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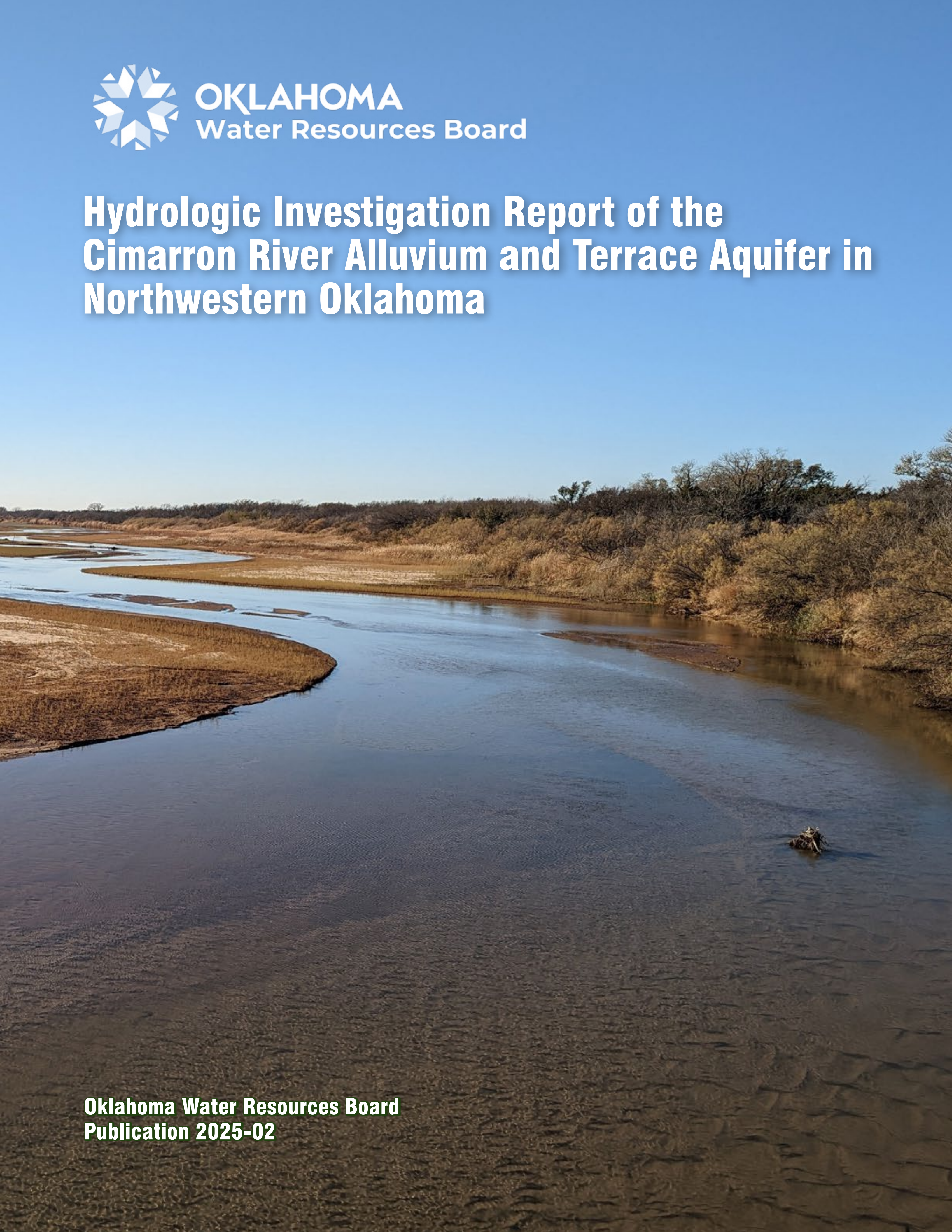
Hydrologic Investigation Report of the Cimarron River Alluvium and Terrace Aquifer in Northwestern Oklahoma



Oklahoma Water Resources Board
Publication 2025-02

Cover. Cimarron River looking west from abandoned bridge off N2830 Road near Dover, Oklahoma. Photograph by Alan LePera, Oklahoma Water Resources Board, November 21, 2022.

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Alan K. Le Pera, R. Jacob Hernandez, and Jessica S. Correll

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Conversion Factors

U.S. Customary Units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,4047.0	square meter (m^2)
acre	0.4047	hectare (ha)
square mile (mi^2)	559.0	hectare (ha)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233.0	cubic meter (m^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233.0	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02834	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02834	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Pressure	
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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.

Hydrologic Investigation Report of the Cimarron River Alluvium and Terrace Aquifer in Northwestern Oklahoma

By Alan K. Le Pera, R. Jacob Hernandez, and Jessica S. Correll

Abstract

The Oklahoma Water Resources Board is mandated by law (82 OK Stat §82-1020.5) to conduct hydrologic surveys and investigations of major and minor groundwater basins in the state to determine the maximum annual yield (MAY) and equal proportionate share (EPS) of each for permitting and administrative purposes. At present (2025), the OWRB has not yet officially established a MAY or EPS for the Cimarron River alluvium and terrace groundwater basin, referred to in this report as the Cimarron River alluvium and terrace aquifer. A proposed maximum annual yield of 835,200 acre-feet (EPS of 1.0 acre-foot/acre/year) was presented to the board for consideration in August 2000, but was not adopted; as such, the default EPS of 2.0 acre-feet/acre/year is currently in effect for the aquifer. This report details the findings of an updated hydrologic investigation for the Cimarron River alluvium and terrace aquifer and provides the necessary information to allow the OWRB to determine a new maximum annual yield.

The Cimarron River alluvium and terrace aquifer in northwestern Oklahoma serves as a major source of groundwater in parts of Alfalfa, Major, Woods, Kingfisher, and Logan counties and is used for irrigation, public supply, industrial, mining, and domestic purposes. The extent of the Cimarron River alluvium and terrace aquifer was modified from the unofficial boundary defined in Adams and Bergman (1996) to reflect changes in the geographical extent of alluvium and terrace deposits as shown in current Oklahoma Geological Survey (OGS) Hydrologic Atlases as well as considerations for hydrologic connectivity and saturated thickness. The defined aquifer underlies an area of approximately 1,279 square miles (818,478 acres).

The unconsolidated Quaternary-age deposits of the Cimarron River alluvium and terrace aquifer unconformably overlie Permian-age bedrock. Aquifer deposits consist of interfingering deposits of gray to reddish-brown locally derived medium- to fine-grained sands, silts, and clays with variable amounts of distally derived medium- to coarse-grained sands and gravels and volcanic ash. Permian-age bedrock units exposed adjacent to and sub-cropping the Cimarron River alluvium and terrace aquifer are predominantly composed of thick sequences of fine-grained sandstones, argillaceous siltstones, red shale, dolomite, gypsum, and salt beds. The total thickness of the aquifer deposits ranges from less than 10 feet to a maximum of about 115 feet, with an average of 45 feet. The saturated thickness of the Cimarron River alluvium and terrace aquifer ranges from less than 5 feet to 93 feet, with a mean of about 26 feet.

Mean annual reported groundwater use from the aquifer was estimated to be about 30,814 acre-feet per year for the period 1967–2023, with irrigation and public supply being the two largest use categories. Mean annual baseflow from the aquifer was estimated to be about 144,808 acre-feet per year for the period 1974–2023. Total mean annual evapotranspiration from the aquifer was estimated to be about 28,850 acre-feet per year, with 6,000 acre-feet per year from wetland areas and 22,850 acre-feet per year from phreatophytes (cottonwoods) within the Cimarron River alluvial valley.

Recharge to the Cimarron River alluvium and terrace aquifer primarily occurs through the deep percolation of precipitation, with return flow from irrigation being a lesser secondary source. Assuming a return flow rate of 12 percent, mean annual return flow was estimated to be about 2,621 acre-feet per year. Mean annual recharge estimated for the 2016–2021 period using the water table fluctuation method ranged from 1.6 to 11.4 inches per year, with a station-averaged mean of 3.2 inches per year (218,261 acre-feet per year) when normalized to the 1895–2023 mean annual precipitation. Mean annual recharge estimated from a simple water budget method was 3.35 inches per year (228,783 acre-feet per year) for the period 1974–2023. Mean annual recharge estimated from a soil-water balance method was 3.13 inches per year (213,486 acre-feet per year) for the period 1980–2023. Recharge as a percentage of annual precipitation ranged from 10.3–11.0 percent.

Aquifer hydraulic properties were estimated using slug tests, well drawdown tests, multi-well pumping tests, and a lithologic-log standardization method. Hydraulic conductivity estimates ranged from 0.2–526.0 feet per day with a mean around 54.2 feet per day. Specific yield estimates derived from the methods used in this study ranged from 0.04–0.26; based on all available data (including model-calibrated Sy estimates for other alluvium and terrace aquifers in the state and multi-well aquifer tests from previous publications) a mean Sy value of 0.13 was estimated for the Cimarron River alluvium and terrace aquifer.

The amount of groundwater in storage in the Cimarron River alluvium and terrace aquifer was tentatively estimated to be about 2.77 million acre-feet, based on the 1,279 square mile aquifer area, the mean saturated thickness of 26 feet, and the specific yield value of 0.13. Varying the specific yield by

± 0.03 resulted in groundwater storage estimates of 2.13 and 3.41 million acre-feet, respectively. These estimations were considered rough approximations of groundwater in storage because they were based on the mean saturated thickness.

The quality of groundwater from the Cimarron River alluvium and terrace aquifer is adequate for most purposes but is generally hard and can vary significantly over short distances. Calcium-bicarbonate is the dominant water type in the aquifer, with higher concentrations of sulfate in Woods County, higher concentrations of sodium in Kingfisher County, and higher concentrations of chloride in the Cimarron River alluvium deposits. Results of a Wilcoxon rank-sum test indicated that differences in nitrate concentrations between areas classified as grasslands/pastures and areas classified as agricultural lands were statistically significant. The median nitrate concentration of samples collected from agricultural areas (12.28 milligrams per liter) was twice as high as the median nitrate concentration of samples collected from grassland/pasture areas (5.55 milligrams per liter).

Introduction

The Cimarron River alluvium and terrace groundwater basin, referred to in this report as the Cimarron River alluvium and terrace aquifer in northwestern Oklahoma serves as a major source of groundwater in Alfalfa, Major, Woods, and Kingfisher counties, and is the primary source of water for the City of Enid (**Figure 1**). According to the 2012 Oklahoma Comprehensive Water Plan (Oklahoma Water Resources Board, 2012), the Cimarron River alluvium and terrace aquifer resides chiefly within the Central Watershed Planning Region (Basin 64) of Oklahoma, which is projected to have a 32 percent increase in total water demand by the year 2060 relative to 2010 demand. In the forthcoming 2025 comprehensive water plan, basin 64 is projected to have a 50 percent increase in public water supply groundwater demand, a 44 percent increase in self-supplied domestic groundwater demand, a 41 percent increase in crop irrigation groundwater demand, and a 6 percent decrease in livestock groundwater demand by 2075, relative to 2020 demands.

Future water demands within the basin were in part based on expected changes in population (Oklahoma Water Resources Board, 2025). The Oklahoma Department of Commerce has projected a 0.88 percent average annual population growth in the study area for the period 2000–2070, with the largest projected growth (about 1.5 percent) for Woods and Major Counties (Chiappe, 2023). Recurring drought conditions and poor-quality surface water sources in western Oklahoma make effective management of the Cimarron River alluvium and terrace aquifer essential.

Oklahoma groundwater law (82 OK Stat §82-1020.5) requires the Oklahoma Water Resources Board to conduct hydrologic surveys and investigations of the state's aquifers to determine the maximum annual yield (MAY) and equal proportionate share (EPS) of each groundwater basin. The MAY is defined as the total amount of freshwater that can be withdrawn from a groundwater basin, allowing for a minimum 20-year life of the groundwater basin (Oklahoma Water Resources Board, 2014). The EPS is defined as the portion of the MAY allocated to each acre of land overlying a groundwater basin, expressed as acre-feet per year (a-f/year). At present (2025), the OWRB has not yet officially established a MAY or EPS for the Cimarron River alluvium and terrace aquifer. A proposed maximum annual yield of 835,200 acre-feet (EPS of 1.0 acre-foot/acre/year) was presented to the board for consideration in August 2000, but was not adopted; as such, the default EPS of 2.0 acre-feet/acre/year is currently in effect for the aquifer.

Purpose and Scope

The purpose of this report is to provide an updated hydrogeologic framework for the Cimarron River alluvium and terrace aquifer, the properties of which will be used to define a maximum annual yield. Specific objectives of the hydrologic investigation included: (1) estimate mean annual recharge to and discharge from the basin, (2) estimate the hydraulic properties of the basin, specifically hydraulic conductivity, and specific yield, (3) estimate the quantity of water in storage in the basin, and (4) describe the type and quality of water in the basin.

The geographic scope of the hydrologic investigation is the extent of alluvium and terrace deposits between Freedom and Guthrie, Oklahoma, a stream distance of approximately 115 miles (**Figure 1**). Alluvium and terrace deposits of the Cimarron River located northwest of the town of Freedom within Oklahoma are considered part of the El Reno minor bedrock aquifer (Belden, 2000). Alluvium and terrace deposits of the Cimarron River located east of Guthrie were modeled as a separate aquifer by the USGS, referred to as the "Cimarron River alluvial aquifer" (Paizis and Trevisan, 2021).

Description of Study Area

The main body of the Cimarron River alluvium and terrace aquifer in Woods, Alfalfa, Major, Garfield, Kingfisher, and Logan counties of northwestern Oklahoma covers an area of approximately 1,279 square miles (818,478 acres; **Figure 1**). The extent of the aquifer boundary as presented in this investigation largely follows the extent published in the USGS Water-Resources Investigation Report 95-4066: Geohydrology of the Alluvium and Terrace Deposits of the Cimarron River from Freedom to Guthrie, Oklahoma by Gregory P. Adams, and DeRoy L. Bergman. Minor changes along the edges of the aquifer boundary were based on updated geologic maps published by the OGS (Miller and Stanley, 2003; Stanley and others, 2002; Stanley and Suneson, 2002). Significant changes to the aquifer boundary included the cutting back of alluvium deposits along tributaries on the south side of the Cimarron River and the exclusion of isolated or partially connected terrace and cover sand deposits in Woods County. The excluded deposits occur as lobes between areas of exposed bedrock which became

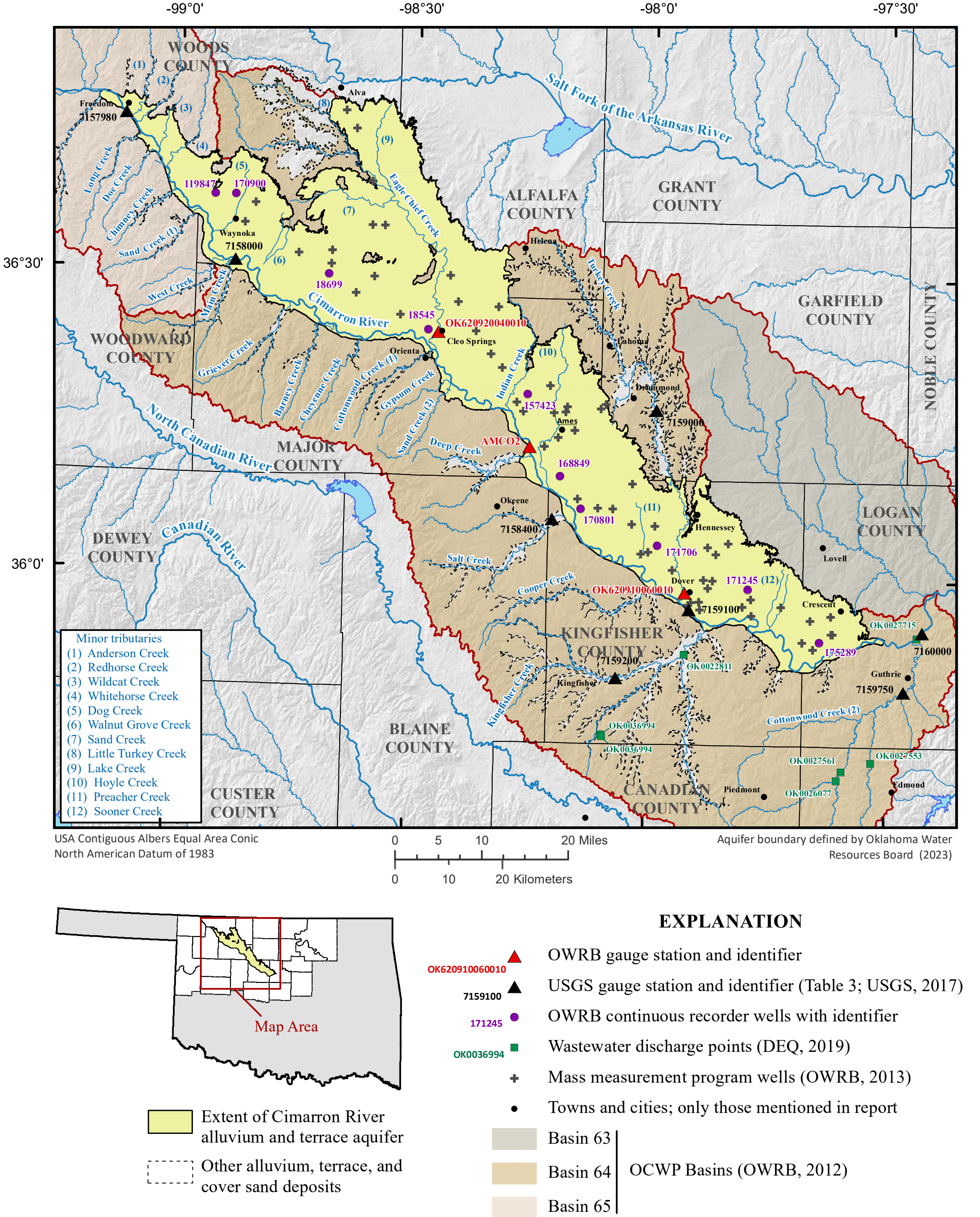


Figure 1. Extent of the Cimarron River alluvium and terrace aquifer, northwestern Oklahoma, and selected streamflow-gauging stations, continuous-recorder monitoring wells, mass measurement wells, and wastewater treatment discharge sites in the study area.

exposed from the downcutting of Eagle Chief Creek and a few of its larger tributaries; the terrace lobes vary in size from about 2.5–18.0 square miles and together cover an area of approximately 39.0 square miles. For a detailed description of the boundary, see Appendix A.

The defined aquifer area is located within the Central Lowland physiographic province of the Interior Plains (Fenneman and Johnson, 1946) and is considered part of the western sand-dune belts geomorphic province (Curtis and others, 2008). The topography of the land surface is the result of the aeolian transport of sediments. Most of the defined aquifer area is covered by terrace deposits; in these areas, the land surface is characterized by expansive hummocky fields of sand dunes stabilized by prairie grasses. In areas covered by alluvium deposits, the land surface topography is generally flat to gently undulating. The topography of the areas with exposed Permian-age bedrock ranges from gently undulating to rugged. The altitude of the aquifer area ranges from 1,760 feet in Woods County to about 920 feet in Logan County. Local relief varies from about 5 feet in prairie-like areas to 10–30 feet in dune areas with some dunes reaching heights exceeding 60 feet (Adams and Bergman, 1996).

Generalized land cover and crop cover over the defined aquifer area are shown in **Figure 2**; grasslands/pastures (41.5 percent) and cover crops (46.1 percent) overlie most of the aquifer with the remaining area split between dedicated forests (5.6 percent), developed land (4.4 percent), wetlands/open water (2.2 percent), and shrublands (0.2 percent) (National Agricultural Statistics Service, 2021). Winter wheat (51.2 percent) and rye (33.9 percent) are the principal crops grown in the defined aquifer area. Crops that cover between 1.6–3.6 percent of the cultivated lands include alfalfa, herbs, soybeans, corn, and triticale (a wheat-rye hybrid); these crops collectively make up about 11.5 percent of the cultivated croplands. Various vegetables, nuts, and fruits make up the remaining 3.4 percent. A table listing land use descriptions can be found in Appendix B. Cattle raised for beef production are the primary livestock raised within the aquifer area (National Agricultural Statistics Service, 2020). Other operations include dairy, poultry, and sheep/lamb farms. Outside of agriculture, oil and gas production, and petroleum service companies are the predominant industry in the study area (Masoner and Mashburn, 2004).

