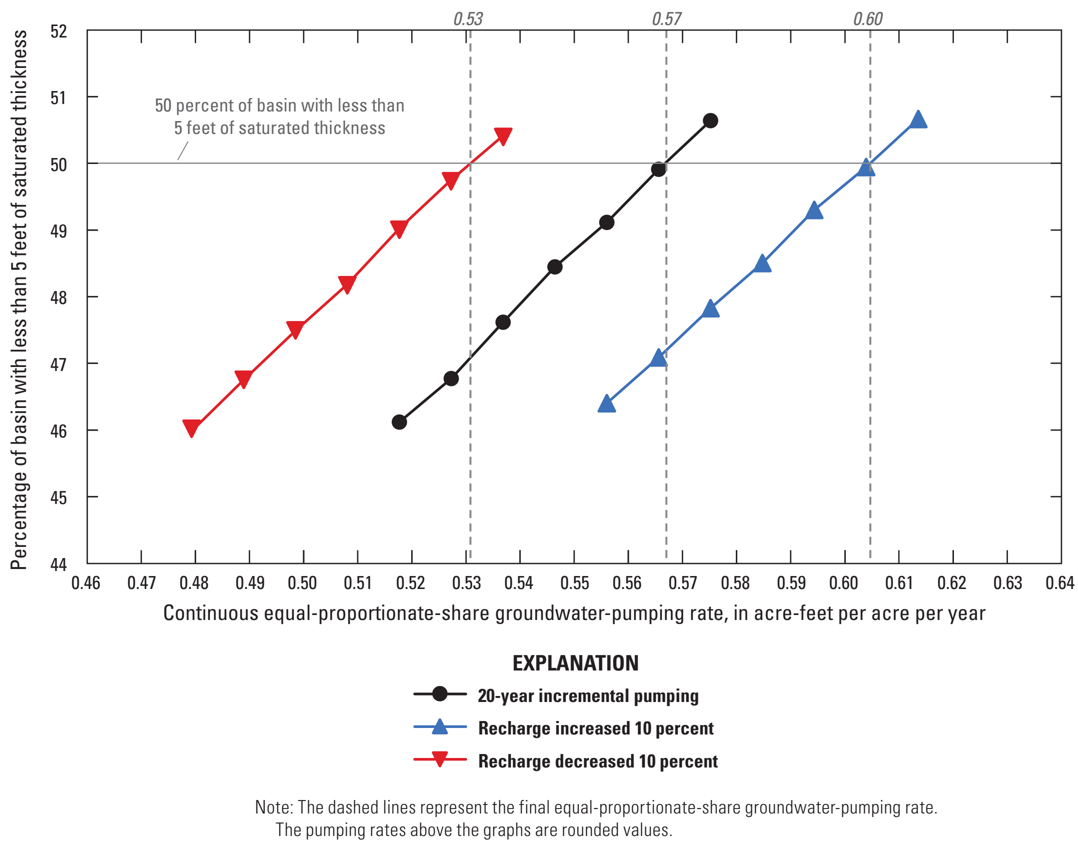


Figure 34. Percentage of Reach I of the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma, with less than 5 feet of saturated thickness after 20 years of various levels of continuous equal-proportionate-share groundwater pumping and scaled recharge.

Table 13. Equal-proportionate-share (EPS) pumping for Reach I and Reach II for select time periods, Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

[All units of pumping are acre-feet per acre per year]

Period (years)	Reach I EPS pumping rate			Reach II EPS pumping rate		
	Recharge reduced by 10 percent	No change in recharge	Recharge increased by 10 percent	Recharge reduced by 10 percent	No change in recharge	Recharge increased by 10 percent
20	0.53	0.57	0.60	0.69	0.73	0.77
40	0.49	0.54	0.58	0.57	0.61	0.65
50	0.48	0.53	0.57	0.60	0.61	0.67

Estimated Equal-Proportionate-Share Pumping in Reach II

The initial annual groundwater-pumping rate for the EPS analysis was 0.33 (acre-ft/acre)/yr. The initial rate was increased incrementally by 0.05 (acre-ft/acre)/yr, and the number of cells with less than or equal to 5 ft of saturated thickness were tallied after 20, 40, and 50 years for each groundwater-pumping rate (table 13). For the 20-year EPS, 50 percent of the basin with less than or equal to 5 ft of saturated thickness was reached at a rate of 0.73 (acre-ft/acre)/yr (fig. 35). As in the Reach I EPS analysis, recharge was varied by 10 percent to provide a range of EPS groundwater-pumping rates. Decreasing recharge 10 percent resulted in an annual rate of 0.69 (acre-ft/acre)/yr, and increasing the recharge 10 percent resulted in a rate of 0.77 (acre-ft/acre)/yr as shown on figure 35.

Increasing the time period for the EPS calculation to 40 years resulted in a substantial decrease in the EPS pumping rate to 0.61 (acre-ft/acre)/yr (table 13). Increasing the time period to 50 years resulted in an EPS pumping rate that was indistinguishable from the 40-year EPS pumping rate of 0.61 (acre-ft/acre)/yr. Including all time periods and changes in recharge, the EPS pumping rate for Reach II varied between 0.57 and 0.77 (acre-ft/acre)/yr.