Climate

The Cimarron River alluvium and terrace aquifer spans parts of the North-Central and Central climate divisions in northwestern Oklahoma; Woods, Alfalfa, Major, and Garfield counties are part of the North-Central climate division, while Kingfisher and Logan counties are part of the Central climate division. The climate of the study area is classified as humid subtropical (Cfa) in the Köppen-Geiger Climate Classification (Kottek and others, 2006), which is characterized by moderate changes in seasonal temperature, year-round precipitation, and hot summers. Normal annual precipitation (1991–2020) ranges from about 26 inches per year in Woods County to 37 inches per year in Logan County (Oklahoma Climatological Survey, 2023a). Normal annual temperature (1991–2020) is about 1–2 degrees Fahrenheit (°F) warmer in the southeast region of the study area than in the northwest region (Oklahoma Climatological Survey, 2023b). On average, daily maximum temperatures in the study area exceed 90 °F for about 75–90 days per year and daily minimum temperatures fall below 32°F for about 85–135 days per year (Oklahoma Climatological Survey, 2023c; 2023d).

Historical climate data summarized monthly for selected counties in northwestern Oklahoma were used to calculate and graph annual and monthly precipitation and temperature statistics for the study area (**Figure 3A–B**; **Table 1**). A locally weighted scatterplot smoothing (lowess) line (Cleveland, 1979) was used to identify climate trends by delineating periods of above- and below-mean annual precipitation and temperature. The National Oceanic and Atmospheric Administration monthly U.S. climate divisional database (NClimDiv) from which these summarized data were acquired utilizes quality-assured and bias-adjusted daily precipitation and temperature records from the National Weather Service Cooperative Observer Program (Vose and others, 2014). NClimDiv county values are derived from climatologically aided interpolations of discrete climate station data using area-weighted averages of grid-based estimates (Vose and others, 2014).

The mean annual precipitation in the study area for the period of record 1895–2023 was 29.0 inches per year, with a minimum of 14.4 inches in 1956 and a maximum of 45.7 inches in 1957 (**Figure 3A**; **Table 1**). The period from 1895–1919 was mainly dry with 15 of the 25 years (60 percent) recording below-mean precipitation; the driest years were 1901 and 1910, which had annual precipitation estimates of 19.8 and 15.4 inches, respectively. A short 4-year period of above-mean precipitation occurred between 1905–08 (**Figure 3A**). The 1920s were mainly wet with 6 of the 10 years (60 percent) recording above-mean precipitation, with the wettest year (1923) recording 36.6 inches (**Figure 3A**).

The period from 1930–80 was characterized as an extended dry period with 36 of the 51 years (71 percent) recording below-mean precipitation (**Figure 3A**). The mean annual precipitation in the study area during this period was 27.3 inches per year (**Table 1**). The 1930–80 period is punctuated by three 2- to 5-year periods of above-mean precipitation which occurred between four hydrologic drought periods in Oklahoma (Shivers and Andrews, 2013; Tian, 2017). The 1929–40 (Dust Bowl) and 1961–72 hydrologic drought periods were among the most persistent of the 20th century, each lasting more than a decade. The 1952–56 hydrologic drought period was the most widespread and severe of the 20th-century drought periods in Oklahoma, affecting all climate divisions of the state. The severity of the 1929–40 and 1952–56 droughts was caused by a combination of multi-year below-mean precipitation coupled with multi-year above-mean temperatures (**Figure 3A–B**). The 1976–81 hydrologic drought period was much less severe than the

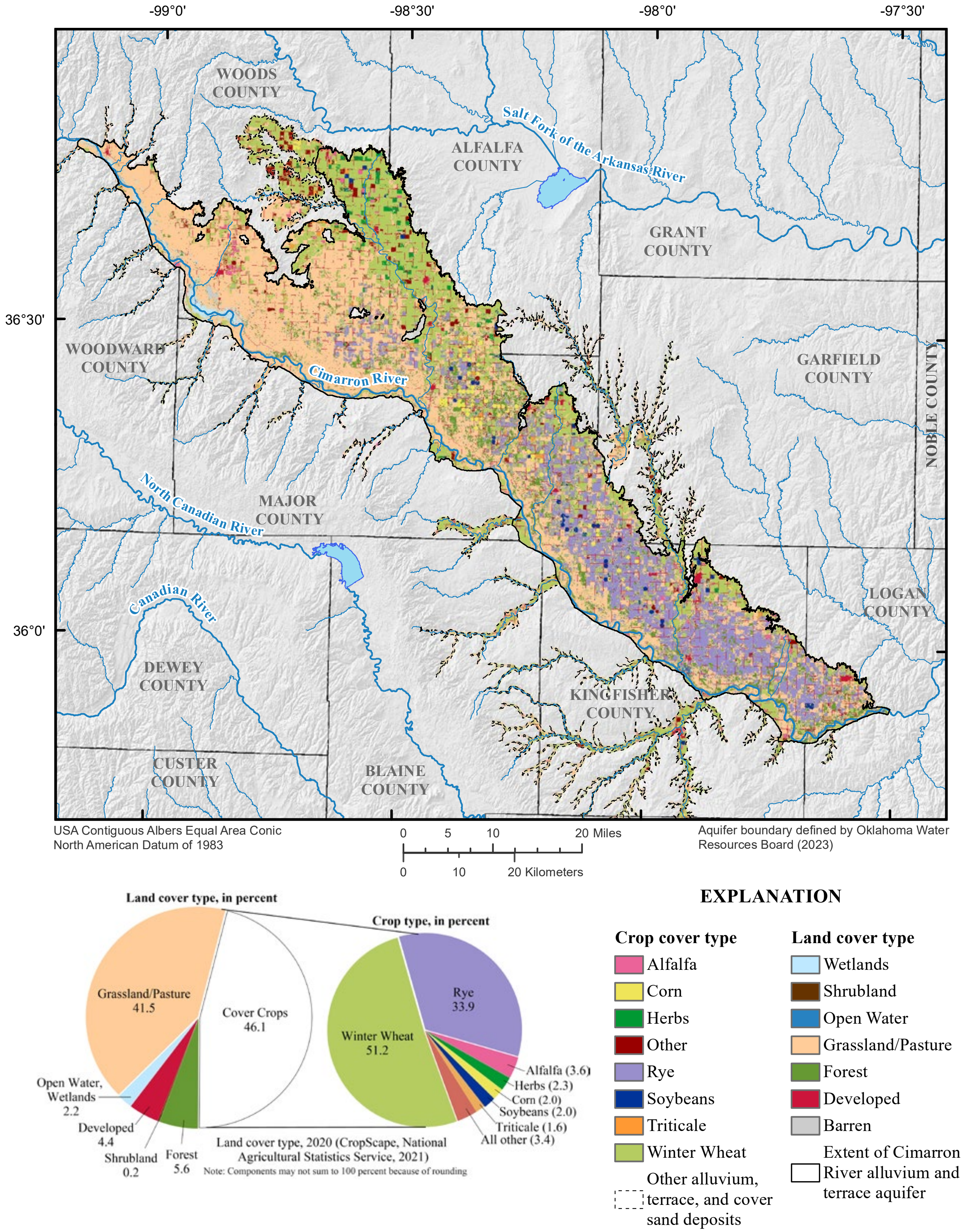


Figure 2. Land and crop cover type over the Cimarron River alluvium and terrace aquifer, northwestern Oklahoma (National Agricultural Statistics Service, 2021).

three preceding 20th-century drought periods because of cooler mean annual temperatures.

The period from 1981–2023 was characterized as an extended wet period with 28 of the 43 years (65 percent) recording above-mean precipitation (**Figure 3A**). The mean annual precipitation in the study area during this period was 31.4 inches per year, with a maximum of 44.4 inches in 2007 and a minimum of 21.2 inches in 2006 (**Table 1**). Although the 2002–06 and 2010–14 hydrologic drought periods were not as severe or prolonged as the 20th-century drought periods, individual years had similar negative departures from the mean and were exceptionally dry.

The mean annual temperature in the study area for the period of record 1895–2023 was 58.9 degrees Fahrenheit (°F), with a maximum of 62.5°F in 2012 and a minimum of 56.2°F in 1895 (**Figure 3B**; **Table 1**). The period from 1895–1920 was mainly cool with 18 of the 26 years (69 percent) recording below-mean temperatures; a short 4-year period of above-mean temperature occurred between 1908–11 (**Figure 3B**). The period from 1921–56 was mainly dry, with 22 of the 36 years (61 percent) recording above-mean temperatures (**Figure 3B**); the period is punctuated by an 11-year period (excluding 1946) of below-mean temperature between the 1929–41 and 1952–56 hydrologic drought periods.

The period from 1957–97 was characterized as an uprecedented (for the period of record) cool period with 31 of the 41 years (76 percent) recording below-mean temperature; the period is punctuated by two 2- to 3-year periods of below-mean temperature, one of which was associated with the 1961–2 hydrologic drought period (**Figure 3B**). The mean annual temperature in the study area during this period was 58.3°F (**Table 1**). The 26-year (and continuing) extended warm period from 1998–2023 rivals that of the historic 1920–41 dry period in the state, with individual years having positive departures from the mean similar in magnitude to individual years during the 1929–40 and 1952–56 hydrologic drought periods (**Figure 3B**).

The mean of 23 global climate models used by the Coupled Model Intercomparison Project 5 (CMIP5) predicts an increase of about 3.3°F in mean annual temperature in the study area between the historical period 1981–2010 and the future period 2025–49, with the potential for an additional 1.2°F increase for the 2050–74 climate period (Alder and Hostetler, 2013). The climate models predict little change (± 0.04 inches) in the mean monthly precipitation between the historical and future climate periods (Alder and Hostetler, 2013). If the future climate predictions hold, water demand and water use in the study area will likely increase, which will put additional stress on the aquifer.

Maximum monthly precipitation occurs in the spring during May and June, with a secondary period of higher precipitation between August and October. Minimum monthly precipitation generally occurs in the winter. Mean monthly precipitation in the study area for the period of record 1895–2023 was greatest (4.4 inches) in May and least (0.9 inches) in January (**Figure 4**). The mean monthly temperature in the study area for the period of record 1895–2023 was greatest (82.3°F) in July and least (34.6°F) in January (**Figure 4**).

Geology

The geologic units in the study area include Quaternary-age alluvium and terrace deposits of the Cimarron River, aeolian deposits, and Permian-age sedimentary bedrock (**Figure 5**). As part of this investigation, staff geologists made changes to published surface geology maps based on a combination of driller's logs, satellite imagery, lidar, and field observations; the changes have not been peer reviewed, so are considered provisional and subject to change. **Table 2** shows a stratigraphic column of the geologic and hydrologic units in the study area. The Cimarron River likely originated during the early Cenozoic Era as one of the numerous eastward-flowing streams that initiated following the uplift of the Rocky Mountains (Fay and others, 1962). Westward

Table 1. Mean annual precipitation and mean annual temperature for selected counties and climate periods, northwestern Oklahoma (Vose and others, 2014).

[FIPS, Federal Information Processing Series; National Weather Service, 2023]

County FIPS	County name	Mean annual precipitation, in inches per year			Mean annual temperature, in degrees Farenheit				
		1895–2023	1930–1980	1981–2023	1895–2023	1895–1920	1921–1956	1957–1997	1998–2023
151	Woods	25.9	24.5	27.3	57.7	56.9	58.1	57.2	58.7
003	Alfalfa	27.7	25.8	30.0	58.2	57.4	58.5	57.7	59.3
093	Major	27.7	26.6	29.5	58.8	58.0	59.1	58.2	59.7
047	Garfield	30.7	29.2	33.3	58.8	58.1	59.2	58.2	60.0
073	Kingfisher	29.8	27.6	33.1	59.9	59.3	60.3	59.2	60.8
083	Logan	32.1	30.2	35.1	59.9	59.4	60.4	59.2	61.0
Study Area		**29.0**	**27.3**	**31.4**	**58.9**	**58.2**	**59.3**	**58.3**	**59.9**

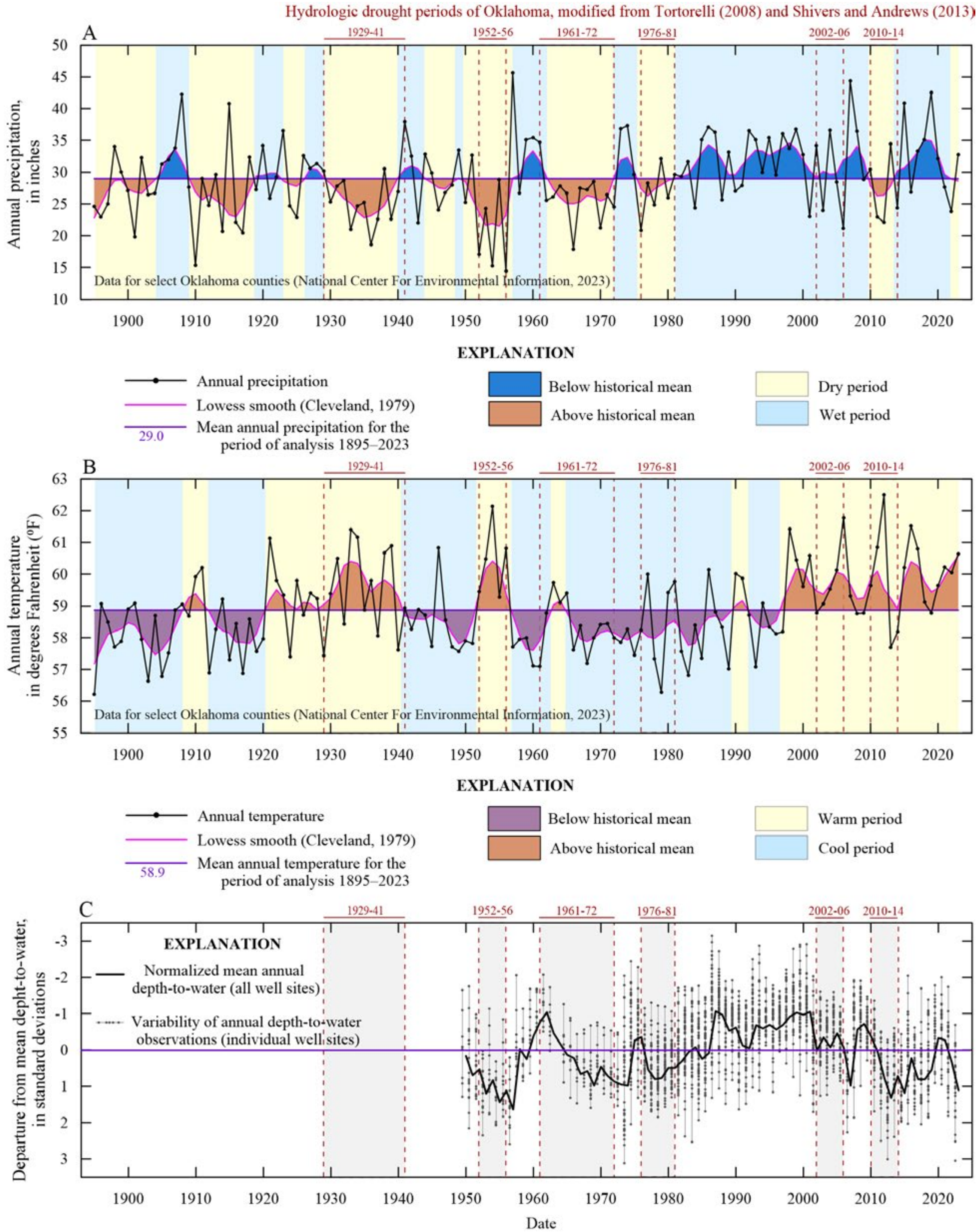


Figure 3. Annual precipitation (A) and annual temperature (B) from selected counties, northwestern Oklahoma, 1895–2023 with lowess lines for delineating periods of above- and below-mean annual precipitation and temperature. (C) Normalized mean depth-to-water for mass measurement sites within the Cimarron River alluvium and terrace aquifer.

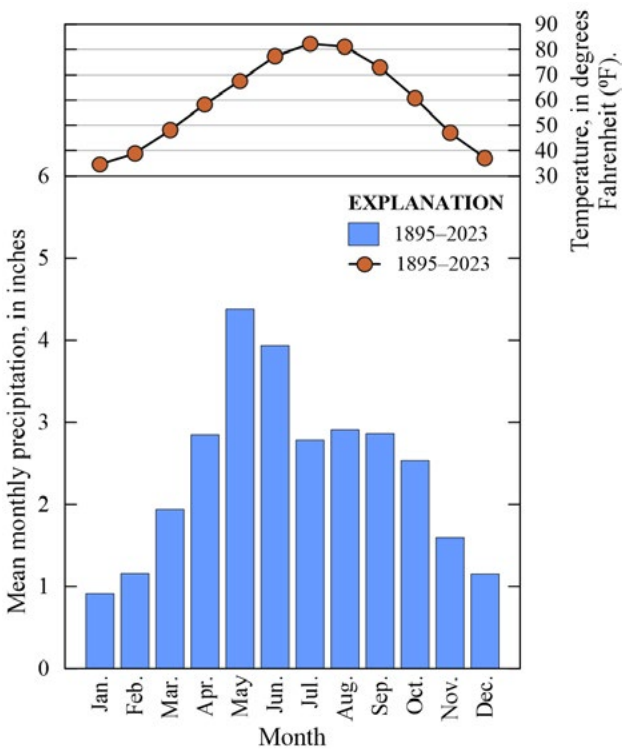


Figure 4. Mean monthly precipitation and temperature in the study area of the Cimarron River alluvium and terrace aquifer for the period of record 1895–2023

development of the stream channel continued through the mid-to-late Cenozoic Era as headwaters slowly carved into the Permian-age bedrock, forming a valley flanked by gentle escarpments (Fay and others, 1962).

Quaternary-Age Deposits

The unconsolidated Quaternary-age deposits of the Cimarron River alluvium and terrace aquifer unconformably overlie Permian-age bedrock. Alluvium deposits represent sediments actively being laid down in a present-day (modern) floodplain, while terrace deposits represent older alluvium deposits laid down in a former floodplain; younger floodplain deposits are separated from older deposits by topographic breaks, many of which are obscured by dune structures and cover sand within the study area (Reed and others, 1952). The alluvium and terrace deposits are lithologically similar and are in general physically and hydraulically connected across the study area (Reed and others, 1952).

Alluvium deposits are delineated along the Cimarron River, its two largest tributaries (Eagle Chief and Turkey Creeks), and many smaller tributaries within the study area (**Figure 5**). Alluvium mainly consists of interfingering deposits of light-tan to gray locally derived clay, silt, and sand with minor amounts of gravel (Morton, 1980; Stanley and others, 2002). Alluvium along the Cimarron River typically ranges in thickness from 0 to 50 feet, with a mean greater than 20 feet (Adams and Bergman, 1996); maximum thickness may be as high as 100 feet locally (Morton, 1980). The meandering nature of the Cimarron River has resulted in an active alluvial floodplain that ranges in width from 0.2 to 2.4 miles, with a mean of about 1.0 mile.

Terrace deposits, including terrace gravels, make up the bulk of the aquifer material. Terrace deposits have a similar composition to alluvium, being composed mostly of locally derived medium- to fine-grained sands, silts, and clays with variable amounts of distally derived medium- to coarse-grained sands and gravels and volcanic ash (Morton, 1980; Stanley, 2021). Gravel lenses commonly consist of rounded pebbles and cobbles of quartz, chert, and quartzite, some as large as six inches (Reed and others, 1952). The color of the terrace deposits is predominantly reddish-brown but varies from light gray to brown (Adams and Bergman, 1996).

The Cimarron River alluvium and terrace aquifer has three distinct terrace shelves (high, intermediate, and low) that occur along the northeast side of the Cimarron River; from low to high, the top of each shelf occurs approximately 20, 90, and 190 feet above the alluvial flood plain (Fay, 1965). The intermediate and high shelves contain minor shelves at 50 and 140 feet above the alluvial flood plain, respectively (Fay and others, 1962). The oldest deposits occur at higher elevations and the youngest deposits occur nearest to the present-day floodplain. The terrace shelves represent cycles of subsequent deposition and erosion through the Pleistocene Epoch as the ancestral Cimarron River migrated laterally toward the southwest along the regional dip of the underlying Permian bedrock (Fay, 1965; Adams and Bergman, 1996). In most areas, the topographic expression of each shelf is obscured by dune structures or post-Pleistocene erosion (Reed and others, 1952).

The thickness of the terrace deposits can differ greatly from one area of the aquifer to another, ranging from 0 to 120 feet, with a mean of around 60 feet (Morton, 1980; Adams and Bergman, 1996). Variations in thickness are attributed to the irregularity of the underlying bedrock surface and post-depositional erosion (Reed and others, 1952). The apparent width of the Terrace deposits within the study area varies from less than one mile to a maximum of approximately 14 miles, with a mean of 9 to 10 miles (**Figure 5**).

Mechanical reworking of the terrace deposits by wind has created large dune fields north of the Cimarron River that form a strip ranging from 7 to 10 miles wide (Reed and others, 1952). Placement of these dunes is believed to be caused by the prevailing southerly winds and their rate of migration is largely controlled by the presence of vegetation (Reed and others, 1952; Miller and Stanley, 2003). Dune material mainly consists of windblown reddish-brown to brown, very fine- to coarse-grained sand with some small amounts of calcareous or argillaceous material (Adams and Bergman, 1996); dunes can reach heights of 70 feet in more stable areas. Unconnected, elongated areas of featureless cover sand exist throughout the study area, but most especially along the northern edge of the aquifer boundary (**Figure 5**). Cover sands have a similar origin to dune sands but are mainly composed of very fine-grained sands, coarse-grained silts, and clay (Miller and Stanley, 2003). Thickness ranges from 0 to 30 feet, with a mean of 5 feet.

Permian-Age Geologic Units

Permian-age bedrock units exposed adjacent to and sub-cropping the Cimarron River alluvium and terrace aquifer are predominantly composed of thick sequences of fine-grained sandstones, argillaceous siltstones, red shale, dolomite, gypsum, and salt beds (Reed and others, 1952; Carr and Bergman, 1976; Morton, 1980; Bingham and Bergman, 1980). Within the study area, Permian-age bedrock units crop out in isolated areas where streams have eroded the alluvium and terrace deposits and in areas where high protrusions of the irregular bedrock surface deterred sedimentation (Christenson, 1983; Adams and Bergman, 1996).

Permian-age bedrock units crop out as bands, which strike north-northwest and have a regional dip that ranges from 4 to 30 feet per mile (Adams and Bergman, 1996). The dip direction rotates from south-southwest to nearly east-west as you travel eastward from Woodward County to Logan County. These bedrock units in descending order from youngest to oldest are the Dog Creek Shale, Blaine Formation, Flowerpot Shale, Chickasha Formation, Duncan Formation, Cedar Hills Sandstone, Hennessey Formation, and Garber Sandstone (**Figure 5**; Morton, 1980; Heran and others, 2003). The Chickasha and Cedar Hills Sandstone formations are no longer considered individual formations but will be discussed herein to describe their relative stratigraphic correlations and physical characteristics as defined in older OGS geology maps.

The Dog Creek Shale and Blaine Formation underlie the alluvium of the Cimarron River in western Woods County but do not directly intersect deposits of the Cimarron River alluvium and terrace aquifer (**Figure 5**). The Flowerpot Shale underlies the aquifer in sections of Woods, Alfalfa, and Major counties. The Flowerpot Shale is composed of reddish-brown silty shale with several thin alternating gypsum or dolomite beds in the upper 50 feet of the formation; the dolomite beds generally only occur in parts of Woods and Woodward counties (Stanley and others, 2002; Miller and Stanley, 2003). Thickness of the Flowerpot Shale is about 180 feet in Woods County; the formation reaches a maximum thickness of about 430 feet in Blaine County and a minimum thickness of 20 feet in Kingfisher County, where it interfingers with the upper part of a lithostratigraphic unit previously mapped as the Chickasha Formation (Morton, 1980; Meiser, 1954; Bingham and Moore, 1975; Fay and others, 1962); the lower part of the unit grades into the underlying Duncan Formation. Previous investigators described the Chickasha Formation as a variegated cross-bedded mudstone conglomerate interbedded with reddish-brown to orange-brown siltstones, shales, and fine- to coarse-grained sandstones about 30 to 100 feet thick in the study area. The upper and lower contacts of the unit are gradational and, in some places, ill-defined. A revised interpretation is that the Chickasha Formation represents a facies transition between the Duncan Formation and Flowerpot Shale (Oklahoma Geologic Survey, email communication, 2021). The geologic quadrangle map of north Oklahoma City does not distinguish the Chickasha Formation as an individual lithostratigraphic unit, opting instead to merge parts of the unit into the Flowerpot Shale and Duncan Formation (Stanley, 2021). Thickness of the merged Chickasha-Flowerpot Shale unit in Kingfisher County is about 115 feet. **Figure 5** shows the approximate extent of the former Chickasha Formation, as depicted in Fay (2010).

The Duncan Formation crops out in Kingfisher County, where it grades northward into the lower part of the Flowerpot Shale and the upper part of the Hennessey Formation, previously mapped as the Cedar Hills Sandstone (Meiser, 1954). The contact between the Duncan and Flowerpot formations is gradational, while the contact with the Hennessey Formation is sharp and planar (Stanley, 2021). The Duncan Formation is mainly composed of reddish-orange to pale brown friable to weakly indurated, fine- to very-fine-grained sandstone with moderately indurated mudstone- and siltstone-pebble conglomerates, and thin interbeds of siltstone locally; the interbeds of siltstone are lenticular in shape, average three feet in thickness and only extend for tens of feet. Thickness of the Duncan Formation ranges from 48 to 328 feet (Stanley, 2021); the thickness includes some parts of the previously mapped Chickasha Formation.

In contrast with older OGS geology maps (Bingham and Moore, 1975; Carr and Bergman, 1976; Bingham and Bergman, 1980; Morton, 1980), the Cedar Hills Sandstone is no longer distinguished as a separate lithostratigraphic unit from the broader Hennessey Formation (Stanley and others, 2002; Miller and Stanley, 2003; Stanley, 2021). The decision to forgo the previous designation is based on revised stratigraphic unit correlations and mapping practices. Previous investigators attempted to distinguish the Cedar Hills Sandstone from other members of the Hennessey Formation based on lithologic composition and correlation with an equivalent sandstone unit in Kansas. The composition of the Cedar Hills Sandstone changes laterally, with the amount and coarseness of interbedded sandstones decreasing southward from the Kansas-Oklahoma border toward Kingfisher County (Bingham and Moore, 1975); the maximum thickness of the member in Oklahoma is about 180 feet. Across most of the study area, the Cedar Hills Sandstone is more of a coarse-grained siltstone (Oklahoma Geologic Survey, email communication, 2021). The Cedar Hills Sandstone is shown in **Figure 5** as part of the Hennessey Formation but is separated out using hashed lines to show the approximate areal extent of the member as previously mapped. The Cedar Hills Sandstone, Duncan Formation, Chickasha Formation, Flowerpot Shale, Blaine Formation, and Dog Creek Shale are all considered part of the El Reno minor aquifer in Oklahoma (Belden, 2000).

The Hennessey Formation underlies the Cimarron River alluvium and terrace aquifer in parts of Major, Garfield, Kingfisher, and Logan counties. The Hennessey Formation is mainly composed of interbedded orange-brown to reddish-brown shales, silty claystones, or mudstones, with local

Table 2. Stratigraphic column of geologic and hydrogeologic units of the Cimarron River alluvium and terrace aquifer study area.

[Avg., Average; ≤, less than or equal to; >, greater than]

System	Epoch	Geologic unit	Description	Thickness, in feet	Aquifer
Quaternary	Holocene	Alluvium (Qal)	Unconsolidated deposits of light-tan to gray locally derived clay, silt, and sand with minor amounts of gravel. Deposited in modern stream channels and floodplains.	0–50[b] Avg. > 20b	[ab]Cimarron River A & T Major
		Terrace Deposits, including dunes (Qtd)	Unconsolidated deposits of reddish-brown to light gray or brown locally derived medium- to fine-grained sand, silt, and clay with variable amounts of distally derived sand and gravel. Dunes created by aeolian reworking of older quaternary-age deposits form mounds supported by vegetation.	0–120[ab] Avg. 60c	
	Pleistocene	Cover Sand (Qcs)	Unconsolidated very-fine grained sand and coarse-grained silt and clay. Forms extensive, thin, featureless topographic surfaces.	0–30[d] Avg. 5d	
		Terrace Gravel (Qtg)	Unconsolidated deposits of distally derived gravel and medium- to fine-grained sand with minor amounts of locally derived silt and clay. Deposited at various elevations above and along the former courses of modern streams.	0–98[d] Avg. ≤ 36	
Permian	Guadalupian	Dog Creek Shale (Pdc)	Interbedded reddish-brown shale, silty shale, and siltstone with several thin stringers of light gray dolomite and white gypsum.	5–100[cd]	
		Blaine Formation (Pbl)	Alternating sequence of two to four gypsum and dolomite beds separated by thick intervals of reddish-brown shale. Gypsum is massive and white.	0–98[cde]	[g]El Reno Minor
		Flowerpot Shale (Pfp)	Reddish-brown silty shale with thin alternating gypsum or dolomite beds in the upper 50 feet of the formation.	0–430[cd]	
		Chickasha Formation (Pc)	Variegated cross-bedded mudstone conglomerate interbedded with reddish-brown siltstones, shales, and fine- to coarse-grained sandstones. Facies transition between the Flowerpot Shale and Duncan Formation.	0–30[c]	
		Duncan Formation (Pdn)	Reddish-brown to orange-brown, fine- to very fine-grained sandstones interbedded with siltstone-pebble conglomerates and thin intervals of siltstone and mudstone. Includes part of 'Chickasha Formation'	0–330[d]	
	Leonardian	Hennessey Formation (Phy)	Interbedded orange-brown to reddish-brown shales, silty claystones, or mudstones, with local occurrences of argillaceous siltstones and fine- to very fine-grained sandstones. Includes the 'Cedar Hills Sandstone' (Pch)	300–1,476[def]	
		Garber Sandstone (Pgr)	Reddish-brown to light-brown, fine- to very fine-grained (less common) sandstones irregularly bedded with varying amounts of red shale, siltstones, breccias, and sandstone- or siltstone-pebble conglomerates	0–1,050[df]	--

[a] Reed and others, 1957

[b] Adams and Bergman, 1996

[c] Morton, 1980

[d] Stanley, 2021

[e] Miller and Stanley, 2003

[f] Stanley and Miller, 2008

[g] Belden, 2000

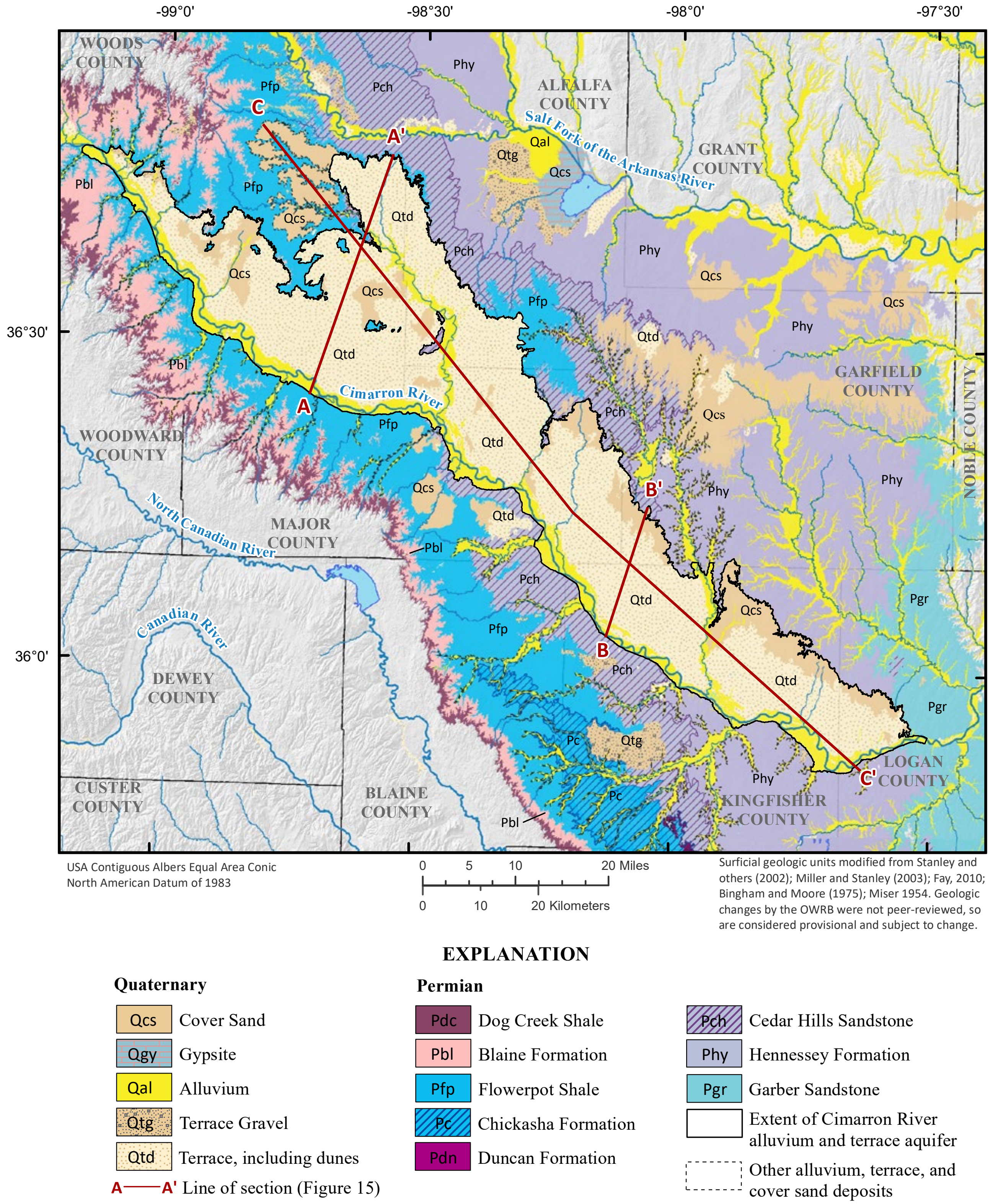


Figure 5. Surficial geologic units in the Cimarron River alluvium and terrace aquifer study area, with cross-section lines A-A’, B-B’, and C-C'.

occurrences of argillaceous siltstones and fine- to very fine-grained sandstones (Stanley and others, 2002; Miller and Stanley, 2003). Sandstones are silty to argillaceous, typically found as thin, lenticular lenses less than three feet thick with limited lateral extents (Stanley, 2021). Thickness of the Hennessey Formation varies between 300 to 1,476 feet, with a mean of about 650 feet (Stanley, 2021); the Bison, Salt Plains, Kingman Siltstone, and Fairmont Shale members of the Hennessey Formation have limited regional distributions and ill-defined contacts and are thus not shown as separate units in **Figure 5**.

The Garber Sandstone underlies about 14 square miles of the aquifer in Logan County. The Garber Sandstone is mainly composed of reddish-brown to light-brown, fine- to very fine-grained sandstones irregularly bedded with varying amounts of red shale, siltstones, breccias, and sandstone- or siltstone-pebble conglomerates (Stanley, 2021). The thickness of individual sandstone beds varies from less than three feet to more than 65 feet, with a mean of about 20 feet. The total thickness of the Garber Sandstone within the study area ranges from 82 feet in Garfield County to a maximum of about 1,050 in Logan County (Stanley, 2021). The Garber Sandstone has been delineated by the OWRB as a contributing hydrogeologic unit in the North-Central Oklahoma Minor aquifer north-east of the study area and major Garber-Wellington Aquifer southeast of the study area (Belden, 1997; Mashburn and others, 2013).

Cross Sections

Three cross-sections of the Cimarron River alluvium and terrace aquifer were created as part of this investigation, showing the land surface elevation, the base of the aquifer, and the 2016 potentiometric surface. Cross-sections A-A’ and B-B’ are oriented northeast-southwest and cross-section C-C’ is oriented northwest-southeast (**Figure 5**).

Cross-section A-A’ (**Figure 6**) spans roughly 27 miles and is located exclusively in Woods County. The most prominent feature in the cross-section is a bedrock ridge (extension of the Gypsum Hills) located approximately eight miles northeast of the Cimarron River. The Permian-age bedrock surface is oriented northwest-southeast and rises in altitude by more than 200 feet between the Cimarron River and the peak in east-central Woods County. On the northeast end of the cross-section, the bedrock rises in altitude by about 70 feet creating a valley that directs groundwater towards Eagle Chief Creek and its tributaries.

On the southwest side of the Permian ridge, groundwater is directed toward the Cimarron River. Eagle Chief Creek and Sand Creek have incised the Permian-age bedrock such that their stream channels are at a lower altitude than the Quaterary-Age deposits. The 2016 potentiometric surface intersects the stream channels of Eagle Chief Creek, Sand Creek, and the Cimarron River suggesting that groundwater is discharging to these streams. The mean saturated thickness along the transect is about 26 feet, with areas northeast of Eagle Chief Creek generally being less than 20 feet and areas southwest of Sand Creek generally being greater than 35 feet.

Cross-section B-B’ (**Figure 6**) spans roughly 14 miles across parts of Kingfisher and Garfield counties. The base of the aquifer dips to the southwest toward the Cimarron River. The gradient of the base is steeper in Garfield County (roughly 25 feet per mile) than in Kingfisher County (roughly 10 feet per mile). The interpolated 2016 potentiometric surface intersects the Cimarron River floodplain indicating groundwater discharge to the stream, a conclusion that is generally supported by data collected from the USGS streamflow gauging stations near Waynoka and Dover, Oklahoma. The aquifer is considerably thicker in the central region of the cross-section than on either end, with a maximum saturated thickness of more than 80 feet.

Cross-section C-C’ (**Figure 6**) spans roughly 94 miles from central Woods County to Logan County. The altitude of the base declines by more than 500 feet (roughly 5 feet per mile) between the northwest and southeast ends of the transect. The cross-section shows that the bedrock topography is uneven and that Little Eagle Chief Creek, Indian Creek, Hoyle Creek, and Turkey Creek have downcut the terrace deposits forming narrow alluvial valleys. Thickness of the terrace deposits is greatest between Hoyle and Turkey Creeks and generally thinner northwest of the town of Aline. Field observations by OWRB staff generally support the classification of previous investigators that Indian Creek is perennial. The cross-section cuts across Hoyle Creek in an area where the contours are bending upstream, indicating flow towards the stream.

Hydrologic Characteristics of the Aquifer

Streamflow and Baseflow

The Cimarron River is a mature, well-developed river with a defined stream channel and floodplain that extends nearly 670 miles from its headwaters in New Mexico through sections of Colorado, Kansas, and Oklahoma, where it effectively terminates at Keystone Reservoir west of Tulsa and merges with the Arkansas River. Surface drainage to the Cimarron River is carried by more than thirty major and minor tributaries between the cities of Freedom and Guthrie (**Figure 1**). North of the Cimarron River, twelve named and multiple unnamed streams transect the aquifer; from west to east, they are Anderson, Redhorse, Wildcat, Whitehorse, Dog, Walnut Grove, Eagle Chief, Indian, Hoyle, Preacher, Turkey, and Sooner creeks. With the exceptions of Whitehorse, Dog, Hoyle, Preacher, and Sooner Creeks (West Fork and East Fork) all the streams north of the Cimarron River originate outside of the aquifer area and have well-developed drainage systems originating in Permian-age geologic units. An earlier report (Adams and Bergman, 1996) classified Anderson, Redhorse, Wildcat, and Walnut Grove creeks as intermittent streams, only having sustained flows when groundwater

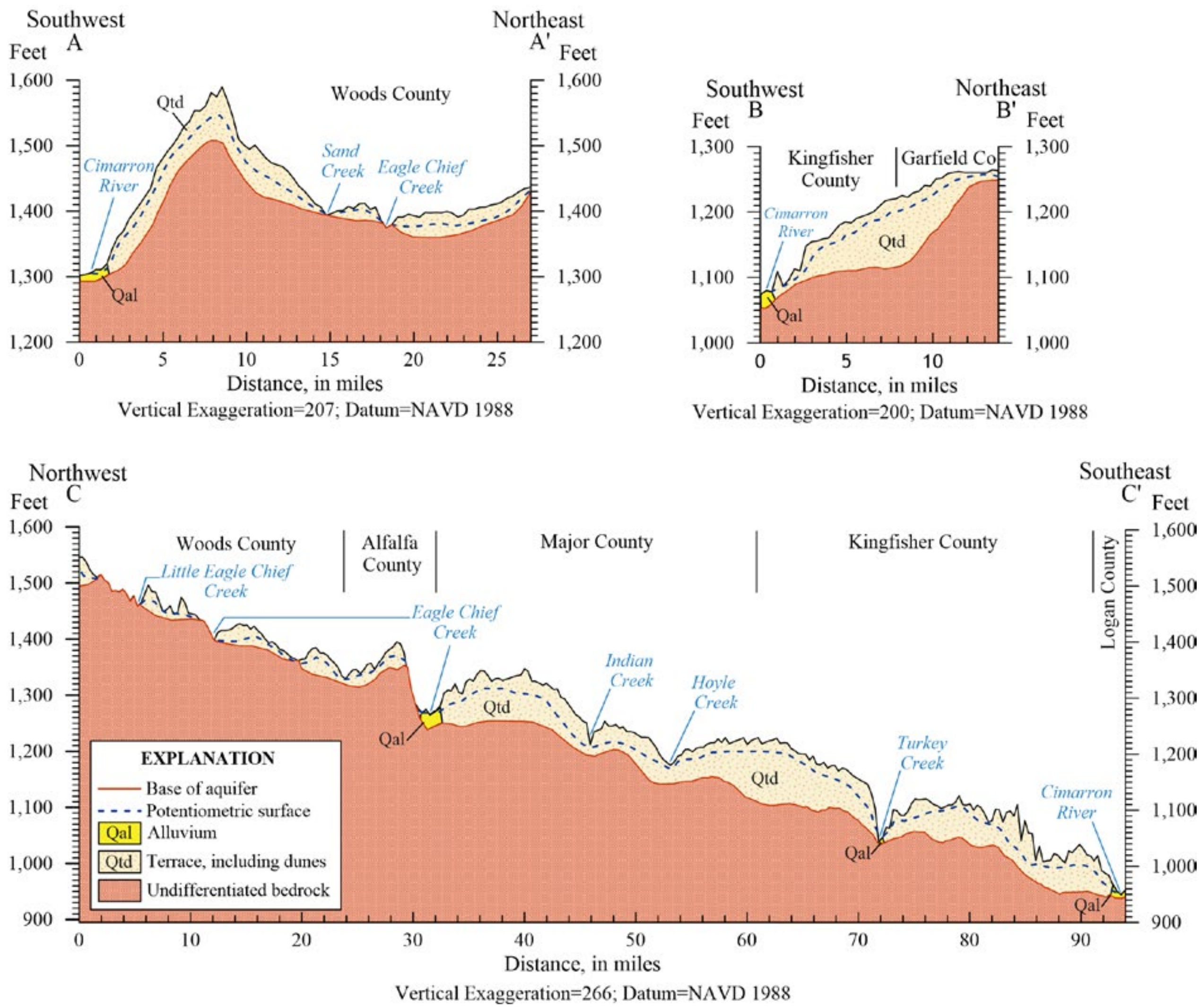


Figure 6. Hydrogeologic cross-sections of the Cimarron River alluvium and terrace aquifer, northwestern Oklahoma.

altitude in the surrounding terrace deposits is high; the same investigators classified Dog, Whitehorse, and Sooner creeks as perennial streams. Hoyle and Preacher creeks are mixed with some reaches being perennial and others being more intermittent; Reed and others (1952) classified both streams as intermittent, having sustained flows during periods throughout the year with high precipitation and no flow during the summer months.