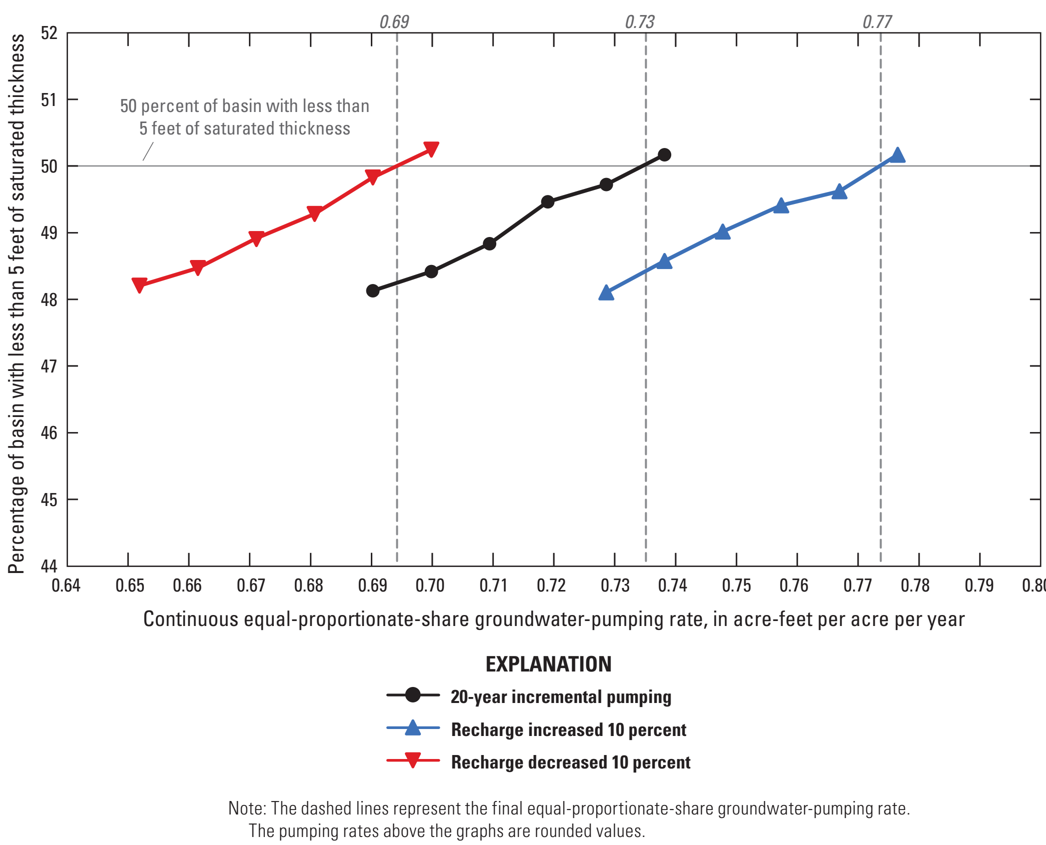


Figure 35. Percentage of Reach II of the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma, with less than 5 feet of saturated thickness after 20 years of various levels of continuous equal-proportionate-share groundwater pumping.

Effects of Projected Water Use and Drought

The two reach models were run as predictive models for hypothetical future scenarios to evaluate the effects of projected water use, such as varying groundwater pumping rates, and prolonged drought on quantities of available water. Simulations included the climate variability present in the study period and provided assessments of potential effects on the hydrologic system under these conditions. Future water availability is defined in this study as the groundwater in storage, streamflow in the Beaver and North Canadian Rivers, and surface water stored in Fort Supply and Canton Lakes.

Projected Water Use

The calibrated numerical groundwater-flow models were used to estimate future effects of water use on groundwater resources of the Beaver-North Canadian River alluvial aquifer. Two water-use analyses were conducted: the first projected 2011 water use for 50 years, and the second increased water use by a total of 32 percent over a hypothetical 50-year period as is projected in the OCWP (Oklahoma Water Resources Board, 2012). The 2011 water-use projection used the monthly groundwater pumping estimated for 2011 repeated for 50 years. To simulate a 32-percent increase in groundwater pumping over 50 years, the monthly groundwater-pumping rates for 2011 were increased in a linear fashion so that after 50 years the annual groundwater pumping had increased by 32 percent.

The simulation period for increasing groundwater pumping in both models was constructed by using hydrologic conditions from a typical year on the basis of annual recharge as described in the “Groundwater Recharge” section of this report. The year with total recharge similar to the mean annual recharge for the model period (fig. 21) and pumping rates close to the mean annual rate (fig. 3) was 2005; 2008 recharge was very close to the mean recharge, but pumping was unusually low. Monthly recharge, ET, streamflow, and releases from lakes were used from 2005 for the entire model run.

The effects of groundwater pumping in both reach models were evaluated by determining changes in groundwater storage over that period. To allow heads to stabilize, the model was run 1 year before the 50-year period, and the heads were saved at the end of that year. The heads in the models were saved again at the end of the 50-year period. The groundwater in storage was calculated by multiplying the saturated thickness in each model cell by the calibrated Sy in that cell. To calculate the change in groundwater in storage caused by groundwater pumping, the model for each reach was run once without pumping and again with groundwater pumping; the difference in water in storage between the end of the model runs provided an approximation of the effect of the groundwater pumping.

In Reach I, the total water in storage at the end of the 50-year period with no groundwater pumping was approximately 2,220 thousand acre-ft. After the same period with groundwater pumping at 2011 rates, there were 2,140 thousand acre-ft, a decrease of 3.6 percent (table 14). For Reach II after 50 years of pumping at the 2011 rate, there were 392 thousand acre-ft in storage with no groundwater pumping and 328 thousand acre-ft in storage with groundwater pumping, a decrease of 2.5 percent.

With a 32-percent increase in groundwater pumping over the 50-year period, the water in storage at the end of the run in Reach I was 2,130 thousand acre-ft, a decrease of 4.0 percent. In Reach II, a 32-percent increase in groundwater pumping resulted in 379 thousand acre-ft of groundwater remaining in storage, a decrease of 3.3 percent (table 14).

Prolonged Drought

Several severe hydrologic droughts have affected the Beaver-North Canadian River alluvial aquifer since records were first collected in 1925. These droughts include the Dust Bowl drought (1929–41) and the droughts of 1952–56, 1961–72, and 1976–81 (Shivers and Andrews, 2013). The period of this study includes the last 2 years of the 1976–81 drought and below normal precipitation that began in 2011, which is considered drought conditions for this analysis. Across the State of Oklahoma, the only year with a greater negative departure from normal than 2011 was 1956, with 2011 being the ninth driest year in the long-term streamflow record at the North Canadian River near Wetumka, Okla. (07242000), streamflow-gaging station (Shivers and Andrews, 2013) located about 80 mi east of Reach II and shown on the inset map of figure 1.