Satellite imagery taken over the last twenty years shows that most of the water in Dog and Preacher creeks drains into marshland areas approximately 0.5 to 0.8 miles north of the Cimarron River (Google Earth Pro, 2021). Likewise, most of the water in Walnut Grove Creek drains into a 3.75-acre cattle pond that has been around since at least 1985. The stream channels of Anderson, Redhorse, Wildcat, and Whitehorse appear unobstructed in the most currently available (2020) satellite imagery over the area.

The three main tributaries draining the aquifer are Eagle Chief Creek, Indian Creek, and Turkey Creek. Eagle Chief Creek is the largest stream in the study area with a drainage area of approximately 483 square miles. Little Eagle Chief Creek, Sand Creek, Lake Creek, and several unnamed tributaries provide small perennial flows to Eagle Chief Creek (**Figure 1**; Adams and Bergman, 1996). Eagle Chief Creek has a broad alluvial valley along most of its extent, except near Cleo Springs, where the valley decreases from 1 mile wide to about 1/3 mile wide. West of the city of Carmen, the stream channel is incised into the underlying 'Cedar Hills Sandstone' bedrock unit; in this area, the stream is considered perennial below the terrace deposit contact and intermittent above the contact (Adams and Bergman, 1996). Eagle Chief Creek drains approximately 28 percent of the Cimarron River alluvium and terrace aquifer.

Indian Creek initiates in Permian-age bedrock about eight miles north of the town of Ringwood and has a drainage area of about 69 square miles, of which 41 square miles is underlain by alluvium and terrace deposits (**Figure 1**). Adams and Bergman (1996) considered Indian Creek to be intermittent upstream of the town and Ringwood and perennial downstream. Historical satellite imagery taken

Table 3. Selected stream gauge stations in the Cimarron River alluvium and terrace aquifer study area, northwestern Oklahoma

[M/D/Y, month/day/year; OWRB, Oklahoma Water Resources Board; USGS, United States Geological Survey; mi2, square miles; --, data not available or not applicable. USGS data can be accessed using the 8- digit station id or station name through the USGS National Water Dashboard or Hydrologic Toolbox. OWRB data can be accessed using the station name through the OWRB Water Data and Analysis Tools Dashboard — Continuous Rivers/Streams Data. Stream gauge locations shown in Figure 1]

Station id	Station name	Station operator	Latitude	Longitude	County	Period of record[1] date (M/D/Y)		Drainage area mi2
						Begin	End	
OK620920040010	Eagle Chief Creek near Cleo Springs, Ok	OWRB	36.405	-98.447	Major	7/26/2016	3/26/2021	469
OK620910060010	Turkey Creek near Dover, Ok	OWRB	35.979	-97.923	Kingfisher	7/26/2016	6/5/2018	412
7159750	Cottonwood Creek near Seward, OK	USGS	35.814	-97.478	Logan	3/1/1973	Present (2025)	320
7158400	Salt Creek near Okeene, OK	USGS	36.103	-98.194	Kingfisher	7/1/1961	9/29/1979	196
7159200	Kingfisher Creek near Kingfisher, OK	USGS	35.834	-98.066	Kingfisher	10/1/1966	9/29/1970	157
7159000	Turkey Creek near Drummond, OK	USGS	36.318	-98.001	Garfield	10/1/1947	9/29/1970	248
--	Turkey Creek near Hennessey, OK*	--	36.170	-97.953	Garfield	10/1/1947	9/29/1970	330
7157980	Cimarron River near Freedom, OK	USGS	36.755	-99.117	Woodward	10/1/1973	9/29/1980	12,917
7158000	Cimarron River near Waynoka, OK	USGS	36.517	-98.880	Woods	10/1/1937	Present (2025)	13,399
AMCO2	Cimarron River near Ames, OK **	OWRB	36.219	-98.253	Major	11/1/2006	Present (2025)	14,597
7159100	Cimarron River near Dover, OK	USGS	35.952	-97.915	Kingfisher	10/1/1973	Present (2025)	15,809
7160000	Cimarron River near Guthrie, OK	USGS	35.921	-97.426	Logan	10/1/1937	Present (2025)	17,006

[1] Period of record may not be continuous.

* Ficticious stream gauge station used for drainage-area ratio method (Hirsch, 1979)

** Sites operated in cooperation with the U.S. Army Corps of Engineers between 1985 and 2019 showed that even during below-average precipitation years and dry season months, water was always present to some degree within the stream channel both north and south of the town of Ringwood (Google Earth Pro, 2021); tributaries of Indian Creek north of the town of Ringwood all appear intermittent, with some being complete dried out in a few images, specifically those taken during summer months. A few of the unnamed tributaries have over time been cut off from Indian Creek by constructed cattle ponds, which capture all upstream flow.

Turkey Creek is the second-largest stream in the study area with a drainage area of approximately 421 square miles, of which 97 square miles is underlain by alluvium and terrace deposits of the Cimarron River alluvium and terrace aquifer. Turkey Creek initiates near the town of Helena and flows to the southeast past the towns of Lahoma and Drummond before contacts deposits of the Cimarron aquifer about five miles north of the town of Hennessey (**Figure 1**). Thin alluvial deposits underlying Turkey Creek north of the town of Hennessey are not considered part of the Cimarron River alluvium and terrace aquifer. Turkey Creek is considered perennial, although the water level in a few reaches can be so low that the stream nearly dissociates into a series of disconnected pools (internal communication, OWRB streams monitoring division).

South of the Cimarron River, surface drainage is carried to the Cimarron River by seventeen named and multiple unnamed streams and tributaries that transect Permian age geologic units; from west to east, they are Long Creek, Doe Creek, Chimney Creek, Sand Creek (1), West Creek, Main Creek, Griever Creek, Barney Creek, Cheyenne Creek, Cottonwood Creek (1), Gypsum Creek, Sand Creek (2), Deep Creek, Salt Creek, Cooper Creek, Kingfisher Creek, and Cottonwood Creek (2) (**Figure 1**). Based on a field site visit, the stream channel of Griever Creek has been destroyed by unnatural causes (plow truck) under the US Highway 412 bridge in Major County.

A baseflow separation tool, available in the USGS Groundwater Toolbox (Barlow and others, 2015) was used to partition streamflow hydrographs from gauge stations along the Cimarron River and a few larger tributaries into direct runoff and baseflow components. The tool uses the baseflow index method of Rutledge, (1998), to compute baseflow volume. The method works by scanning streamflow hydrographs using an antecedent regression to identify periods that coincide with negligible surface runoff, designating baseflow to be equal to streamflow during these periods, and linearly interpolating baseflow for periods that do not meet the antecedent recession requirement. The fractional ratio of baseflow volume to streamflow volume is referred to as the baseflow index (BFI), written as a percentage.

In addition to the baseflow separation analysis, which was used to evaluate long-term fluctuations in streamflow and baseflow within the study area, a series of measurements were made in January 2020 to evaluate differences in baseflow contribution to the Cimarron River between tributaries draining Permian-age bedrock units and tributaries draining Quaternary-age alluvium and terrace deposits.

Baseflow Separation Analysis for Long-Term Trends

At the time of this study, there were no USGS streamflow gauging stations on any of the Cimarron River tributaries that drain the aquifer. To aid in the analysis, the OWRB installed streamflow gauges on Eagle Chief Creek near Cleo Springs (OK620920040010) and Turkey Creek near Dover (OK620910060010) (**Figure 1**; **Table 3**). The Cleo Springs stream gauge was activated on July 26, 2016, and was discontinued on March 26, 2021. The Turkey Creek stream gauge was activated on the same day but was discontinued on June 5, 2018, due to resource allocation changes. Between 2016 and 2021, there were multiple instances of one or both stream gauges becoming non-operational for short periods, either because of equipment errors or theft. Short gaps (1 to 5 days) in the streamflow record of either gauge station were linearly interpolated before being imported into the USGS baseflow separation tool based on increasing or decreasing trends in daily streamflow estimates; larger gaps in the streamflow record were left blank. Streamflow, baseflow, and baseflow index estimates at both OWRB gauge stations were analyzed monthly.

Monthly streamflow measurements from the OWRB gauge station near Cleo Springs ranged from 12.1 cubic feet per second in December 2016 to 363.9 cubic feet per second in May 2018, with a period of record mean of 67.6 cubic feet per second (**Table 4**). Daily streamflow values in Eagle Chief Creek most frequently fell between 20 to 50 cubic feet per second. Most high-flow events ranged from 100 to 1,000 cubic feet per second, but most frequently fell between 100 to 300 cubic feet per second; during high-flow events stream stage was as much as 15 feet above the mean. The mean monthly baseflow to Eagle Chief Creek was estimated to be 37.3 cubic feet per second with a BFI of 67.7 percent (**Table 4**); the monthly BFI was generally highest during the dry winter season and lowest during the wet spring season.

Monthly streamflow measurements at the OWRB gauge station near Dover ranged from 4.9 cubic feet per second in September 2016 to 189.0 cubic feet per second in April 2017, with a period of record mean and median of 30.4 and 7.6 cubic feet per second, respectively (**Table 4**). The relatively large difference between the mean and median indicates that the mean is heavily biased by several high-flow events and that normal monthly flow in the creek is likely closer to the median. At times during the period of record, field staff noted that reaches of the creek were not flowing and that during high-flow events, the stream stage was as much as 10 feet above the mean. Daily streamflow values in Turkey Creek most frequently fell between 5 to 10 cubic feet per second. Most high-flow events fell between 100 to 300 cubic feet per second. The mean monthly baseflow for Turkey Creek was estimated to be 21.7 cubic feet per second with a BFI of 87.9 percent (**Table 4**).

Streamflow in Turkey Creek includes flow contributions from outside of the defined aquifer boundary, specifically the area north of the city of Hennessey (**Figure 1**). Within this reach, Turkey Creek receives baseflow from Permian-age bedrock units and quaternary-age alluvium, and run-off from the surrounding drainage basin. Flow contribution to Turkey Creek from the drainage area north of the city of Hennessey was estimated based on mean annual streamflow values from the USGS gauge station (07159000) near Drummond, Oklahoma (**Figure 1**; **Table 3**); period of record 1947–70. The Drummond gauge station was located approximately 8.7 miles northwest of the defined aquifer boundary. To better approximate flow contributions from the drainage area north of the city of Hennessey, the drainage-area ratio method was used to approximate the mean annual streamflow for a fictitious gauge station located at the point where Turkey Creek intersects the defined aquifer boundary (roughly half a mile north of the Garfield-Kingfisher county line).

The drainage-area ratio method is based on the assumption that the ratio of the flows at two gauge stations within a common drainage basin is equal to the ratio of the drainage areas of the two gauge stations (Hirsch, 1979). Streamflow at the fictitious gauge station was estimated by multiplying mean annual streamflow estimates at the Drummond gauge station by the drainage area ratio of the two stations. The drainage area of the Drummond gauge station was 248 square miles, while the drainage area of the fictitious gauge station was estimated to be 330 square miles, which equated to a ratio of 1:1.33.

Annual streamflow estimates at the Drummond gauge station for the period 1948–69 ranged from 1.2 to 181.7 cubic feet per second with a mean of 50.2 cubic feet per second (**Table 5**). The mean annual baseflow was estimated to be 3.6 cubic feet per second with a BFI of about 12.0 percent (**Table 5**). Based on the calculated ratio, annual streamflow at the fictitious gauge station was estimated to range from 1.6 to 241.7 cubic feet per second, with a mean of 54.4 cubic feet per second. The mean annual baseflow was estimated to be 5.4 cubic feet per second (**Table 5**).

Data from four USGS stream gauge stations located on the Cimarron River were used in this long-term trend analysis (**Figure 1**). Detailed gauge station location information is listed in **Table 3**; from west to east along the Cimarron River, the gauges were located south of the town of Freedom near State Highway 50 (USGS 07157980), south of the city of Waynoka near U.S. Highway 281 (USGS 07158000), south of the town of Dover near U.S. Highway 81 (station 07159100), and north of the city of Guthrie near U.S. Highway 77 (USGS 07160000).

Streamflow at the gauge station near Freedom originates almost entirely from outside the study area; of the 12,917 square mile drainage area captured by the gauge station, only about 6 square miles are contained within the defined aquifer boundary. Therefore, deducting streamflow measurements at the Freedom gauge station from streamflow measurements at the three downstream gauge stations would have the apparent effect of removing flow contributions to the Cimarron River from the drainage basin northwest of the study area. This simple deduction method assumes that streamflow at a downstream gauge will always or nearly always be greater than streamflow at any upstream gauge over the same period (i.e., the stream is gaining) and that there is little to no loss in streamflow volume between gauges.

In order to calculate long-term flow contributions to the Cimarron River from the drainage basin northwest of the study area, an artificial streamflow record had to be constructed for the Freedom gauge station because it only had a period of record of about seven years (**Table 3**). To do this, a linear regression relationship was developed between the Freedom gauge station and downstream Waynoka gauge station for the common period of record 1974–79, using mean monthly streamflow estimates (**Figure 7A**). Mean monthly streamflow estimates were used in the regression analysis instead of the daily streamflow values because they resulted in a smaller variability between the observed and predicted values; the coefficient of determination (R2) for the mean daily streamflow datasets was 72.7 percent, while the coefficient of determination for the mean monthly streamflow datasets was 88.6 percent.

Correlation between the observed and predicted values was improved slightly (R2=97.0 percent) following a square root transformation of both the response and explanatory variables; because we were more interested in the predictive outcomes of the model rather than the ability to make inferences about model coefficients, the root square transformation was considered reasonable for this analysis. The square root transformation was applied to both variables to normalize the skewness of their distributions and reduce the heteroscedasticity of the regression residuals. ‘Observed’ mean monthly streamflow at the Freedom gauge station for the period 1974–79 ranged from 0.0 to 1,012.6 cubic feet per second with a mean of 170.9 cubic feet per second. Predicated mean month streamflow at the Freedom gauge station for the same period ranged from 0.0 to 1,131.9 cubic feet per second with a mean of 165.7 cubic feet per second. The transformed linear regression model was used to construct mean monthly streamflow records at the Freedom gauge station for the period 1938–2023; mean annual streamflow was estimated to be 178.0 cubic feet per second (**Table 5**).

Because monthly averages were used in the regression rather than daily averages, the predicted streamflow records could not be imported into the USGS baseflow separation tool which uses a partition of daily streamflow records to estimate daily baseflow. Instead, a second linear regression relationship was developed between the Freedom gauge station and downstream Waynoka gauge station for the common period of record 1974–79, using mean monthly baseflow estimates (**Figure 7B**). Like streamflow, a square root transformation was applied to both input variables to improve correlation; the coefficient of determination for the regression was 97.8 percent. ‘Observed’ mean monthly baseflow at the Freedom gauge station during the period 1974–79 ranged from 0.0 to 168.2 cubic feet per second with a mean of 51.8 cubic feet per second. The predicted

Table 4. Summary statistics of monthly streamflow, baseflow, and baseflow index values at two OWRB stream gauge stations in the Cimarron River alluvium and terrace aquifer study area, summarized through 2021.

[ft^3/s, cubic feet per second; %, percent; BFI, baseflow index; --, data not available or not applicable. Values computed using the BFI code Rutledge, (1998) in the USGS Groundwater Toolbox (Barlow and others, 2015). Orange and blue were used to delineate dry and wet years, respectively; see climate Figure 3. Stream gauge locations are shown in Figure 1, and stream gauge information is listed in Table 3]

Year	Month	OK620920040010 Eagle Chief Creek near Cleo Springs, OK				OK620910060010 Turkey Creek near Dover, OK			
		Mean streamflow	Median streamflow	Mean baseflow		Mean streamflow	Median streamflow	Mean baseflow	
		ft^3/s	ft^3/s	ft^3/s	% (BFI)	ft^3/s	ft^3/s	ft^3/s	% (BFI)
2016	Jul.	--	--	--	--	--	--	--	--
	Aug.	17.1	15.1	14.8	86.6	5.7	5.7	5.5	98.0
	Sept.	28.7	16.2	16.6	57.8	4.9	4.8	4.3	89.5
	Oct.	--	--	--	--	--	--	--	--
	Nov.	14.1	13.8	13.3	94.7	5.8	5.8	5.7	97.3
	Dec.	12.1	12.0	11.8	98.1	--	--	--	--
2017	Jan.	23.6	12.8	12.5	52.7	--	--	--	--
	Feb.	22.9	14.9	14.9	65.1	--	--	--	--
	Mar.	34.1	16.4	16.4	48.1	49.4	35.5	37.3	75.5
	Apr.	49.6	21.5	19.6	39.4	189.0	115.2	104.1	55.1
	May	52.4	29.8	25.8	49.4	185.1	133.3	143.0	77.3
	Jun.	29.5	25.8	24.8	84.0	--	--	--	
	Jul.	30.6	23.7	23.2	75.8	21.1	7.5	11.0	52.0
	Aug.	56.0	23.4	21.8	38.9	6.9	6.9	6.9	99.7
	Sept.	25.7	21.1	19.6	76.3	7.3	7.2	7.1	97.6
	Oct.	36.6	20.9	20.7	56.5	7.6	7.3	7.3	96.5
	Nov.	22.1	22.1	22.0	99.5	7.5	7.4	7.4	98.7
	Dec.	23.9	23.8	23.7	99.2	7.6	7.6	7.6	99.3
2018	Jan.	22.1	22.1	22.0	99.5	7.7	7.7	7.6	99.4
	Feb	26.0	23.2	22.4	86.1	7.6	7.6	7.5	98.9
	Mar.	58.8	15.9	23.1	39.4	7.8	7.7	7.7	99.3
	Apr.	48.7	23.4	23.6	48.4	7.8	7.7	7.6	96.6
	May	363.9	220.1	69.4	19.1	12.3	7.3	7.2	59.0
	Jun.	--	--	--	--	--	--		
	Jul.	111.8	55.0	80.3	71.9	--	--	--	--
	Aug.	92.8	57.1	40.7	43.9	--	--	--	--
	Sept.	152.8	40.0	26.1	17.1	--	--	--	--
	Oct.	360.6	291.0	185.5	51.5	--	--	--	--
	Nov.	--	--	--	--	--	--	--	--
	Dec.	--	--	--	--	--	--	--	--

Daily mean streamflow data used to construct these statistics were provisional at the time of analysis

Table 4. Summary statistics of monthly streamflow, baseflow, and baseflow index values at two OWRB stream gauge stations in the Cimarron River alluvium and terrace aquifer study area, summarized through 2021 — continued

[ft^3/s, cubic feet per second; %, percent; BFI, baseflow index; --, data not available or not applicable. Values computed using the BFI code Rutledge, (1998) in the U.S. Geological Survey Groundwater Toolbox (Barlow and others, 2015). Orange and blue were used to delineate dry and wet years, respectively; see climate Figure 3. Stream gauge locations are shown in Figure 1, and stream gauge information is listed in Table 3]

Year	Month	OK620920040010 Eagle Chief Creek near Cleo Springs, OK				OK620910060010 Turkey Creek near Dover, OK			
		Mean streamflow	**Median streamflow**	**Mean baseflow**		**Mean streamflow**	**Median streamflow**	**Mean baseflow**	
		ft^3/s	**ft^3/s**	**ft^3/s**	**% (BFI)**	**ft^3/s**	**ft^3/s**	**ft^3/s**	**% (BFI)**
2019	Jan.	115.2	108.0	85.2	74.0	--	--	--	--
	Feb.	52.3	44.8	43.6	83.5	--	--	--	--
	Mar.	98.5	47.1	39.5	40.1	--	--	--	--
	Apr.	--	--	--	--	--	--	--	--
	May.	188.5	122.2	67.1	35.6	--	--	--	--
	Jun.	101.1	66.0	62.3	61.6	--	--	--	--
	Jul.	44.4	43.3	41.3	93.1	--	--	--	--
	Aug.	58.6	37.9	33.1	56.6	--	--	--	--
	Sept.	54.8	37.1	34.0	62.0	--	--	--	--
	Oct.	44.1	40.5	37.6	85.4	--	--	--	--
	Nov.	44.6	40.1	38.6	86.6	--	--	--	--
	Dec.	43.7	36.2	35.0	80.2	--	--	--	--
2020	Jan.	38.5	30.8	29.9	77.7	--	--	--	--
	Feb.	40.8	33.6	31.8	77.8	--	--	--	--
	Mar.	77.4	47.2	42.4	54.8	--	--	--	--
	Apr.	54.7	45.7	45.1	82.4	--	--	--	--
	May.	46.4	43.8	39.4	84.9	--	--	--	--
	Jun.	45.7	32.9	30.9	67.5	--	--	--	--
	Jul.	143.8	49.4	39.3	27.4	--	--	--	--
	Aug.	56.8	47.2	43.7	76.9	--	--	--	--
	Sept.	48.0	43.5	41.8	87.1	--	--	--	--
	Oct.	54.3	40.1	38.3	70.6	--	--	--	--
	Nov.	45.0	39.8	39.0	86.6	--	--	--	--
	Dec.	48.9	41.0	38.8	79.4	--	--	--	--
2021	Jan.	68.0	49.6	43.7	64.2	--	--	--	--
	Feb.	51.6	49.4	47.3	91.6	--	--	--	--
	Mar.	--	--	--	--	--	--	--	--
Period of Record Monthly Mean		**67.6**	**48.3**	**37.3**	**67.7**	**30.4**	**7.6**	**21.7**	**87.9**

Table 5. Summary statistics of annual streamflow, baseflow, and baseflow index values for selected U.S. Geological Survey [USGS] stream gauge stations in the Cimarron River alluvium and terrace aquifer study area. The delimiter "‖" is used to separate unmodified estimates derived from the USGS baseflow separation tool (left) from modified estimates (right) calculated after the removal of streamflow contributions from the drainage basin northwest of the Freedom gauge station.

[ft^3/s, cubic feet per second; %, percent; BFI, baseflow index; --, data not available or not applicable. Values of baseflow calculated using the BFI base-flow separation method in the U.S. Geological Survey Groundwater Toolbox (Barlow and others, 2015). Stream gauge locations are shown in Figure 1, and stream gauge information is listed in Table 3]

Station id	Station name	Period of analysis	Mean annual streamflow	Mean annual baseflow	
			ft^3/s	ft^3/s	% (BFI)
Cimarron River tributaries draining Permian-age geologic units[1]					
7159750	Cottonwood Creek near Seward, OK	1974–1981, 1990–2001, 2016–2023	188.8	61.9	35.4
7158400	Salt Creek near Okeene, OK	1962–1966, 1974–1978	38.6	8.7	26.5
7159000	Turkey Creek near Drummond, OK	1948–1969	50.2	3.6	12.0
--	Turkey Creek near Hennessey, OK	1948–1969	66.8	5.4	12.0
7159200	Kingfisher Creek near Kingfisher, OK	1967–1969	29.8	2.1	7.8
Cimarron River gauges					
7157980	Cimarron River near Freedom, OK	1974–1979	170.9	51.8	30.0
--	Cimarron River near Freedom, OK	1938–2023	178.0	55.7	38.2
7158000	Cimarron River near Waynoka, OK	1938–2023	258.9	73.7	34.8
AMCO2	Cimarron River near Ames, OK	2007–2012, 2015–2017, 2023	358.1	106.7	35.1
7159100	Cimarron River near Dover, OK	1974–2023	757.4	271.7	38.8
7160000	Cimarron River near Guthrie, OK	1938–1975, 1984–2023	1,109.3	408.2	38.8
Cimarron River gauges (42-year common period of record)					
7157980	Cimarron River near Freedom, OK	1974–1975, 1984–2023	126.2 ‖ 0.0	63.4 ‖ 0.0	50.2 ‖ --
7158000	Cimarron River near Waynoka, OK	1974–1975, 1984–2023	183.3 ‖ 57.1	83.9 ‖ 26.1	45.8 ‖ --
7159100	Cimarron River near Dover, OK	1974–1975, 1984–2023	773.6 ‖ 646.9	286.1 ‖ 237.8	37.0 ‖ --
7160000	Cimarron River near Guthrie, OK	1974–1975, 1984–2023	1,332.4 ‖ 1,206.2	539.9 ‖ 486.1	40.5 ‖ --
Cimarron River gauges (10-year common period of record)					
7157980	Cimarron River near Freedom, OK	2007–2012, 2015–2017, 2023	79.0 ‖ 0.0	36.5 ‖ 0.0	46.2 ‖ --
7158000	Cimarron River near Waynoka, OK	2007–2012, 2015–2017, 2023	114.8 ‖ 35.1	48.3 ‖ 15.0	42.1 ‖ --
AMCO2	Cimarron River near Ames, OK	2007–2012, 2015–2017, 2023	358.1 ‖ 278.7	106.7 ‖ 82.8	29.8 ‖ --
7159100	Cimarron River near Dover, OK	2007–2012, 2015–2017, 2023	559.4 ‖ 480.2	208.0 ‖ 177.8	37.2 ‖ --
7160000	Cimarron River near Guthrie, OK	2007–2012, 2015–2017, 2023	1,034.6 ‖ 953.9	403.8 ‖ 371.5	39.0 ‖ --

[1] Streams draining Permian geologic units are flanked by alluvium deposits 20-50 feet thick.

mean monthly baseflow at the Freedom gauge station for the same period ranged from 0.0 to 224.5 cubic feet per second with a mean of 52.2 cubic feet per second. The transformed linear regression model was used to construct mean monthly baseflow records at the Freedom gauge station for the period 1938–2023; mean annual baseflow was estimated to be 55.7 cubic feet per second with a BFI of 38.2 percent (**Table 5**).

Mean annual streamflow, baseflow, and baseflow index values for the USGS stream gauge stations near Waynoka, Dover, and Guthrie are shown in **Figure 8**; the Cimarron River gauge station near Freedom was not shown for two reasons: (1) the period of record for the raw data was only about 7 years and (2) the constructed streamflow and baseflow estimates derived from the linear regression relationships would look identical to the Waynoka gauge station but with smaller magnitudes.

Annual streamflow estimates at the Waynoka gauge station (**Figure 8A**) for the period of record 1938–2023 ranged from 18.9 to 1,120.6 cubic feet per second, with a mean of 258.9 cubic feet per second (192,486.4 acre-ft/yr). Mean annual baseflow was estimated to be 73.7 cubic feet per second (53,320.2 acre-ft/yr) with a BFI of about 34.8 percent (**Table 5**). Annual streamflow estimates at the Dover gauge station (**Figure 8B**) for the period of record 1974–2023 ranged from 105.1 to 1,797.7 cubic feet per second, with a mean 757.4 cubic feet per second (548,310.8 acre-ft/yr). Mean annual baseflow was estimated to be 271.7 cubic feet per second (196,680.1 acre-ft/yr) with a BFI of about 38.8 percent (**Table 5**). Annual streamflow estimates at the Guthrie gauge station (**Figure 8C**) for the period 1938–1975 and 1984–2023 ranged from 94.4 to 3,271.0 cubic feet per second with a mean of 1,109.3 cubic feet per second (803,074.8 acre-ft/yr). Mean annual baseflow was estimated to be 408.2 cubic feet per second (295,545.0 acre-ft/yr) with a BFI of about 38.8 percent (**Table 5**).

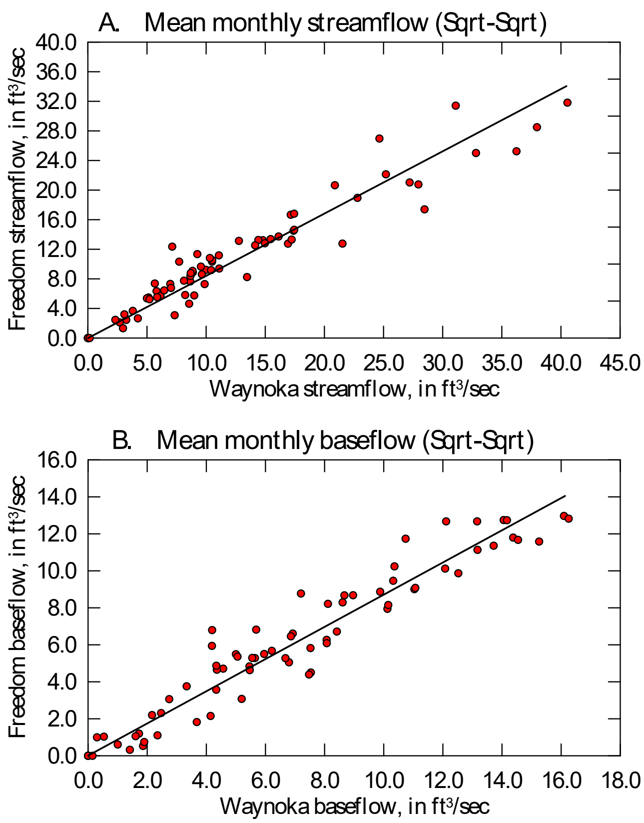


Figure 7. Linear regression relationship of (A) mean monthly streamflow estimates and (B) mean monthly baseflow estimates at the U.S. Geological Survey Cimarron River stream gauge stations near Freedom and Waynoka for the common period of record 1974–1979

The common period of record for the four Cimarron River gauge stations was 1974–75 and 1984–2023; annual streamflow and baseflow statistics for the common period of record indicate that the Cimarron River is a gaining stream. In **Table 5**, there are two values of streamflow and baseflow for each gauge station, separated by the delimiter "‖." Values listed on the left of the delimiter are the unmodified mean annual streamflow and baseflow estimates derived from the USGS baseflow separation tool; values listed on the right of the delimiter are modified estimates of streamflow and baseflow calculated after the removal of streamflow contributions to the Cimarron River from the drainage basin northwest of the Freedom gauge station.

From the gauge station near Freedom to the gauge station near Waynoka, a stream distance of about 24 miles, mean annual baseflow increased from 0.0 to 26.1 cubic feet per second, equivalent to about 1.1 cubic feet per second per river mile (**Table 5**). From the gauge station near Waynoka to the gauge station near Dover, a stream distance of about 85 miles, mean annual baseflow increased by more than nine times to 237.8 cubic feet per second, equivalent to 2.5 cubic feet per second per river mile. This reach encompasses about 74.3 percent of the total area of the Cimarron River alluvium and terrace aquifer and contains the three main streams draining the aquifer, as well as twelve of the sixteen tributaries south of the river. Mean annual baseflow at the Salt Creek gauge station (USGS 07158400) was 8.7 cubic feet per second when analyzed for the 1962–66 and 1974–78 periods of record (**Figure 1; Table 5**).

From the gauge station near Dover to the gauge station near Guthrie, a stream distance of about 41 miles, the mean annual baseflow increased to 486.1 cubic feet per second, equivalent to about 6.1 cubic feet per second per river mile (**Table 5**). The relatively large increase in baseflow between the Dover and Guthrie gauge stations may be attributed to the contributions of Kingfisher and Cottonwood creeks (**Figure 1**). Kingfisher Creek has a drainage area of about 511 square miles, a portion of which crosses isolated terrace deposits and part of the Cedar Hills sandstone minor aquifer unit (Belden, 2000). Cottonwood Creek has a drainage area of about 379 square miles, a portion of which overlies the Garber sandstone aquifer unit (Belden, 1997). Mean annual baseflow at the Cottonwood Creek gauge station near Seward (USGS 07159750) was estimated to be 61.9 cubic feet per second when analyzed for the 1974–81, 1990–2001, and 2016–23 periods of record. Mean annual baseflow at the Kingfisher

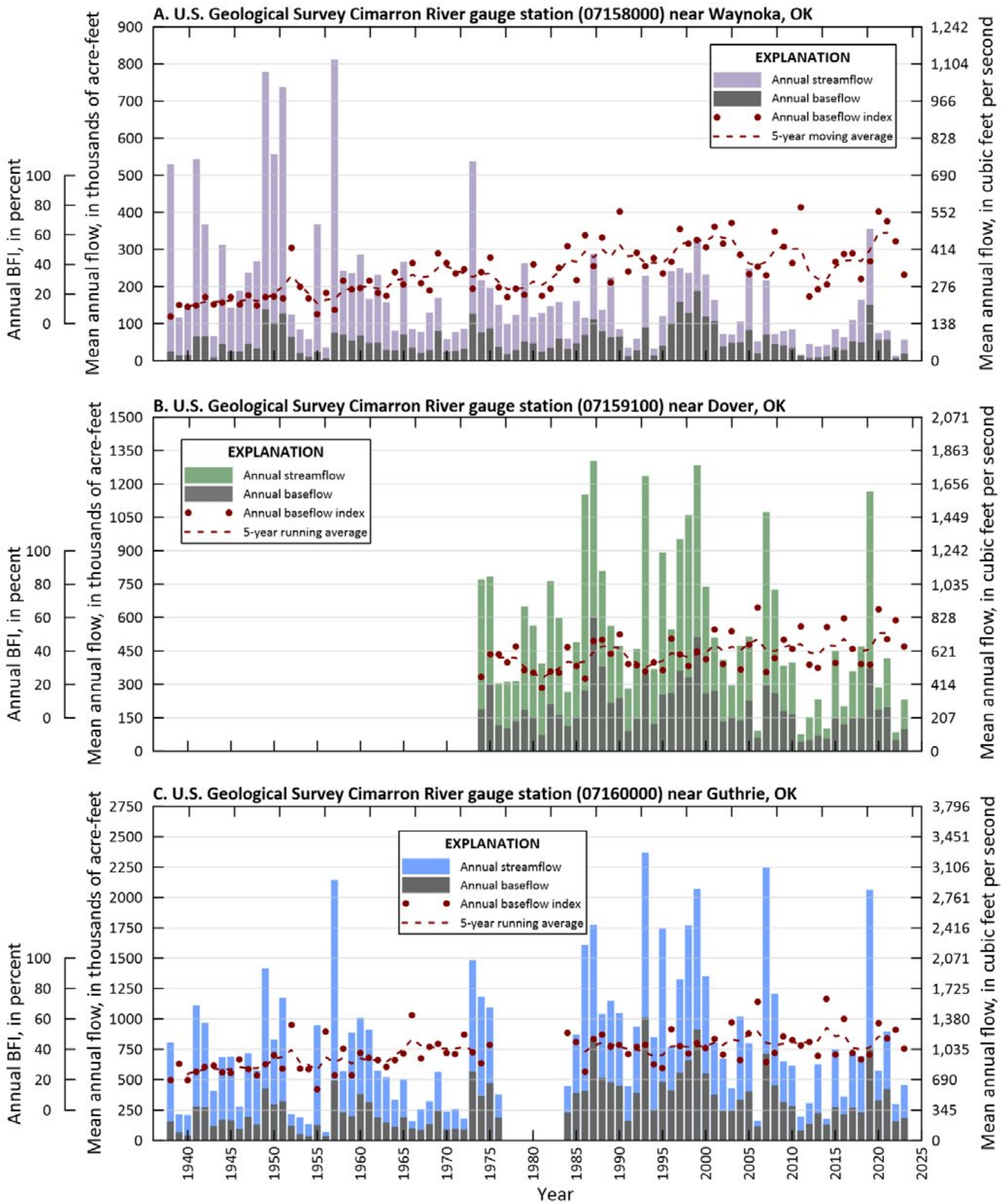


Figure 8. Annual streamflow, baseflow, and baseflow index (BFI) values for the USGS Cimarron River stream gauge stations near the city of Waynoka (07158000), town of Dover (07159100), and city of Guthrie (07160000), 1938–2023.

Creek gauge station near Kingfisher (USGS 07159200) was estimated to be 2.1 cubic feet per second when analyzed for the 1967–69 period of record (**Table 5**); the gauge station only captures about 33 percent of the creeks drainage area.

A shorter common period of record was also analyzed so that the Cimarron River gauge station located southeast of the town of Ames (AMCO2) could be included; the common period of record for the five Cimarron River gauge stations was 2007–12, 2015–17, and 2023. The common period was characterized by mean annual streamflow and baseflow estimates that were about 30–40 percent lower than the longer common period of record (**Table 5**). From the gauge station near Waynoka to the gauge station near Ames, a stream distance of about 53 miles, mean annual baseflow increased from 15.0 to 82.8 cubic feet per second, equivalent to 1.3 cubic feet per second per river mile. From the gauge station near Ames to the gauge station near Dover, a stream distance of about 32 miles, mean annual baseflow increased from 82.8 to 177.8 cubic feet per second, equivalent to 3.0 cubic feet per second per river mile.

There was insufficient data to construct long-term flow contributions from tributaries draining Permian-age geologic units south of the Cimarron River. As such, the modified baseflow estimates do not exclusively represent discharge from the Cimarron River alluvium and terrace aquifer. Baseflow discharge measurements taken in 1986 from selected tributaries between the Waynoka and Dover guage stations indicated that tributaries draining Permian-age geologic units contributed about 20 percent of total baseflow in the Cimarron River (Adams and Bergman, 1996). Baseflow discharge is dynamic, so the 20 percent estimate represents the conditions during the 1986 sampling periods. However, the estimate implies that flow contributions from tributaries south of the Cimarron River are not insignificant.

Surface Water Synoptic for Baseflow Contribution Analysis

A series of streamflow measurements were taken on January 8–9, 2020 to evaluate baseflow contributions to the Cimarron River. Measurements were made during a period in which runoff was considered negligible, therefore streamflow was considered to have been entirely derived from baseflow. Baseflow discharge measurements were obtained from 13 Cimarron River tributaries between the USGS gauge station near Waynoka and the USGS gauge station near Dover (**Figure 1**). Nine measurement sites were on tributaries draining Permian-age geologic units south of the Cimarron River and four sites were on streams draining Quaternary-age alluvium and terrace deposits north of the river (**Table 6**).

The Cimarron River reach between Dover and Guthrie was not included in the synoptic for multiple reasons: (1) The OWRB did not have the resources to install a stream gauge on Kingfisher Creek, (2) Kingfisher and Cottonwood creeks were both too deep to safely traverse with a manual flow-tracker, (3) approximately fifteen percent (5.9 miles) of the stream distance between the two gauge stations is considered outside of the defined aquifer boundary, and (4) natural low-flow conditions within the reach are augmented by effluent outflows discharged into Kingfisher and Cottonwood Creeks from multiple municipal and industrial wastewater treatment plants serving Oklahoma City, Edmond, and Bethany (**Figure 1**). The estimated annual streamflow contribution of all the wastewater treatment plants to the Cimarron River ranged from 251.8 to 286.3 million gallons per year, equivalent to 772.7 to 878.6 acre-feet per year (Oklahoma Department of Environmental Quality, email communication, 2019). The Cimarron River reach between Freedom and Waynoka was not included because flows within associated tributaries were negligible, with most having no discernible flow.

Measurements taken from the USGS stream gauge network for January 8–9, 2020, indicated that the total gain in the Cimarron River between Waynoka and Dover was 122.9 cubic feet per second. The contribution of flow from streams draining Permian-age geologic units and associated alluvium was about 45.2 cubic feet per second, which was deducted from the total gain. The total baseflow contribution from the aquifer was 77.7 cubic feet per second; approximately 55.3 cubic feet per second came from perennial streams draining Quaternary-age alluvium and terrace deposits (**Table 6**). The remaining 23.9 cubic feet per second was considered channel seepage, which calculates to about 0.26 cubic feet per second per river mile. During the synoptic, streams draining Permian-age geologic units and associated alluvium between Waynoka and Dover contributed about 37 percent of the total baseflow in the Cimarron River.

Groundwater-level Fluctuations

Depth-to-water observations can be used to characterize the responses of an aquifer to different stresses, such as precipitation and groundwater use. Long-term periodic depth-to-water observations collected annually can help provide insight into the effects of regional groundwater development and climate variability on groundwater storage, while depth-to-water observations collected hourly at selected well sites can help show the response of an aquifer to stresses on shorter times scales such as seasonable pumping and recharge events (Neel and others, 2018).