Table 14. Changes in water in storage after 50 years of groundwater pumping at the 2011 rate and increasing the 2011 rate by 32 percent over a 50-year period for the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

[All units thousands of acre-feet]

Reach	Water in storage without pumping	Water in storage with pumping	Percent decrease
2011 pumping for 50 years			
Reach I	2,220	2,140	3.6
Reach II	392	382	2.5
32 percent cumulative increase in pumping over 50 years			
Reach I	2,220	2,130	4.0
Reach II	392	379	3.3

The primary source of water to the Beaver-North Canadian River alluvial aquifer hydrologic system is recharge from precipitation. Thus, a multiyear hydrologic drought is one of the most consequential climatic events for the Beaver-North Canadian River alluvial aquifer because the decreased precipitation results in decreased recharge. Models for both reaches were run in predictive mode over a hypothetical 10-year drought period by using two simulations. One simulation was used to calculate effects of drought on groundwater storage, and the other to calculate the effects of drought on streamflow and lake storage. Both simulations compared conditions during the hypothetical drought to the model run with calibrated model inputs.

Change in Groundwater Storage

In an unconfined aquifer such as the Beaver-North Canadian River alluvial aquifer, the volume of groundwater that can be pumped from storage is the product of the saturated thickness and the Sy of the aquifer (Fetter, 1994). Changes to inflow such as recharge and outflows such as pumping and discharge to streams can cause water to either be added to or removed from aquifer storage. To estimate the change in groundwater in storage resulting from a sustained hydrologic drought, the head and water in storage reference point was set as the end of the steady-state model for 1980. To simulate drought conditions, ET and recharge model inputs for 2011 were repeated over the 10-year period. The year 2011 did not have the least amount of recharge, but precipitation during 2011 was lower than any year in the model period of 1980–2011 (fig. 7; fig. 8). Groundwater-pumping rates for 2011 were used during the hypothetical drought.

The drought simulation included an initial steady-state stress period, followed by 10 years (120 transient stress periods) under drought conditions. To ensure that the transient period showed the effect of drought on the hydrological system, the steady-state stress period was adjusted so that it was approximately the same recharge and ET as the first stress period of the drought. This adjustment removed any adjustment period that the transient model would incur if the steady-state conditions were substantially different from the first stress period of the drought.

Figure 36*A* shows that through the 10 years of simulated drought in Reach I, the decrease in recharge caused an annual deficit in the groundwater-flow system. This deficit caused seasonal changes to be superimposed on a linear decrease in groundwater in storage. The change in water in storage over the drought period was measured by using a 5-month moving average of stress-period volumes. The difference between the moving-average values at the beginning (3,580 thousand acre-ft at stress period 4) and end of the simulation (3,340 thousand acre-ft at stress period 118) was 240 thousand acre-ft, a decrease of about 7 percent in Reach I (fig. 36*A*). Figure 36*B* shows a similar decline in the total volume of groundwater in storage in Reach II from 1,120 to 1,040 thousand acre-ft, a difference of 80 thousand acre-ft or about 7 percent during the simulated 10-year drought period.

This analysis of the effects of drought on the Beaver-North Canadian River alluvial aquifer is approximate and is only representative of 1 drought year repeated over a decade. Actual droughts could potentially have a greater effect, and hydrological conditions would be expected to fluctuate. This analysis, however, does provide a generalized representation of how the system responds to drought conditions and that the loss of water in storage during such a simulated drought is substantial. The system could take several years to return to normal conditions.

Effects of Drought on Streamflow and Lake Storage

To simulate the effects of a prolonged drought on surface water, the calibrated model recharge was scaled down by 75 percent in both reach models during a period with relatively average hydrologic conditions (1994–2004). Changes in simulated streamflow in the North Canadian River at the Seiling streamflow-gaging station in Reach I and at the North Canadian River near Yukon, Okla. (07239700), streamflow-gaging station (referred to in the remainder of this report as the “Yukon streamflow-gaging station”) in Reach II and lake volumes at Canton Lake were analyzed by comparing nondrought and drought conditions. This analysis is approximate because simulated streamflow in the numerical groundwater-flow models represents changes in base flow from the Beaver-North Canadian River alluvial aquifer and did not include runoff peak flow. For this section, “simulated streamflow” refers to the combined simulated base flow and other inflows such as releases from Canton and Fort Supply Lakes upstream from the streamflow-gaging station.

At the Seiling streamflow-gaging station in Reach I, simulated streamflow during the hypothetical 1994–2004 drought dropped to nearly no flow during low-flow periods (for example, during selected times in the summers of 2001–3), and during high flows the flow decreased by over 50 percent by the end of the drought (fig. 37). A moving average of the percentage change in streamflow decreased approximately 75 percent at the end of the drought period. The moving average of the simulated streamflow was still about 10 percent less than the nondrought simulated streamflow at the end of the simulation period in 2011.