Historic

Long-term annual depth-to-water measurements have been collected by the OWRB in the Cimarron River alluvium and terrace aquifer since the 1950s. These data can also be found in the USGS National Water Information System (NWIS) database under unique site numbers that differ from the OWRB well identifiers. In 2012, the Oklahoma legislature and governor appropriated funding to establish a formal long-term, aquifer-based groundwater monitoring and assessment program (GMAP), which has continued the work started in the 1950s, but with an expanded scope and a larger network of groundwater monitoring wells.

Table 6. Estimates of baseflow discharge in the Cimarron River and select tributaries located between the USGS stream gauge station nearWaynoka and the USGS stream gauge station near Dover.

[mi2, square miles; ft3/s, cubic feet per second; --, data not available or not applicable. Griever Creek on the south side of the Cimarron River was excluded from the analysis because the stream channel below U.S. Highway 412 had been destroyed by artificial processes, cutting off flow from more than 90 percent of the drainage basin. Flow in Sooner Creek was below the minimal depth tolerance of the manual flow tracker, resulting in highly erroneous discharge velocities]

Station number	Station name	Drainage area mi^2	Latitude	Longitude	Measurement date (M/D/Y)	Discharge ft^3/s
7158000	Cimarron River near Waynoka, Ok	13,339.0	36.517	-98.880	1/8/2020	132.0[1]
7159100	Cimarron River near Dover, Ok	15,809.0	35.952	-97.915	1/8/2020	254.9[1]
Total gain in reach:						122.9
Cimarron River tributaries draining Quaternary-age aquifer deposits						
OK620920040010	Eagle Chief Creek near Cleo Springs, Ok	469.0	36.405	-98.447	1/8/2020	30.8[1]
OK620910060010	Turkey Creek near Dover, Ok	421.0	35.979	-97.923	1/8/2020	10.7[3]
--	Indian Creek near Ringwood, OK	74.6	36.290	-98.300	1/9/2020	10.2
--	Hoyle Creek near Okeene, OK	60.1	36.156	-98.214	1/9/2020	3.6
--	Sooner Creek near Dover, OK	18.7	35.922	-97.743	1/9/2020	--
Total inflow from streams draining the Cimarron River alluvium and terrace aquifer						55.3
Cimarron River tributaries draining Permian and Quaternary-age geologic units south of the Cimarron River						
--	Main Creek near Waynoka, OK	94.8	36.492	-98.890	1/8/2020	9.3
--	Griever Creek near Waynoka, OK	87.3	36.413	-98.784	1/8/2020	--
--	Barney Creek near Orienta, OK	55.0	36.405	-98.702	1/8/2020	0.4
--	Cheyenne Creek near Orienta, OK	39.3	36.362	-98.620	1/8/2020	1.2
--	Cottonwood Creek near Orienta, OK	53.9	36.362	-98.486	1/8/2020	2.3
--	Gypsum Creek near Fairview, OK	13.4	36.319	-98.436	1/8/2020	0.4
--	Sand Creek near Fairview, OK	41.8	36.310	-98.426	1/8/2020	3.4
--	Deep Creek near Okeene, OK[2]	108.4	36.200	-98.264	1/9/2020	6.8
--	Salt Creek near Okeene, OK[2]	196.4	36.103	-98.193	1/9/2020	17.3
--	Cooper Creek near Dover, OK	122.5	35.983	-97.997	1/9/2020	4.1
Total inflow from streams draining geologic units south of the Cimarron River						45.2

[1] Mean daily discharge from active stream gauge stations.

[2] Permian creeks with wide alluvial floodplain

[3] Approximated based on the ratio of mean monthly streamflow at the Eagle Chief Creek and Turkey Creek gauge stations in January 2018 (the only year with streamflow measurements for the month of January at both gauge stations)

There were a total of 150 mass measurement sites (active and inactive) within the study area that had historical depth-to-water observations through 2023; sites with fewer than two annual observations were excluded from the total. The year of first observation and period of record differed between sites, with 58 sites having data gaps of one or more consecutive observations, and 101 sites with discontinued monitoring. As of 2023, 49 sites are measured annually as part of the GMAP.

To sufficiently show the effects of long-term stresses on groundwater storage and subsequent water levels a minimum observation period of 12 years was used in the analysis (Neel and others, 2018). Of the original 150 sites, 43 had 30 years or more of observations, 29 had between 12–35 years of observations and 78 had fewer than 12 years of observations. Roughly half (34) of the 78 sites with fewer than 12 years of observations were newer GMAP sites with periods of record that started in 2017. The locations for the 72 sites with at least 12 historical water-level observations are shown in **Figure 1**. A table listing the location details and periods of record for the 72 water level sites can be found in Appendix C.

Depth-to-water data was normalized using the Z-score (standard test) method, which allows observations from different mass measurement sites to be compared directly by removing variability between wells caused by an asymmetrical water table. Z-score is a statistical calculation that compares the values of individual data points to the mean of a dataset; it is calculated by subtracting the mean of the sample dataset from each depth-to-water observation and then dividing by the standard deviation of the sample dataset. A Z-score of zero is equivalent to the mean depth-to-water in an individual or group of mass measurement sites over a period of record. A positive Z-score indicates depth-to-water increased relative to the mean, thus a lower water level relative to the mean. A negative Z-score indicates depth-to-water decreased relative to the mean, thus a higher water level relative to the mean (Neel and others, 2018).

Figure 3C shows the normalized mean depth-to-water trend line for the selected sites within the Cimarron River alluvium and terrace aquifer; vertical bars with dots signify the variability of annual depth-to-water observations at individual mass measurement sites. Except for 1964, which had zero observations, each year had at least eight observation sites; the average for the period of record (1950–2023) was 31 sites. In general, extended periods of below mean depth-to-water (positive Z-score) coincided with historical dry periods in Oklahoma and extended periods of above mean depth-to-water (negative Z-score) coincided with historical wet periods, although with some transitional response delay.

Continuous

Continuous depth-to-water recorders installed as part of this study were used to observe seasonal trends and local stresses acting on the aquifer. Recorders were installed in ten groundwater wells spatially distributed throughout the defined aquifer area, which collected data during the 2015–2024 period (**Figure 1**). Three of the ten wells were excluded from analysis for the following reasons: (1) recorders installed in monitoring wells 170900 and 170801 were pulled out prematurely by the landowner after less than four months and were never reinstalled, and (2) monitoring well 119847 demonstrated multiple instances of erratic, sharp changes in water level (one to four feet) that did not reflect precipitation influxes or local stresses such as nearby pumping. **Table 7** lists the location, total depth, and periods of record for the ten continuous groundwater monitoring wells. The total depth of the wells ranged from 31 to 69 feet, with an average of 53 feet. Depth-to-water was logged hourly at each monitoring site and the data was collected approximately every three months. Water-level drift between visits was corrected by applying a linear calibration to the data based on depth-to-water measurements made in the field at the time of collection.

OWRB well 171706 was located in a field roughly 1,500 feet (equidistant) from three irrigation wells with pivots. This site was chosen to monitor the effects of irrigation pumping on localized groundwater levels during the growing season. **Figure 9** shows that water levels declined by about 4–6 feet during the 2016–2018 growing seasons, with recovery occurring until the start of the next season. The numerous, short-lived (2-5 days) water level fluctuations superimposed onto the broader seasonal trends do not coincide with daily or seasonal barometric pressure changes and have signatures unlike the pressure-sensitive noise (spikes) shown on the hydrograph for OWRB well 171245. Although not consistent, several of the fluctuations coincided with anomalous changes in temperature (**Figure 8** inset). The changes may be related to humidity cycles or thermal pumping or lag within the vent tube. OWRB well 175289 appears to demonstrate a delayed seasonal water level change signal.

OWRB monitoring well 18699 is located in a pasture far away from any irrigated lands. **Figure 9** shows an overall declining trend during the 2016–2018 period that ended in 2019 (an exception wet year; **Figure 3**), with water level rising by about 5.6 feet. In areas of the aquifer where the water table is deep, recharge generally takes longer to reach the saturated zone, resulting in muted water level responses. The water level bumps marked A–C in **Figure 9** resemble focused episodic recharge events (Butler and others,2021) and may in part be related to the impoundment of water in a low-lying area directly northwest of the well site; these bumps do not coincide with a single precipitation event and generally occur between April and August of each year. Aerial photos taken intermittently over the last 20 years show that the impoundment area is typically dry; however, the October 2019 photo shows the area was full of water. During a field visit in 2024, water in the impounded area had risen to the base of the well casing.

The similarity of the water level fluctuations in OWRB wells 18699 and 168849 suggests that the water level bumps are likely related to seasonal rainfall, with the shallower water table well showing more abrupt rises and falls in water level compared to the deeper water table well.

Table 7. Location, total depth, and period of record information for groundwater wells completed within the Cimarron River alluvium and terrace aquifer used for short-term continuous water-level monitoring.

[M/D/Y, month/day/year; Total well depth measured in feet below land surface. Continuous recorder locations area shown in Figure 1]

Well ID	Latitude	Longitude	County	Well use	Total well depth	Period of record date (M/D/Y)	
						Begin	End
119847	36.6246	-98.9246	Woods	Domestic	30.7	4/7/2016	9/23/2020
18699	36.4958	-98.6813	Woods	Industrial	69.3	1/27/2016	Present (2025)
170900	36.6250	-98.8787	Woods	Mining	59.0	1/27/2016	3/18/2016
168849	36.1686	-98.1873	Major	Observation	58.5	7/7/2016	9/13/2022
157423	36.3041	-98.2583	Major	Agriculture	47.0	1/27/2016	9/30/2016
18545	36.4076	-98.4695	Major	Industrial	53.0	1/27/2016	8/14/2017
171245	35.9857	-97.7906	Kingfisher	Industrial	55.0	12/18/2015	3/21/2017
171706	36.0565	-97.9812	Kingfisher	Irrigation	50.7	12/18/2015	4/01/2020
170801	36.1149	-98.1491	Kingfisher	Irrigation	41.0	1/21/2016	5/18/2016
175289	35.8990	-97.6399	Logan	Observation	63.5	1/21/2016	2/15/2019

At the time of this publication (2025), all but one of the original ten groundwater monitoring recorders have been discontinued for redeployment in other aquifers. Although not included in this study, the OWRB has deployed two depth-to-water recorders near the town of Cleo Springs in Major County to monitor localized changes in groundwater levels over the next few years. Depth-to-water recording at well 18547 (36.4512, -98.4965) began in October 2024 and at well 233081 (36.3944, -98.4413) began in March 2025.

Groundwater Use

An understanding of groundwater availability in the study area has improved since the early 20th century in large part because of the growth of the City of Enid and the need to find additional sources of water for public supply. Groundwater use in the Cimarron aquifer was briefly discussed in a 1905 publication on the geology and water resources of Oklahoma, which referred to the terrace deposits as “sand hills.” Wells completed within the alluvium and terrace deposits were reported to consistently yield abundant quantities of good-quality water and were generally used by farmers for stock ponds and domestic purposes (Gould, 1905). In 1905, most water in the study area was sourced from springs, with wells generally used only in areas where there were no springs. Of the 481 wells reported in Logan, Kingfisher, Garfield, and Woods counties in 1905, approximately half targeted the Cimarron River alluvium and terrace aquifer (Gould, 1905). No specific quantities or pumping rates were mentioned. Throughout the 1920s water from springs and surface reservoirs remained the dominant source for domestic, stock, and public supply purposes within the study area. However, groundwater well installations within the Cimarron River alluvium and terrace aquifer increased as agricultural communities continued to expand out from rural towns (Redfield, 1927).

The City of Enid, which is about 15 miles northeast of the study area, has been a water use stakeholder in the area since 1923 when a study was commissioned by the city’s waterworks plant to evaluate groundwater availability in a small area between Cleo Springs and Ringwood (**Figure 1**; Renick, 1925). By the late 1940s, cities across northwestern Oklahoma, including Enid, Fairview, Kingfisher, Okeene, Hennessey, Alva, and Waynoka, were all actively using groundwater from the Cimarron River alluvial and terrace aquifer as a primary or supplementary source of water for public supply (Schoff, 1949; Schoff, 1950; Reed and others, 1952). Industry and irrigation had not yet become major groundwater uses in the study area. In 1950, 19 public supply wells were active within the Cimarron River alluvium and terrace aquifer. Six targeted alluvium deposits and thirteen targeted terrace deposits. Estimated withdrawals for individual wells varied from approximately 56 acre-feet per year to 310 acre-feet per year, and the total amount of water withdrawn was about 1,120 acre-feet per year (Reed and others, 1952). By the mid-1980s every major town and city within the study area was using groundwater for public supply. The City of Enid alone increased the number of municipal wells they operated from five in 1950 to 89 in 1988 (Reed and others, 1952; Adams and Bergman, 1996).

Available water use records indicate that the first irrigation wells in the study area were developed between 1945 and 1949 in an area covering approximately 362 acres of cropland between Eagle Chief Creek and Turkey Creek (Reed and others, 1952). By 1965, the number of irrigation wells grew from fewer than a dozen to more than 30, and development had expanded westward toward Waynoka and eastward toward Crescent (U.S. Geologic Survey, 1966).

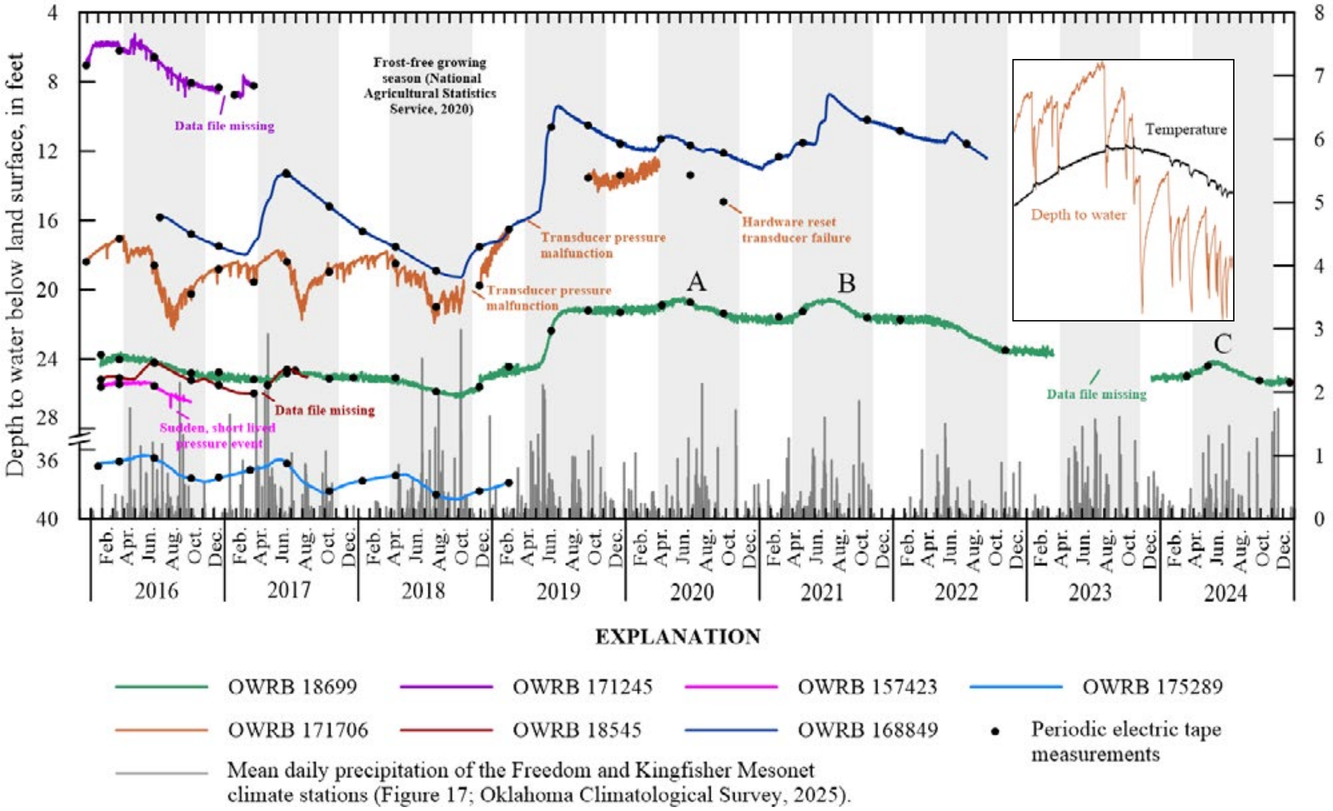


Figure 9. Depth-to-water for selected groundwater monitoring wells completed in the Cimarron River alluvium and terrace aquifer, northwestern Oklahoma, December 2015 through December 2024. Inset shows short-lived fluctuations in water level coinciding with anamlous changes in temperature over a five month period in OWRB well 171706.

By 1985, irrigated land covered approximately 50,000 acres (six percent) of the total land surface within the study area (Adams and Bergman, 1996).

Industrial use of groundwater from the Cimarron River alluvium and terrace aquifer has always been relatively small compared to public supply and irrigation. In 1950, the only permanent installation classified as industrial supply was a well field near Ames which provided water for the St. Louis-San Francisco railway (Reed and others, 1952). Oil and gas operations in the area also utilized groundwater, but a reliable estimate of the amount used in drilling is not available as such records were generally not kept. The discovery of the Sooner Trend and Ringwood oil fields in 1945 likely contributed to increased industrial usage from the aquifer (Boyd, 2002).

In 1964, the Oklahoma Water Resources Board established a requirement pursuant to Oklahoma groundwater law that water use permit holders submit annual water use reports (Oklahoma Register, 1964). Water use data collected and maintained by the OWRB and municipalities prior to 1967 are considered incomplete, with the level of uncertainty increasing the further back in time records were recorded. However, the water use data that was collected prior to 1967 indicates an increasing dependence on the Cimarron River alluvium and terrace aquifer over time. Reported withdrawals from Cimarron River alluvium and terrace aquifer increased from approximately 2,500 acre-feet in 1950 to more than 12,200 acre-feet in 1967 with an average year-over-year increase of 7.9 percent (Adams and Bergman, 1996).

Annual OWRB water use reports are divided into use categories including public water supply, irrigation, industrial, mining, commercial, agriculture, power, and recreation, fish, and wildlife. Annual reporting of groundwater use is not required for self-supplied domestic water wells that use less than 5 acre-feet per acre per year or for water pumped for irrigation of less than 3 acres (Oklahoma Water Resources Board, 2014). The ‘mining’ category generally refers to any operation extracting mineral resources, but within the study area is predominantly related to oil and gas and sand/gravel extraction operations. The ‘public supply’ category encompasses groundwater use by municipalities, rural water districts, schools, and housing developments. Groundwater use data utilized in this study were reviewed to ensure quality and completeness.

Long-term Permitted Groundwater Use

As of the end of the calendar year 2023, the number of active long-term groundwater permits within the defined aquifer boundary was 578 (**Figure 10**); 230 prior rights and 348 temporary. Annual groundwater use was summarized for the period 1967–2023 based on self-reported use estimates from 656 historical long-term permits. A total of 146 permits assigned to the Cimarron River alluvium and terrace aquifer either never reported any water use or lacked documentation within the OWRB database. Of the 802 total historical permits within the groundwater basin,78 never officially received an authorized prior right, and 45 were mistakenly permitted to the Cimarron aquifer when they should have been permitted to the El Reno minor aquifer.

Mean annual groundwater use for the period of record 1967–2023 was estimated to be about 30,814 acre-feet per year with a median of 26,262 acre-feet (**Table 8; Figure 11A**). The highest reported annual groundwater use for the period of record occurred in 2022 (58,936 acre-feet), and the lowest reported annual use occurred in 1967 (12,937 acre-feet). Total annual reported groundwater use ranged from 12 percent of total annual permitted groundwater use in 1992 to 95 percent in 1973, with a mean of 28 percent for the period 1973–2023. The number of missing annual use reports ranged from 2 in 1975 to 94 in 1990, with a mean of 54 for the period of record (**Figure 11B**). The number of missing annual use reports excluded those with justifiable absences including periods where the OWRB was waiting for legal documentation to complete a change of ownership or was unaware of a land transfer.

Five periods were analyzed based on trends in total reported groundwater use: 1967–78, 1979–86, 1987–2000, 2001–09, and 2010–23. The period 1967–78 was marked by a steady rise in groundwater use (**Figure 11A**). In general, the rising trend is consistent with a rise in the number of active groundwater permits from 101 in 1967 to 251 in 1978 (**Figure 11B**) and coincides with two periods of drought (1961–72 and 1976–81; **Figure 3A–B**). Mean annual groundwater use for the 1967–78 period was 26,154 acre-feet per year with a median of 25,161 acre-feet (**Table 8**).

To note, before 1980, irrigators were only required to report the number of acres irrigated and the number of times irrigation occurred. Annual water use was estimated for these reports based on a sliding scale of the number of acres irrigated (§785:30-11-2 (b)). The assumed application amounts may have resulted in estimations of irrigation water use between 1967 and 1980 that were greater or lesser than the actual amounts. After 1980, irrigators were required to also report application amounts in inches, which allowed for direct estimation of water use.

The period 1979–86 was marked by an overall decline in annual groundwater use (**Figure 11A**). The largest contributor to the decline was the decline in irrigation usage. During the first few years of this period, the entire state of Oklahoma was still dealing with drought conditions, so groundwater withdrawals were necessary to irrigate croplands (46.8 percent of the defined aquifer area, **Figure 2**). As drought conditions across the state began to wane in the 1980s, so did the amount of reported groundwater use for irrigation; between 1982–86, reported usage declined by about 6,900 acre-feet. During this five-year period, the total number of acres irrigated decreased from 19,800 to 8,500 (National Agricultural Statistics Service, 2017). Mean annual groundwater use for the 1979–86 period was 22,642 acre-feet per year with a median of 19,046 acre-feet (**Table 8**). Some of the decline in annual groundwater use during this period may be related to an increase in the number of missing annual use reports from 9 in 1979 to 80 in 1986 (**Figure 11B**).

During the 1987–2000 period, groundwater use remained relatively low (**Figure 10A**), averaging about 20,106 acre-feet per year, with a median of 20,627 acre-feet (**Table 8**). This period was characterized by above-average annual precipitation (**Figure 3A**). Consequently, less groundwater was needed to irrigate crops and fill municipal reservoirs. The average number of active permits during this 14-year period was 283 with most (91 percent) reporting zero use annually (**Figure 10B**). The average number of missing annual use reports during this period was about 78 per year.

Groundwater use during the 2001–09 period was higher than in the preceding 14-year period but was also relatively constant (**Figure 10A**). The period was marked by a minor drought between 2002–06 which was eased by record-breaking rainfall in the latter half of 2007 (Shivers and Andrews, 2013; Arndt, 2002; **Figure 3A**); groundwater use was lowest in 2007 and highest in 2006. Mean annual groundwater use for the 2001-09 period was 29,691 acre-feet per year with a median of 30,086 acre-feet (**Table 8**). The average number of missing annual use reports during this period was about 58 per year.

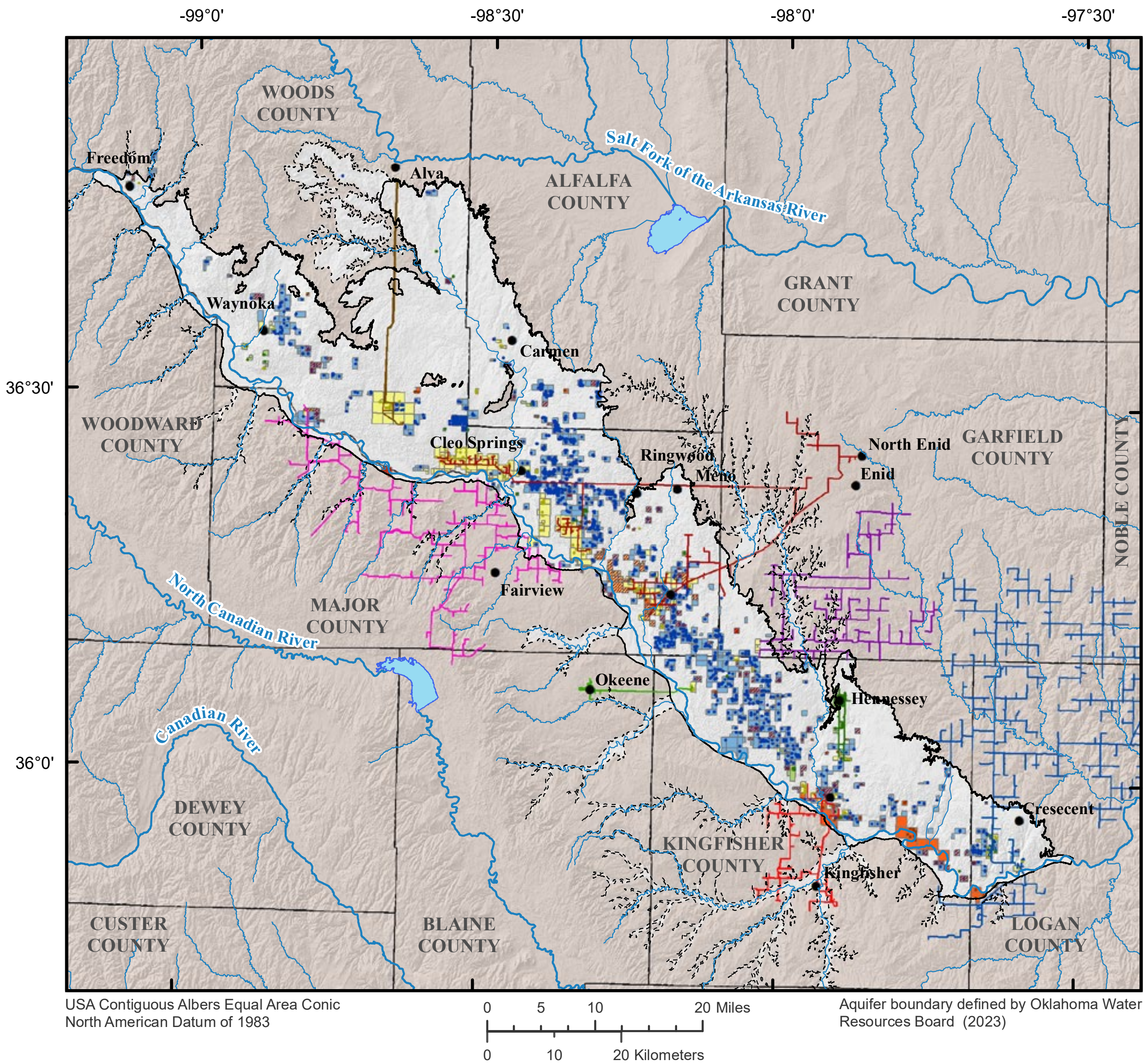
Groundwater use increased steadily during the first five years of the 2010–23 period as the state entered into a 239-week-long drought period lasting from November 2, 2010, until May 26, 2015—the most severe period of drought occurred in September 2011, when 80 percent of the state was enduring extreme drought conditions (National Integrated Drought Information System, 2020). Groundwater use leveled off over the last 10 years of the 2010–23 period but remained relatively high, averaging 54,466 acre-feet per year. Mean annual groundwater use for the 2010–20 period was 49,589 acre-feet per year, with a median of 50,489 acre-feet (**Table 8**). The number of missing annual use reports declined over this period, with a high of 45 in 2013 and a low of 28 in 2017.

Irrigation is the predominant water-use category within the study area, constituting 70.9 percent of total reported groundwater usage for the 1967–2023 period of record.

Table 8. Summary statistics of total annual reported groundwater use from the Cimarron River alluvium and terrace aquifer, 1967–2023.

[All units are in acre feet per year]

Period of record	Annual reported groundwater use			
	Mean	**Median**	**Minimum**	**Maximum**
1967–1978	26,154	25,161	12,937	48,194
1979–1986	22,642	19,046	17,083	37,921
1987–2000	20,106	20,627	14,783	25,921
2001–2009	29,691	30,086	24,358	34,276
2010–2023	50,906	53,010	37,818	58,936
1967–2023	30,814	26,262	12,937	56,936



EXPLANATION

Rural water supply systems (OWRB, 1998)

- City of
- City of Enid
- City of Hennessey
- City of Kingfisher
- City of Okeene
- Garfield Co RWD #5
- Logan Co RWD #2 and Sw Mgmt #3
- Major Co RWD #1

● Towns & cities with permitted groundwater rights in the aquifer

Allocated groundwater rights— Permitted land areas and wells

- Irrigation
- Mining
- Other
- Public Supply
- Inactive Permits
- Extent of Cimarron River alluvium and terrace aquifer
- Other alluvium, terrace, and cover sand deposits

Figure 10. Land areas and wells permitted for groundwater use from the Cimarron River alluvium and terrace aquifer, 2023.

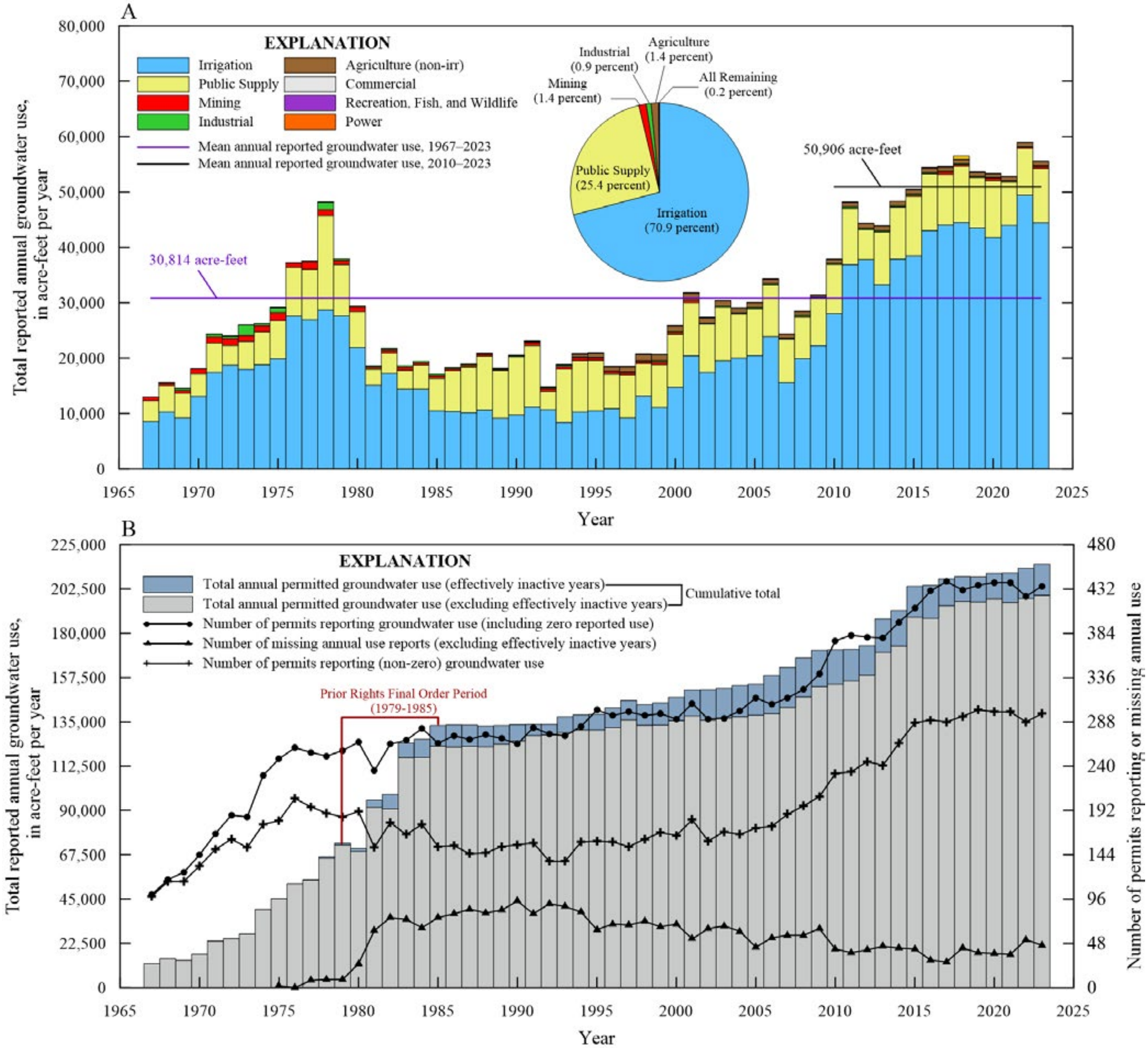


Figure 11. (A) Total reported annual groundwater use by water demand category from the Cimarron River alluvium and terrace aquifer, 1967–2023, (B) Total annual permitted groundwater use and number of reporting or missing annual use reports. Effectively inactive years were those underoing a change of ownership or other clerical modification or periods in which the Board was unaware of the sale of lands dedicated to the permit.

Public water supply accounted for 25.4 percent of reported groundwater use and the remaining 3.7 percent encompassed all other water-use categories (**Figure 10A**). Irrigation consistently made up 40 percent or more of total groundwater use annually, with a low of 44.4 percent in 1993 and a high of 85.2 percent in 2012. Public water supply use remained relatively constant throughout the period of record, averaging 7,816.1 acre-feet per year.

The rise of non-irrigation agricultural groundwater usage in the mid-1990s and onward can be attributed to the development of confined animal feeding operations within the study area, as determined from annual usage reports citing poultry and hog farms. Annual reported groundwater use for mining operations declined by 89 percent between the first and second halves of the period of record, most notably after 2001 (**Figure 10A**). The decline can be attributed to the transition from regular long-term groundwater permits to provisional-temporary groundwater permits by affiliates of the oil and gas industry, beginning around 1992. **Table 9** lists the reported mean annual groundwater use by water-use category from the Cimarron River alluvium and terrace aquifer, 1967–2023.

Table 9. Mean annual reported groundwater use by water-use category from the Cimarron River alluvium and terrace aquifer, 1967–2023.

[PWS, public water supply. All groundwater use estimates are in acre feet per year. Values in parenthesis are percentages of total mean annual groundwater usage]

Period of record	Water-use category								
	Irrigation	PWS	Industrial	Mining	Agriculture	Commercial	Power	Recreation	Other
1967–1978	18,091.2 (69.2)	6,568.4 (25.1)	526.1 (2.0)	954.8 (3.7)	4.5 (0.0)	0.0 (0.0)	0.0 (0.0)	8.6 (0.0)	0.7 (0.0)
1979–1986	16,440.1 (72.6)	5,418.1 (23.9)	271.6 (1.2)	509.1 (2.2)	1.7 (0.0)	0.7 (0.0)	0.0 (0.0)	0.0 (0.0)	0.4 (0.0)
1987–2000	10,694.7 (53.2)	8,334.2 (41.5)	179.6 (0.9)	368.5 (1.8)	432.8 (2.2)	50.3 (0.2)	0.0 (0.0)	45.9 (0.2)	0.5 (0.0)
2001–2009	19,933.1 (67.1)	8,641.5 (29.1)	185.0 (0.6)	84.6 (0.3)	787.2 (2.7)	38.9 (0.1)	0.0 (0.0)	19.2 (0.1)	1.6 (0.0)
2010–2023	40,504.0 (79.6)	9,207.1 (18.1)	185.4 (0.4)	171.6 (0.3)	752.4 (1.5)	0.4 (0.0)	0.0 (0.0)	39.3 (0.1)	45.3 (0.1)
1967–2023	21,838.5 (70.9)	7,816.1 (25.4)	267.7 (0.9)	418.5 (1.4)	416.6 (1.4)	18.7 (0.1)	0.0 (0.0)	25.8 (0.1)	11.7 (0.0)

Provisional-temporary Groundwater Permits

Provisional-temporary groundwater permits are issued by the OWRB to approved applicants with an effective period of 90 days after issuance, excluding for the oil and natural gas industries. Provisional-temporary permits are issued for short-term intended use, generally in the interim before a long-term permit is approved or in cases where the applicant or lessor has undedicated lands that can be used to supplement the allocation amount of an existing long-term permit. Standalone provisional-temporary permits are issued in the absence of an existing long-term permit, commonly for oil and natural gas leesees. Unlike long-term permits, provisional temporary permits are not required to submit use reports as it is assumed that the authorized volumes will not be exceeded. Although OWRB has been able to issue provisional-temporary permits since 1972, records begin in 1992.

Figure 12 shows the total authorized annual provisional-temporary groundwater use for selected water-use categories in the Cimarron River alluvium and terrace aquifer for the period 1992–2023. Total authorized groundwater use ranged from 3.0 acre-feet per year in 2021 to 2,650.6 acre-feet per year in 2013, with a median of 355.6 acre-feet per year. The average authorized groundwater use for individual permits over the period of record was 24.1 acre-feet, with a median of 2.0 acre-feet.

Between 1992 and 2023, a total of 927 provisional-temporary groundwater permits were issued in the Cimarron River alluvium and terrace aquifer, the majority (86 percent) of which were issued for oil and natural gas uses. Irrigation was the predominant water-use category, constituting 62.9 percent of the total authorized groundwater use over the period of record. The second largest water-use category was oil and gas at 22.1 percent, which was subdivided into drilling operations (13.1 percent) and crude oil and natural gas production (9.0 percent). Public supply accounted for 11.3 percent of the total authorized groundwater use, with all other water-use categories (including mining operations for sand and gravel) accounting for the remaining 3.7 percent.

Of note, the number of provisional-temporary permits issued for oil and natural gas use generally followed market volatility. Following the late 2008 and 2014 market crashes (U.S. Energy Information Administration, 2024), the number of authorized permits declined by more than 55 percent. Conversely, during years with strong market evaluations or improving market conditions, the number of permits issued generally increased, except for the post-Covid-19 bump in 2021 (continued into 2022) as pandemic-related restrictions were loosening and global petroleum demand was outpacing supply (Troderman, 2022). The notable increase in authorized groundwater use between 2016 and 2018 may be related to increased activity in the STACK play in northwestern Oklahoma (Eucker and Ashby, 2020).

Hydrogeology

The principal water-bearing units in the study area are the Quaternary-age alluvium and terrace deposits. The geospatial extent of these deposits within the study area is shown in **Figure 5**. Regionally, the Cimarron River alluvium and terrace aquifer is unconfined, although there may be some localized confining conditions.

Regional Groundwater Flow

Regional groundwater flow in the Cimarron River alluvium and terrace aquifer generally flows south-southwest toward the Cimarron River, with some flow toward the northern edge of the defined aquifer boundary. Groundwater also flows toward the stream channels of the three major Cimarron River tributaries draining the aquifer, namely Eagle Chief Creek, Indian Creek, and Turkey Creek, respectively. A potentiometric surface map was created for the Cimarron River alluvium and terrace aquifer based on 141 depth-to-water measurements collected between March 2–10, 2016 as well as 43 supplemental measurements collected between January 6 and February 6, 2016, as part of the OWRB GMAP program. The depth-to-water measurements ranged from 1.0 to 61.3 feet below the land surface with a mean of 17.0 feet below the land surface.

The potentiometric surface is the altitude to which water will rise and become static in a tightly cased well screened in a confined aquifer. The potentiometric surface can vary temporally and geographically within a single aquifer and is depicted on maps as a planar surface with contours or lines of equal altitude. Groundwater flows perpendicular to the orientation of the potentiometric surface contours from areas of higher altitude to areas of lower altitude. In unconfined aquifers, such as the Cimarron River alluvium and terrace aquifer, the potentiometric surface is equivalent to the water table which generally does not rise above the altitude of the land surface, except near streams (wetlands) and some ponds.

Water-level altitude at each well location was estimated by subtracting the depth-to-water measurement from the local land-surface altitude. The land-surface altitude was determined by using a differentially corrected Global Positioning System (GPS) with a vertical accuracy of 15-50 centimeters (5.9-19.7 inches) that was referenced to the North American Vertical Datum of 1988 (NAVD 88). The 2016 potentiometric surface was interpolated using the mathematical deterministic method (inverse distance weighted; Shepard, 1968) and contoured at an interval of 25 feet (**Figure 13**). The computer-generated altitude contours were manually adjusted to better conform to land-surface topography; in some areas 10 to 15 foot contours were added to better constrain the interpolation.

The 1986 potentiometric surface map of Adams and Bergman (1996) showed contours sharply bending upstream along Eagle Chief Creek, Indian Creek, and Turkey Creek with more subdued upstream bending along Dog, Hoyle, and Sooner creeks. The upstream bending of the contours indicates groundwater is discharging to these streams. The decreasing degree of upstream bending along Hoyle Creek north of the town of Ames indicates a poorer connection with the aquifer; this stream reach is likely more intermittent than the stream reach south of the town of Ames. The altitude of the 1986 potentiometric surface was highest in Woods County along the northern edge of the defined aquifer boundary and lowest near the Cimarron River in Logan County. Areas with little to no saturated thickness were considered to have limited groundwater flow.

The general patterns and directions of groundwater flow in the 2016 potentiometric surface map (**Figure 13**) were similar to the 1986 map by Adams and Bergman (1996).