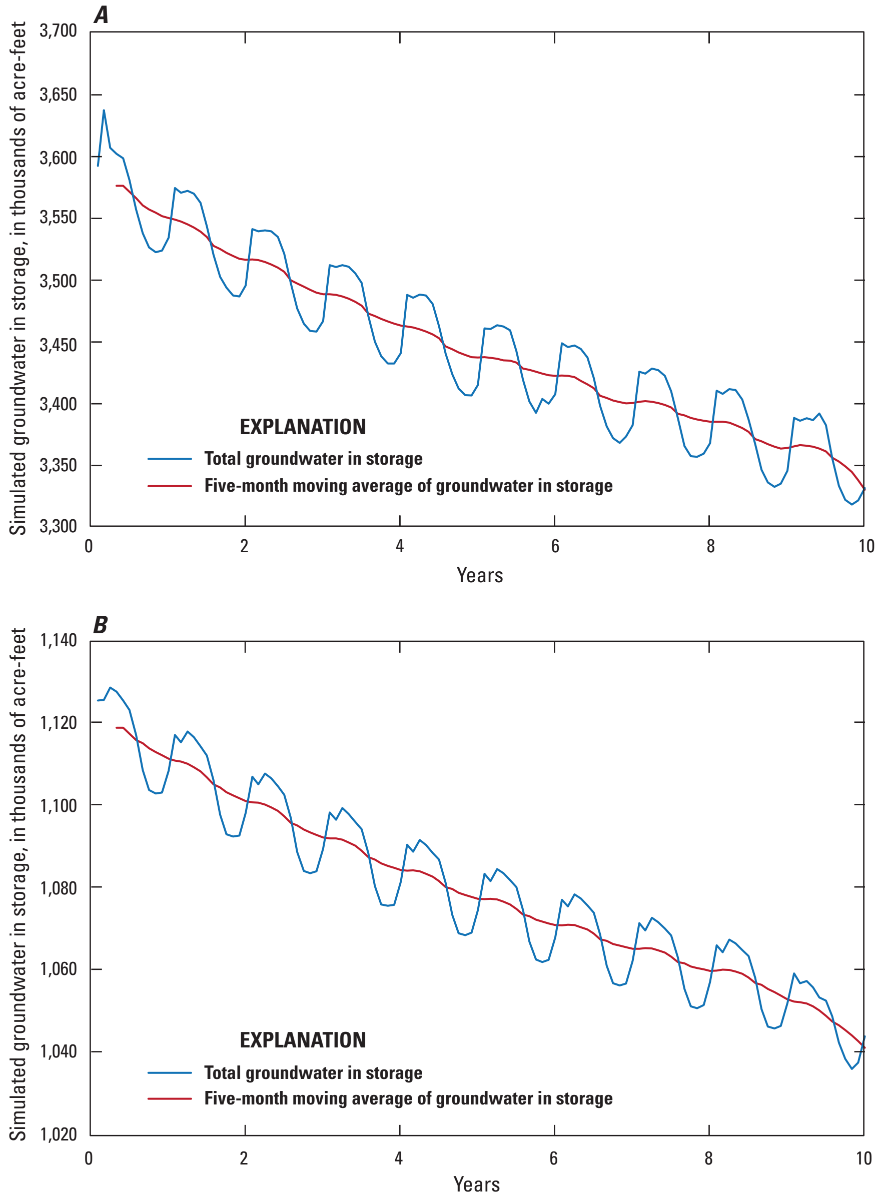


Figure 36. Change in groundwater in aquifer storage in *A*. Reach I, and *B*. Reach II during a hypothetical severe 10-year drought for the Beaver-North Canadian River alluvial aquifer, northwestern Oklahoma.

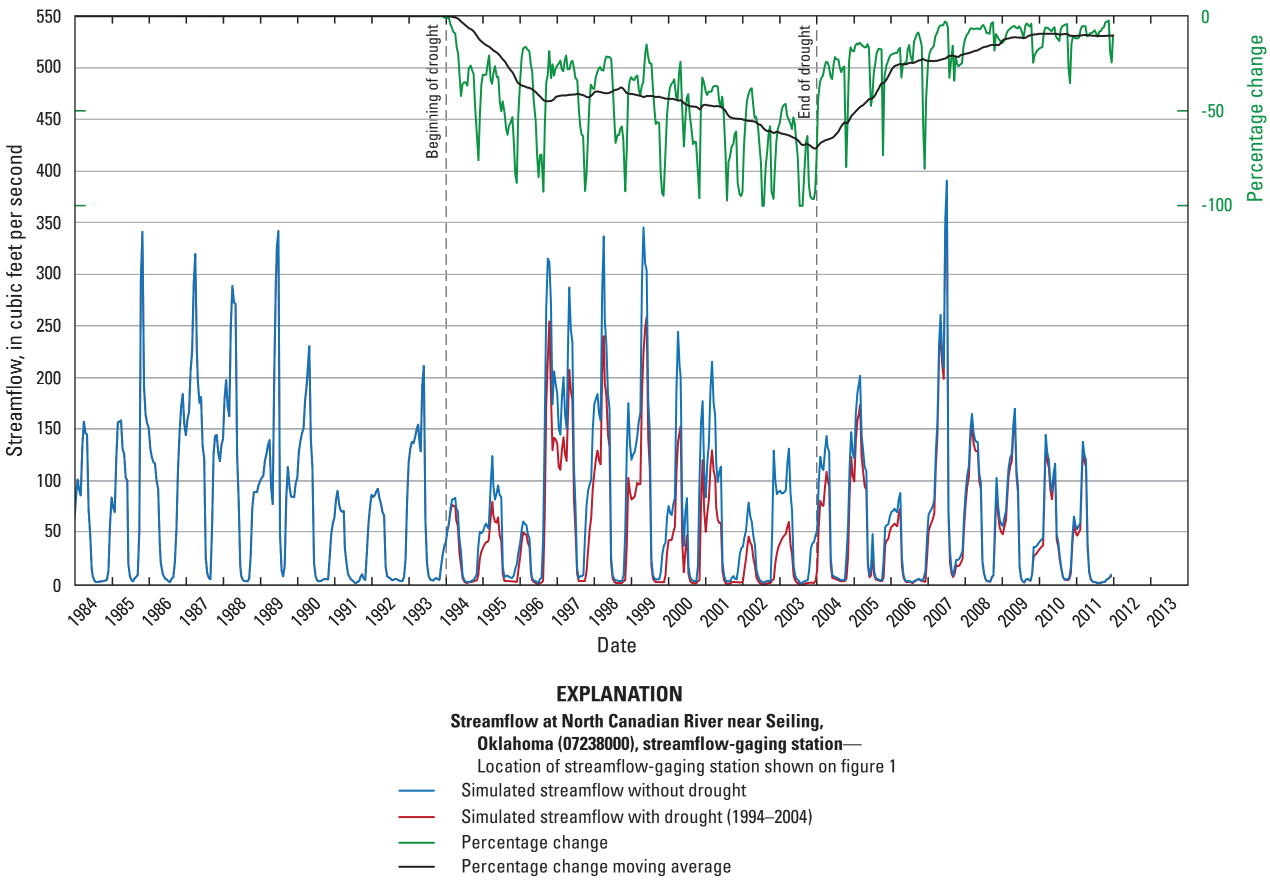
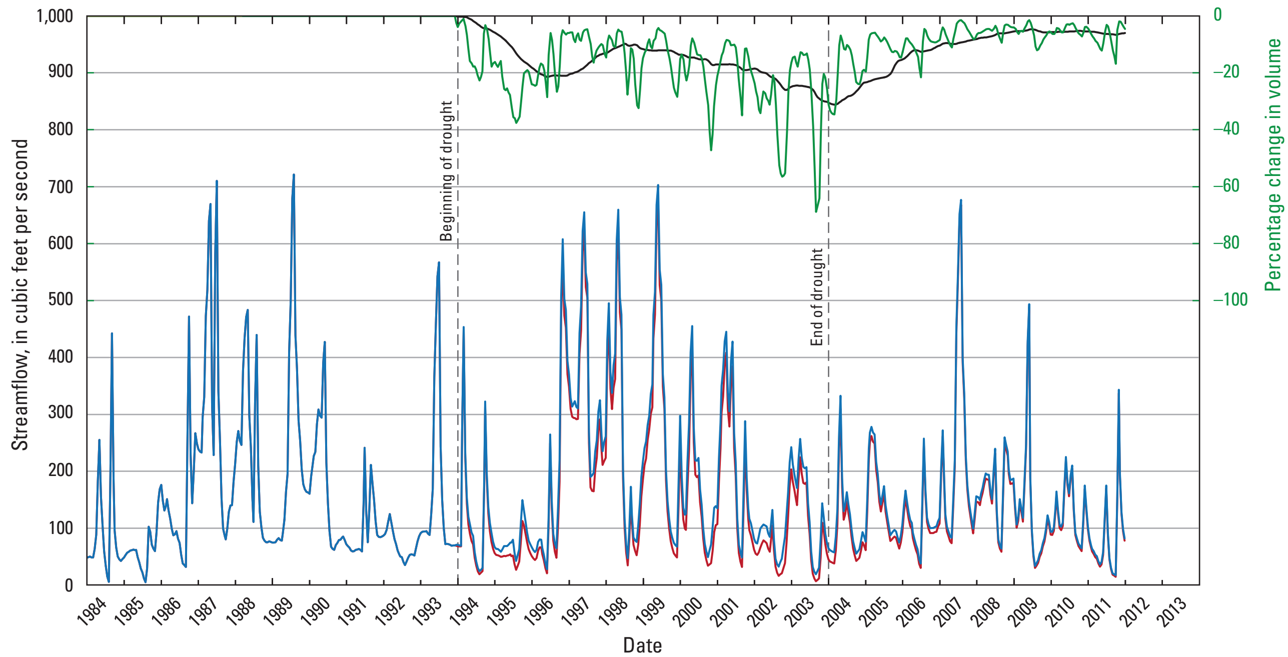


Figure 37. Changes in streamflow at the North Canadian River near Seiling, Oklahoma (07238000), streamflow-gaging station during a hypothetical drought, 1994–2004. “Simulated streamflow” refers to the combined simulated base flow and other inflows such as lake streamflow releases.

Drought analysis for Reach II was performed on the North Canadian River by using simulated streamflow at the Yukon streamflow-gaging station. Effects of the hypothetical drought were less pronounced at the station than was apparent in Reach I at the Seiling streamflow-gaging station. Simulated high streamflow at the Yukon streamflow-gaging station decreased more than 20 percent by the end of the hypothetical 1994–2004 drought, and simulated low flows decreased by more than 60 percent during the fall of 2003 (fig. 38). A moving average of the percentage change in simulated streamflow decreased by approximately 35 percent at the end of the hypothetical drought in 2004 and recovered to a decrease of only about 5 percent by 2011 (fig. 38). Effects of simulated hypothetical drought may have been less at the Yukon streamflow-gaging station because of released flow from Canton Lake that countered the decrease in base flow.

In Reach I, the model runs under hypothetical drought conditions during 1994–2004 showed a substantial decrease in simulated Canton Lake storage compared to nondrought conditions (fig. 39). After the hypothetical drought began, water volume progressively dropped until the drought ended in 2004. Simulated Canton Lake storage was still less than 50 percent of the nondrought simulated lake storage at the end of the model simulation in 2011. By the end of the hypothetical drought, the volume in Canton Lake had decreased by 83 percent. Effects of drought were related to lower base flow to the Beaver and North Canadian Rivers as seen in the effects of drought on simulated streamflow at the Seiling streamflow-gaging station and thus flow to the lake. This analysis may overestimate the decrease in lake storage because the lake operators will stop releasing water from the lake when the lake stage reaches a specified level.



EXPLANATION

Streamflow at North Canadian River near Yukon, Oklahoma (07239700), streamflow-gaging station—
Location of streamflow-gaging station shown on figure 1

- Simulated streamflow without drought
- Simulated streamflow with drought (1994–2004)
- Percentage change
- Percentage change moving average

Figure 38. Changes in streamflow at the North Canadian River near Yukon, Oklahoma (07239700), streamflow-gaging station during a hypothetical drought, 1994–2004. “Simulated streamflow” refers to the combined simulated base flow and other inflows such as lake streamflow releases.

Model Limitations

All models are constructed with a limited amount of data and, thus, are necessarily simplifications of actual systems. When creating a model of a large area, it is necessary to make more simplifications than when creating models of smaller areas. Model limitations are a consequence of uncertainty in three basic aspects of the model, including inadequacies, inaccuracies, or simplifications in (1) observations used in the model, (2) representation of geologic complexity in the hydrogeologic framework, and (3) representation of the groundwater system in the model. It is important to understand how these characteristics limit the use of the model.

Head observations used to calibrate the models were well distributed across the Beaver-North Canadian River alluvial aquifer during 1980 and 2011, but during the intervening years, head data were more sparse, and though the models reproduced sampled heads fairly accurately, the sparse temporal nature of the data introduces uncertainty in future model projections.

This model was constructed to simulate the period 1980–2011, and all projections were simulated by using data from this period. The 50-year transient simulations project the analysis 18 years beyond 2011 by using hydrologic data from 1980 to 1998, and it is assumed that future climate will be similar to 1980–98, which did not include any of the severe drought periods such as those that occurred during the 1930s, 1950s, or 1976–81. Thus, the EPS and water-use scenarios simulated in this report are biased by the climate during the period of the study presented in this report.

The parameters and boundary conditions for the models used in this report were generalized for large areas and are not to be used for local analyses. Though the calibration process produced parameterized models that matched observed groundwater heads very closely, the two parameters that the simulated heads were most sensitive to and were the primary parameters for calibration (Kh and recharge) are correlated. With correlated parameters, there are multiple combinations of the parameter values that will produce the same result, and the result is not unique. Thus, though the parameters in the models were restricted to reasonable values, without additional direct parameter measurements there is considerable uncertainty in local results.

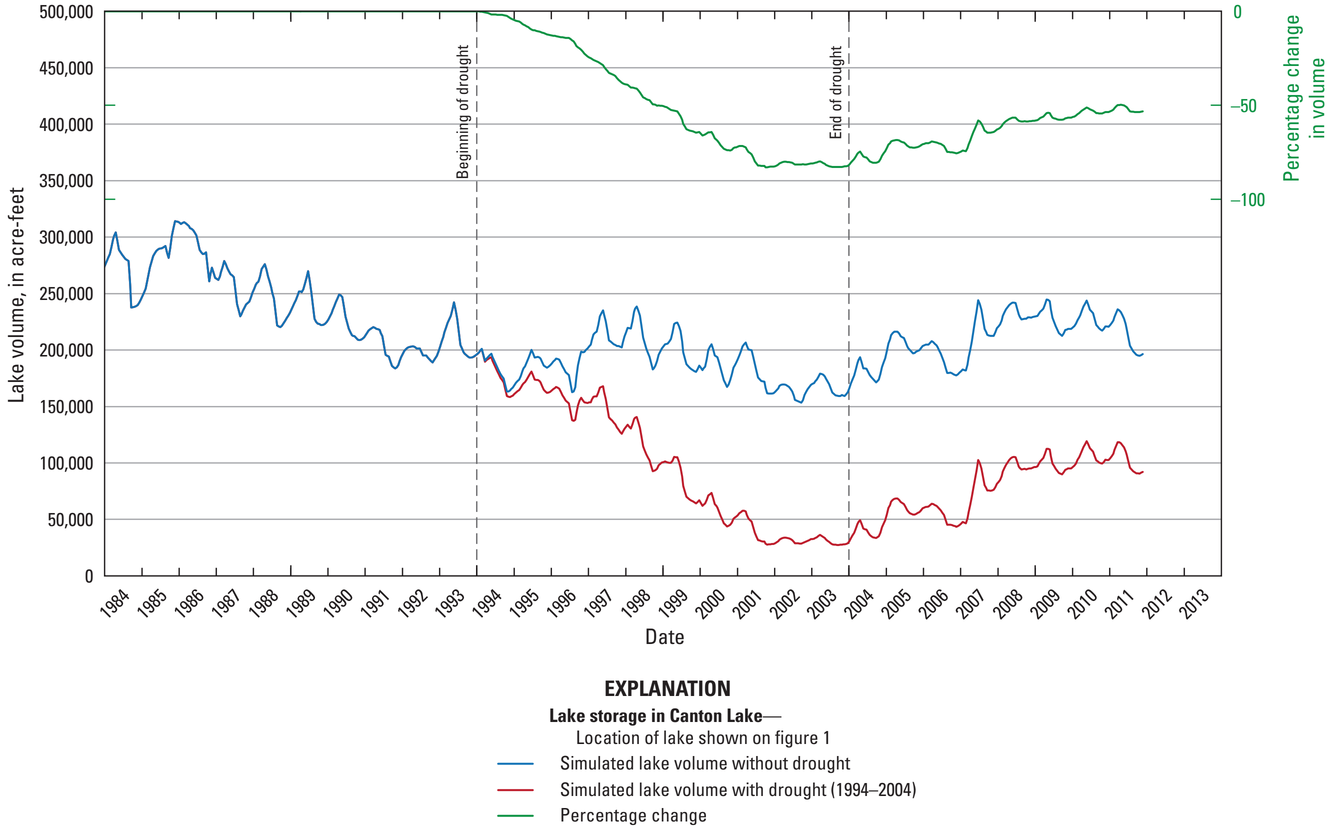


Figure 39. Simulated changes in Canton Lake water in storage during a hypothetical drought, 1994–2004.

Summary

Across northwestern Oklahoma, the Beaver and North Canadian Rivers provide water for numerous uses and are important sources of the water that is stored in Canton Lake. The Beaver and North Canadian Rivers are an important conveyance for water released from Canton Lake and diverted to Lake Hefner Canal for part of the Oklahoma City, Okla., public water supply. The Beaver-North Canadian River alluvial aquifer is hydraulically connected to the Beaver and North Canadian Rivers, and on the basis of base-flow estimates, more than half of the streamflow in the river comes from the Beaver-North Canadian River alluvial aquifer. The Beaver-North Canadian River alluvial aquifer provides groundwater resources for public water supplies at several small cities, domestic wells, irrigation, nonirrigation agriculture, industry, mining, recreation, commercial, and other uses.

This report describes the hydrogeologic framework and groundwater flow in the Beaver-North Canadian River alluvial aquifer in northwestern Oklahoma and construction and results of a numerical groundwater-flow model used to simulate the groundwater-flow system from 1980 through 2011 and for various future scenarios. Predictive simulations include the calculation of the equal-proportionate-share (EPS) groundwater-pumping rate and effects of groundwater pumping and severe droughts on groundwater in storage and surface water.

The Beaver-North Canadian River alluvial aquifer is a long, narrow alluvial aquifer that spans variations in climate for approximately 175 miles from the Oklahoma Panhandle to the western margin of Oklahoma City in central Oklahoma. Analysis of the Beaver-North Canadian River alluvial aquifer was divided into Reach I above the Canton Dam and Reach II downstream from the dam. Land use on the Beaver-North Canadian River alluvial aquifer was mostly upland grasses/forbs and planted/cultivated agriculture and did not change substantially during the period of study. Mean annual precipitation during the period of study varied from 23.5 inches per year in the semiarid west to 35.7 inches per year in the subhumid east. Mean monthly precipitation at the Woodward weather station in Reach I and the Watonga weather station in Reach II showed strong seasonality and slightly higher precipitation at Watonga. Wet and dry periods were delineated by deviations of total annual precipitation from the mean annual precipitation at Woodward and Watonga. Both stations experienced dry periods coincident with regional hydrologic droughts and dry periods after 2010.

Surface-water use for the Beaver and North Canadian Rivers and groundwater use for the Beaver-North Canadian River alluvial aquifer are managed by the Oklahoma Water Resources Board (OWRB). The groundwater-use analysis full period of record, 1967–2011, was divided into two sub-intervals, 1970–80 and 1981–2011, because of varying groundwater use. Groundwater use in Reach I and Reach II was substantially greater from 1970 to 1980 compared to the rest of the period. The total mean annual groundwater use in Reach I was 15,309 acre-feet per year (acre-ft/yr) during 1967–2011; 20,724 acre-ft/yr during 1970–80, and 13,739 acre-ft/yr during 1981–2011. Total mean annual groundwater use in Reach II was similar but slightly less than in Reach I, with 14,098 acre-ft/yr during 1967–2011; 19,963 acre-ft/yr during 1970–80; and 12,285 acre-ft/yr during 1981–2011.

Irrigation composed 72 percent of groundwater use in Reach I and 48 percent of groundwater use in Reach II during the 1967–2011 period. Public water supply was a much smaller proportion of total groundwater use in Reach I (15 percent) than in Reach II (39 percent). The proportion of groundwater use for power was 10 percent in Reach I and 5.2 percent in Reach II. All other water-use categories in Reach I only composed 2.2 percent of groundwater use in Reach I. In Reach II, industrial, mining, and commercial categories combined accounted for 4.4 percent of groundwater use; recreation, fish, and wildlife water use accounted for 2.3 percent; and nonirrigated agriculture and other accounted for 1.5 percent.

Only irrigation and public water supply were used in the numerical groundwater-flow models. During the period of groundwater-flow models (1980–2011), there were 301 irrigation and 57 public water-supply wells that were tied to active groundwater permits. There were 58 temporary and permanent surface-water diversions used in the model, with a total of approximately 1,240 acre-ft/yr; 70 acre-ft/yr from Reach I and 1,170 acre-ft/yr from Reach II.

Fort Supply and Canton Lakes impound streamflow for release during dry months; Canton Lake releases water that is diverted to the Lake Hefner Canal near the eastern end of the Beaver-North Canadian River alluvial aquifer to augment the public water supply in Oklahoma City. Streamflow into the study area from the Beaver River decreased from 1978 to 1994 because of groundwater depletion in the High Plains aquifer to the west, which reduced base flow upstream. Base flow along the Beaver and North Canadian Rivers in the study area is variable, but overall the Beaver and North Canadian Rivers are gaining streams, and streamflow increases downstream. The only perennial tributary to the North Canadian River is Wolf Creek, which flows from the west, outside the extent of the Beaver-North Canadian River alluvial aquifer. Wolf Creek flows into Fort Supply Lake and the North Canadian River in Reach I.

The Beaver-North Canadian River alluvial aquifer is an unconsolidated Quaternary-age valley-bottom and terrace alluvial deposit that overlies low-permeability Permian-age bedrock. The Beaver-North Canadian River alluvial aquifer included the underlying Tertiary-age Ogallala Formation in the farthest northwestern extent of the aquifer. The mean saturated thickness of the Beaver-North Canadian River alluvial aquifer was estimated to be 36 ft in Reach I and 29 ft in Reach II. The maximum saturated thickness of the Beaver-North Canadian River alluvial aquifer was estimated to be 308 ft in Reach I and 86 ft in Reach II. The thickest parts of Reach I included the underlying Ogallala Formation.

Groundwater flow in the Beaver-North Canadian River alluvial aquifer was generally from northwest to southeast along the trend of the aquifer and toward the Beaver and North Canadian Rivers, and recharge in upland areas along the eastern margin of the aquifer produced a general flow from east to west; in some local areas in the uplands, recharge created a groundwater divide causing groundwater to flow toward the eroded northeastern boundary of the aquifer. Observation wells measured over the period of study on the Beaver-North Canadian River alluvial aquifer show a minor upward trend in groundwater head.

The hydraulic parameters of the Beaver-North Canadian River alluvial aquifer are highly variable. Published aquifer tests and laboratory tests of aquifer materials were used in this report to estimate horizontal hydraulic conductivity (Kh) and specific yield (Sy) for borehole-log lithologic descriptions to interpolate properties throughout the entire Beaver-North Canadian River alluvial aquifer. The Kh and Sy were then adjusted during numerical groundwater-flow model calibration. Calibrated model Kh was estimated to range from 4 to 279 feet per day (ft/d). The mean Kh was 70 ft/d in Reach I and 92 ft/d in Reach II.

Base flow in both reaches was analyzed by using published studies, one seepage run performed for this study, and base-flow separation analysis of streamflow data in Reach I. Seepage run measurements from 1979 and 2012 in Reach I indicated that base flow was very similar at the two times and that the Beaver and North Canadian Rivers upstream from Canton Lake was generally gaining except for several reaches upstream from Wolf Creek. The mean base flow from seepage runs was 31 cubic feet per second (ft^3/s). Base-flow separation analysis indicated that the mean base-flow index for the Beaver and North Canadian Rivers in Reach I was 0.63, and the total base-flow flow in Reach I during the period of study was 69,000 acre-feet (acre-ft). Base-flow separation was not performed on Reach II because of flow control by Canton Dam. One seepage run in Reach II indicated that the North Canadian River gained a total of 14.2 ft^3/s between Canton Lake and the Lake Hefner Canal diversion.

Groundwater recharge was estimated by using a soil-water-balance (SWB) model. This model produced monthly and annual arrays of recharge across the Beaver-North Canadian River alluvial aquifer. Total recharge was found to be most sensitive to precipitation and root-zone depth. A 10-percent increase in daily precipitation applied during the model run resulted in a 26-percent increase in total recharge, and a 10-percent decrease in precipitation caused a 23-percent decrease in recharge. Recharge was very sensitive to root-zone depth as well. Recharge decreased 9 percent with a 10-percent increase in root-zone depth and increased 8 percent with a 10-percent decrease in root-zone depth. The estimated mean annual recharge from the SWB model was 136,400 acre-ft in Reach I and 82,400 acre-ft in Reach II, for a total of 218,800 acre-ft. The total estimated recharge from 1980 to 2011 was approximately 4,350 thousand acre-ft for Reach I and 2,600 thousand acre-ft for Reach II.

Local groundwater-recharge estimates were made at two sites in Reach I located at observation wells near the North Canadian River and streamflow-gaging stations with precipitation gages by using the water-table fluctuation method. The Woodward site was at observation well OW-4 and near the streamflow-gaging station on the North Canadian River at Woodward, Okla. (07237500). The Seiling site was at observation well OW-5, which was near the streamflow-gaging station on the North Canadian River near Seiling, Okla. (07238000). At both wells OW-4 and OW-5, instruments collected continuous water-level measurements for parts of 2012 and 2013. Water-level fluctuations were compared to precipitation and stream-stage measurements at both sites to estimate groundwater recharge. The sites were not close enough to the North Canadian River streamflow-gaging stations to determine seasonal changes in base flow, but both sites were generally gaining base flow. The total precipitation and recharge for the Woodward and Seiling sites were calculated for the water year 2013. The Woodward site had a total of 14.18 inches (in.) of precipitation, and 6.3 in. of recharge were calculated, for 44 percent of precipitation. The mean percentage of precipitation that was estimated to become recharge in the SWB model for the period 1980–2011 at that location was 9.2 percent, although adjacent SWB-model cells were as high as 20 percent of precipitation. The Seiling site had a total of 26.84 in. of precipitation during the water year 2013, and a total of 6.9 in. of recharge was estimated, for 25.9 percent of precipitation. At the Seiling site, the mean percentage of precipitation that became recharge in the SWB model for the period 1980–2011 was 23.0 percent.

Other water-budget categories for the Beaver-North Canadian River alluvial aquifer included well pumping, evapotranspiration (ET) by plants, seeps and springs, and lateral groundwater flow to and from other geological units. Only the well pumping for irrigation and public water supply was directly quantified in this report. The total volume of water pumped by wells during the study period was 14,500 acre-ft in Reach I and 10,100 acre-ft in Reach II, for a total of 24,600 acre-ft.

The numerical groundwater-flow model objectives included simulating the transient groundwater flow in both reaches of the Beaver-North Canadian River alluvial aquifer from 1980 to 2011 to address long-term groundwater pumping and drought scenarios, including calculation of the EPS pumping rates. A steady-state model for 1980 and a transient model using monthly stress periods from 1981 to 2011 were constructed for both reaches of the Beaver-North Canadian River alluvial aquifer. Models were calibrated by using groundwater-head observations and adjusting recharge from the SWB model and Kh interpolated from published aquifer tests and lithologic borehole logs. The water budgets from the numerical flow model and the conceptual flow model showed that recharge in both reaches was much greater than stream base flow, and the balance was discharged primarily to ET.

Several analyses were performed by using the numeric groundwater-flow models as predictive models, including estimating the EPS pumping rate for both reaches. The EPS is defined by the OWRB as an annual per-acre groundwater-pumping rate that will reduce saturated thickness in half of the aquifer to 5 feet or less over a period of 20 years; additional estimates were made for periods of 40 and 50 years. A range of values was calculated by determining the EPS rate with recharge reduced by 10 percent and increased by 10 percent. Other analyses included using models to estimate the effects of groundwater pumping and a prolonged drought on groundwater in storage and streamflow and lake storage of water.

For a 20-year period, the EPS pumping rate was found to be 0.57 (0.53–0.60) acre-feet per acre per year ([acre-ft/acre]/yr) in Reach I and 0.73 (0.69–0.77) (acre-ft/acre)/yr in Reach II. For a 40-year period, the annual EPS pumping rate was determined to be 0.54 (0.49–0.58) (acre-ft/acre)/yr in Reach I and 0.61 (0.57–0.65) (acre-ft/acre)/yr in Reach II. For a 50-year period, the EPS pumping rate was determined to be 0.53 (0.48–0.57) (acre-ft/acre)/yr in Reach I and 0.61 (0.60–0.67) (acre-ft/acre)/yr in Reach II.

Groundwater pumping at 2011 rates for 50 years caused a decrease of groundwater in aquifer storage by 3.6 percent in Reach I and 2.5 percent in Reach II. Increasing the 2011 groundwater-pumping rate to a cumulative increase of 32 percent over 50 years resulted in a decrease in groundwater in storage of 4.0 percent in Reach I and 3.3 percent in Reach II.

Drought scenarios used the reach models to simulate a hypothetical 10-year severe drought. A 10-year period using recharge and ET rates from the dry year of 2011 caused a cumulative decrease of groundwater in storage of about 7 percent in Reach I and 7 percent in Reach II. The transient models were also used to simulate a hypothetical drought that was assumed to cause a 75-percent decrease in recharge for the 10-year period 1994–2004, and the effects on surface-water storage in Canton Lake and streamflow in the North Canadian River were estimated. Mean streamflow at the Seiling streamflow-gaging station in Reach I decreased by 75 percent at the end of the drought period and had recovered to 10 percent of nondrought streamflow by the end of the simulation in 2011. Mean streamflow at the Yukon streamflow-gaging station in Reach II decreased by approximately 35 percent at the end of the drought and recovered to a decrease of about 5 percent by 2011. Recovery of flow at the Yukon streamflow-gaging station may have been aided by releases from Canton Lake. At the end of the hypothetical drought, Canton Lake storage had decreased by 83 percent and did not recover by the end of 2011.

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