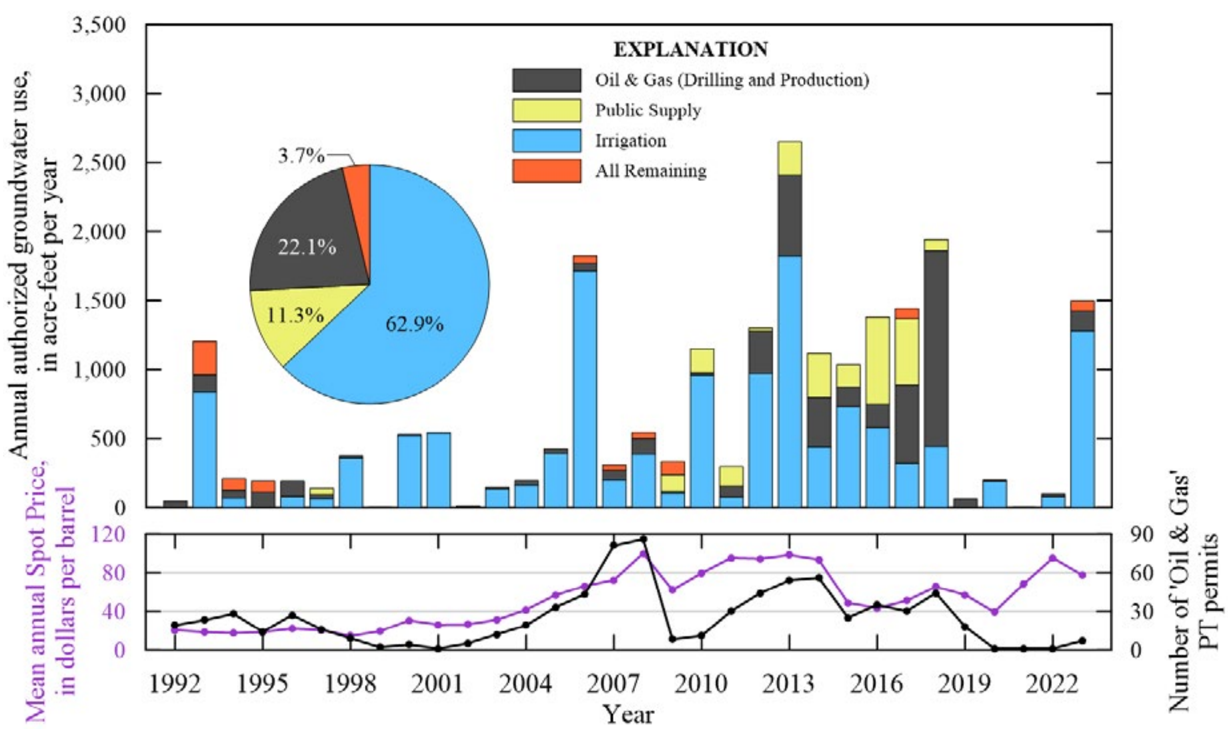


Figure 12. Total authorized annual groundwater use issued for 90-day provisional-temporary (PT) permits from the Cimarron River alluvium and terrace aquifer, 1992–2023.

In some areas the 2016 potentiometric surface contours were upgradient from the 1986 contours (of equal value), indicating that depth-to-water in those areas was greater in 2016 than in 1986. Conversely, in some areas, the 2016 potentiometric surface contours were downgradient from the 1986 contours (of equal value), indicating that the depth-to-water in those areas was lower in 2016 than in 1986. The main difference between the two potentiometric surface maps is the areas classified as having little to no saturated thickness; the difference is likely related to differences in interpolation methods, the spatial distribution of wells, and the definition of "little" saturated thickness. For this investigation "little" refers to areas with a saturated thickness of less than 5 feet. Additional well controls and streamflow measurements would be needed to define local areas of streamflow loss on the potentiometric surface.

Aquifer Base

The base of the Cimarron River alluvium and terrace aquifer was determined from 1,309 lithologic logs, submitted to the OWRB by well drillers, following the completion of a groundwater well. Lithologic descriptions were used to delineate the boundary contact between Quaternary-age and Permian-age geologic units. Bedrock units are commonly described in lithologic logs as either “red shale” or “red bed.” These descriptions along with others related to lithification, such as “hard rock” or “sand rock” were used as indicators of the base of the aquifer. Most (97 percent) of the wells used in this analysis were completed in the underlying bedrock. Depth-to-base estimates ranged from 2–120 feet below the land surface with a mean of 44 feet below the land surface. Depth-to-base estimates were generally greater in the central regions of the aquifer and shallower along major tributaries and near the edges of the defined aquifer boundary. The 1,310 depth-to-base estimates were interpolated using the inverse distance weighted method of Shepard (1968) to create a depth-to-base raster in feet below the land surface. The altitude base map was created by subtracting the depth-to-base raster from a 10-meter land surface Digital Elevation Model (DEM). The computer-generated altitude contours were manually adjusted and additional contours were added as constrains in areas with shallow dips and in areas where interpolation caused the altitude of the base to rise above the potentiometric surface where groundwater wells indicated it should be below.

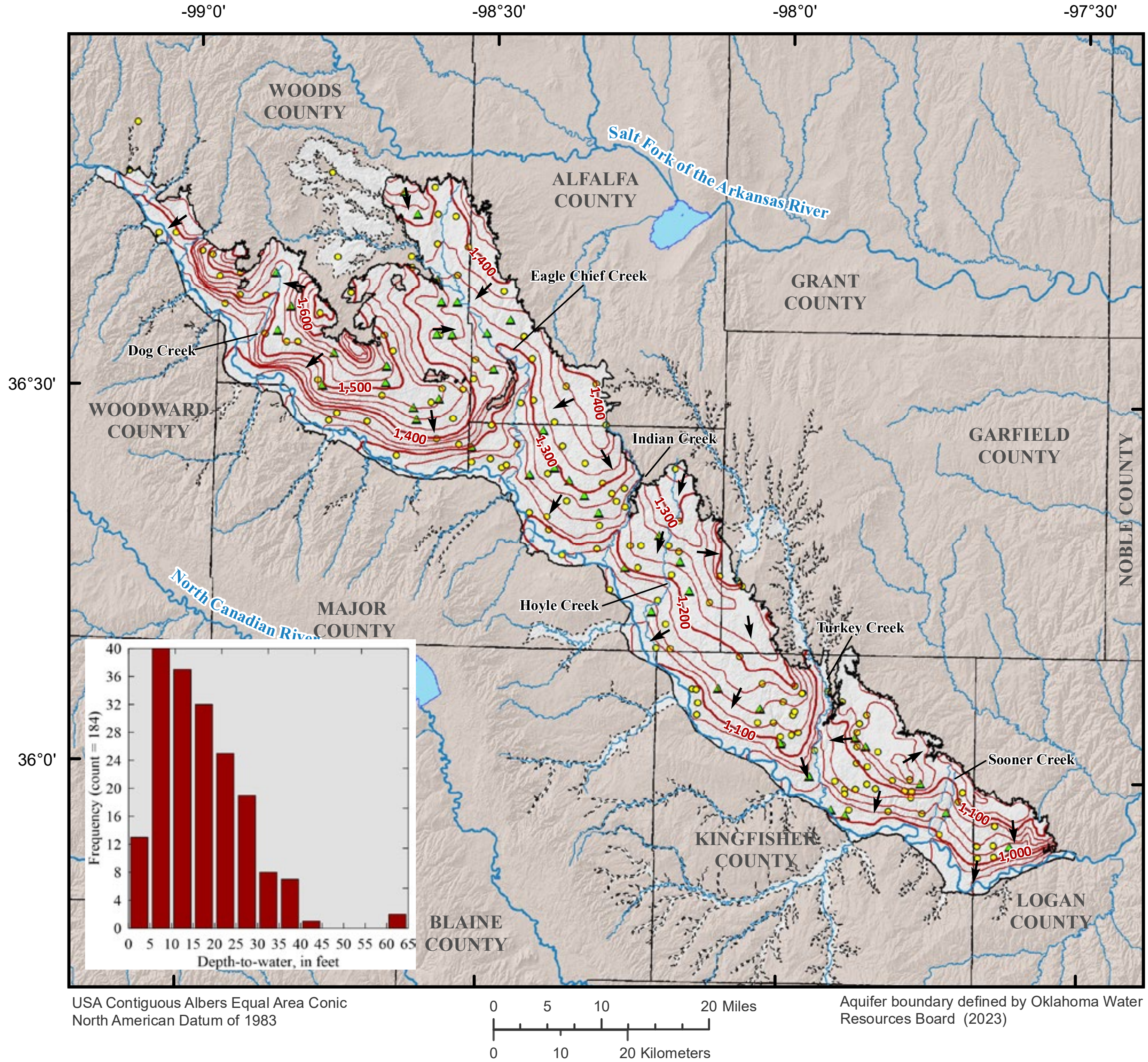
Figure 14 shows the altitude of the base of the Cimarron River alluvium and terrace aquifer. The altitude of the base of the Cimarron River alluvium and terrace aquifer decreases from 1,700 feet in Woods County to less than 910 feet in Logan County (a gradient of about 7 feet per mile). Terrace deposits of the Cimarron River alluvium and terrace aquifer overlie a Permian-age topographic ridge in the northwestern region of the study area. The topographic ridge is oriented northwest-southeast and extends toward the county line junction of Woods, Alfalfa, and Major counties. The curvature of Eagle Chief Creek is related to this structural feature, changing its orientation from northwest-southeast in Woods County to north-south in Alfalfa County. The dip of the base is steepest in the region directly south of the outcropping ridge in central Woods County, near the city of Waynoka; in this locality, the gradient is 60 feet per mile. In the area of Cleo Springs, the base of the Cimarron is characterized as a semi-consolidated layer of tan colored, coarse-grained sand and varicolored granule- to pebble-sized gravel.

Aquifer Saturated Thickness

The saturated thickness of the Cimarron River alluvium and terrace aquifer was determined by subtracting the base altitude map from the 2016 potentiometric surface altitude map. The saturated thickness of the aquifer ranges from less than 5 feet to 93 feet, with a mean of about 26 feet (**Figure 15**). The aquifer is quasi-compartmentalized into four areas with saturated thicknesses greater than 30 feet; these areas are separated from one another by the three major Cimarron River tributaries draining the aquifer (Eagle Chief, Indian, and Turkey creeks). The four areas are considered hydrologically connected and not isolated groundwater basins. The thickest areas occur in the central regions of the quasi-compartmentalized zones along a northwest-southeast trend line across the defined aquifer area, with the thickest area being located near the intersection of the Garfield, Major, and Kingfisher county lines. The saturated thickness is thinnest along the northern edge of the aquifer boundary and along the margins of the outcropping bedrock units in Woods and Alfalfa counties. In total, approximately 110 square miles (8.6 percent) of the defined aquifer area had a saturated thickness of five feet or less. Areas where the water table was below the aquifer base were converted to zero saturated thickness and considered dry aquifer deposits. The 25–30 feet of saturated thickness north of an parallel to Eagle Chief Creek aligns with the orientation of a proposed ancient stream segment that connected the Cimarron River to the Salt Fork River west of Alva during the Pleistocene Epoch (Fay, 1965).

Groundwater Recharge

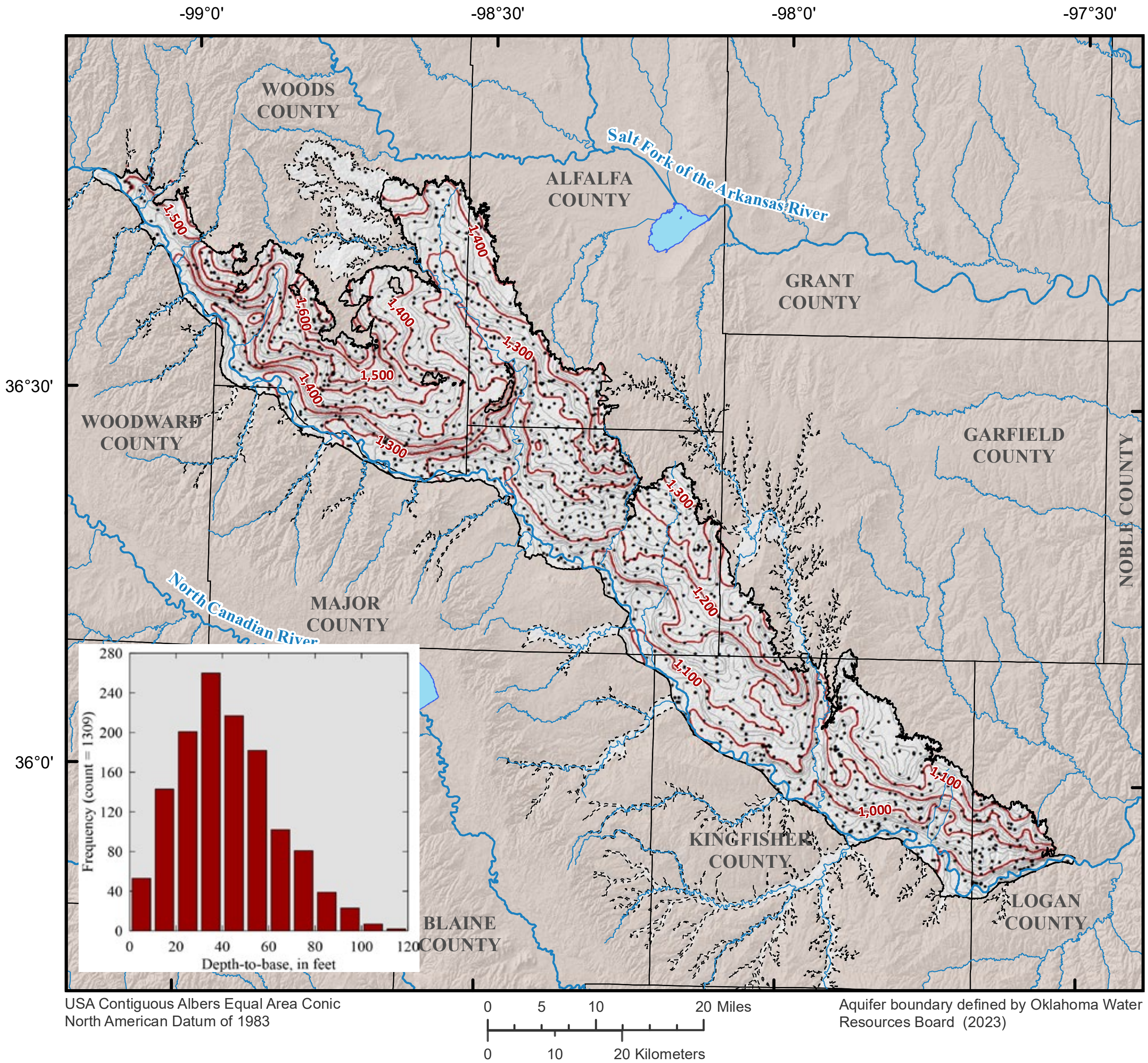
Recharge is defined in this investigation as the process by which surface water infiltrates the subsurface and becomes part of the groundwater flow system. Recharge to the Cimarron River alluvium and terrace aquifer primarily occurs through the deep percolation of precipitation. Irrigation return flow (excess of irrigation water that is not removed by surface drainage or evapotranspiration that infiltrates back into the saturated zone [Dewandel and others, 2008]) was considered the second largest source of recharge to the aquifer, and potentially the only source of recharge during extended dry periods within cropland areas. Return flow percentages vary based on the type of irrigation system used (drip, impact sprinkler, low-pressure center pivot, etc.), crop canopy, soil type, and climate conditions; an estimated 20 percent was used in the previous investigation by Adams and Bergman, (1996). If the 20 percent estimate is applied to the mean annual total reported groundwater use for irrigation (21,839



EXPLANATION

- Extent of Cimarron River alluvium and terrace aquifer
- Other alluvium, terrace, and cover sand deposits
- Groundwater flow direction
- Groundwater wells with depth-to-water measurement, January 6–February 6, 2016
- Groundwater wells with depth-to-water measurement, March 2–10, 2016 synoptic
- 1,200 Potentiometric-surface contour— Shows the altitude in feet above the North American Vertical Datum of 1988. Interval is 25 feet.

Figure 13. Potentiometric surface contour map of the Cimarron River alluvial and terrace aquifer,



EXPLANATION

Aquifer-base contour— shows detailed altitude of bedrock in feet above North American Vertical Datum 1988. Variable Interval

—1,200— Aquifer-base contour— shows detailed altitude of bedrock in feet above North American Vertical Datum 1988. Interval is 50 feet

• Groundwater well with depth-to-base pick from OWRB well driller's database

Other alluvium, terrace, and cover sand deposits

Extent of Cimarron River alluvium and terrace aquifer

Figure 14. Altitude of the base of the Cimarron River alluvium and terrace aquifer

acre-feet per year for the period 1967–2023; **Table 9**) then the mean annual return flow would be approximately 4,368 acre-feet per year.

As of the end of the calendar year 2023, the number of active long-term surface water permits for irrigation use within the defined aquifer boundary was ten. Annual surface water use for irrigation was summarized for the period 1967–2023 based on self-reported use estimates from 53 historical long-term permits. Mean annual reported water use for the period of record was about 125 acre-feet per year or about 25 acre-feet per year as return flow (assuming 20 percent). During the last decade (2013–2023) mean annual reported water use was about 233 acre-feet per year or about 47 acre-feet per year as return flow (assuming 20 percent).

Other sources of recharge include leakage through stream channels and ponds, inter-aquifer flux, and inflows from alluvium and terrace deposits along the upstream boundaries of the defined aquifer area. The contribution of these sources was not quantified in this investigation but were considered negligible by Adams and Bergamn (1996).

The rate of groundwater recharge is sensitive to multiple factors, the most important being the amount of precipitation, soil moisture content, and root-zone depth. Other factors include air temperature, surface topography, land use, and the vertical hydraulic conductivity of the geologic material in the unsaturated zone. The rate of recharge is often difficult to quantify because it cannot be measured directly; data collected from climate stations, stream gauges, and continuous groundwater records can be used to indirectly estimate recharge. Methods used for estimating recharge have different data requirements, strengths, weaknesses, and applicability. For these reasons, recharge is often estimated by multiple methods and the results are compared. Recharge to the Cimarron River alluvium and terrace aquifer was estimated using the water table fluctuations method, a simple water-budget method, and a soil-water-balance method.

Water-Table Fluctuation Method

The water-table fluctuation (WTF) method (Healy and Cook, 2002) is based on the premise that short-term (hours to a few days) rises in groundwater level in an unconfined aquifer are caused by recharge arriving at the water table following one or more precipitation events. Using the WTF method, recharge (R) was calculated as:

$$R = Sy(\Delta h/\Delta t) \qquad (1)$$

where

Sy is specific yield (dimensionless);

Δh is the change in water level, in inches; and

Δt is the change in time, in months

Changes in water level are estimated as the difference between the peak of a water-level rise and the expected water level at the time of the peak had no precipitation event(s) occurred. Because the WTF method approximates recharge during periods of water-level rise, there is some estimation error related to unaccounted recharge that occurs during periods of apparent water-level decline. In shallow water-table aquifers, water-level rises and declines are rapid, so the estimation error for total recharge is low, but not zero. However, in deeper water-table aquifers, the water-level hydrographs tend to display more cumulative water-level rises in response to multiple precipitation events over longer durations. Estimation error presumably increases for aquifers with deeper water tables because of the natural dispersion of infiltrated water within the unsaturated zone and redistribution (lateral flow) of water within the saturated zone between wetting fronts, the consequence being stunted water-level rises. Further, unlike shallow water-table aquifers which may display rapid rises in water-level throughout the year, deeper water-table aquifers tend to show more seasonality in water-level changes.

Among the seven continuous water-level recording wells installed by the OWRB in the Cimarron River alluvium and terrace aquifer with periods of record greater than four months, none were ideally suited for the WTF method. The OWRB monitoring wells 171245 and 157423 had periods of record that were inadequate for the water-table fluctuation method, and the water level hydrograph for monitoring well 171706 showed seasonal pumping signals (**Figure 9**). Although not ideal, recharge estimates were obtained for OWRB monitoring wells 18545, 175289, 18699, and 168849 (**Figure 16A–D; Table 10**). Of the four sites, OWRB well 168849 had the shallowest water table, with fluctuations occurring between 9–20 feet below the land surface, and OWRB well 175289 had the deepest water table, with fluctuations occurring between 36–39 feet belowthe land surface.

Annual recharge was estimated for 1 year (starting in July) during 2016–17 at monitoring well 18545, for 3 years during 2016–18 at monitoring well 175289 and for a 4 years during 2016–21 at monitoring wells 168849 and 18699. The 2017–18 period was excluded from the analysis at monitoring wells 68849 and 18699 because water levels were declining at both sites over the full period. Recharge estimates were calculated annually using a specific yield value of 0.13 (see lithologic-log standardization section). Daily precipitation records were obtained from the Waynoka (9404), Crescent 5WSW (2242), Orienta 1SSW (6751), and Ames (0215) cooperative observer climate stations (**Figure 17**; Oklahoma Climatological Survey, 2025b).

Using daily precipitation records from the nearest climate stations and a specific yield of 0.13, mean annual recharge estimates for the study area were 3.0 inches during 2016–17 (9.1 percent of mean annual precipitation [32.5 in/yr]), 11.4 inches during 2018–19 (24.0 percent of mean annual precipitation [46.1 in/yr]), 1.6 inches during 2019–20 (6.8 percent of mean annual precipitation [23.1 in/yr]), and 3.7 inches during 2020–21 (9.3 percent of mean annual precipitation [37.9 in/yr]). The 2017–18 estimated annual recharge was 1.8 inches (5.6 percent of mean annual precipitation [31.7 in/yr]) near well 175289. When normalized by the mean annual precipitation for the period

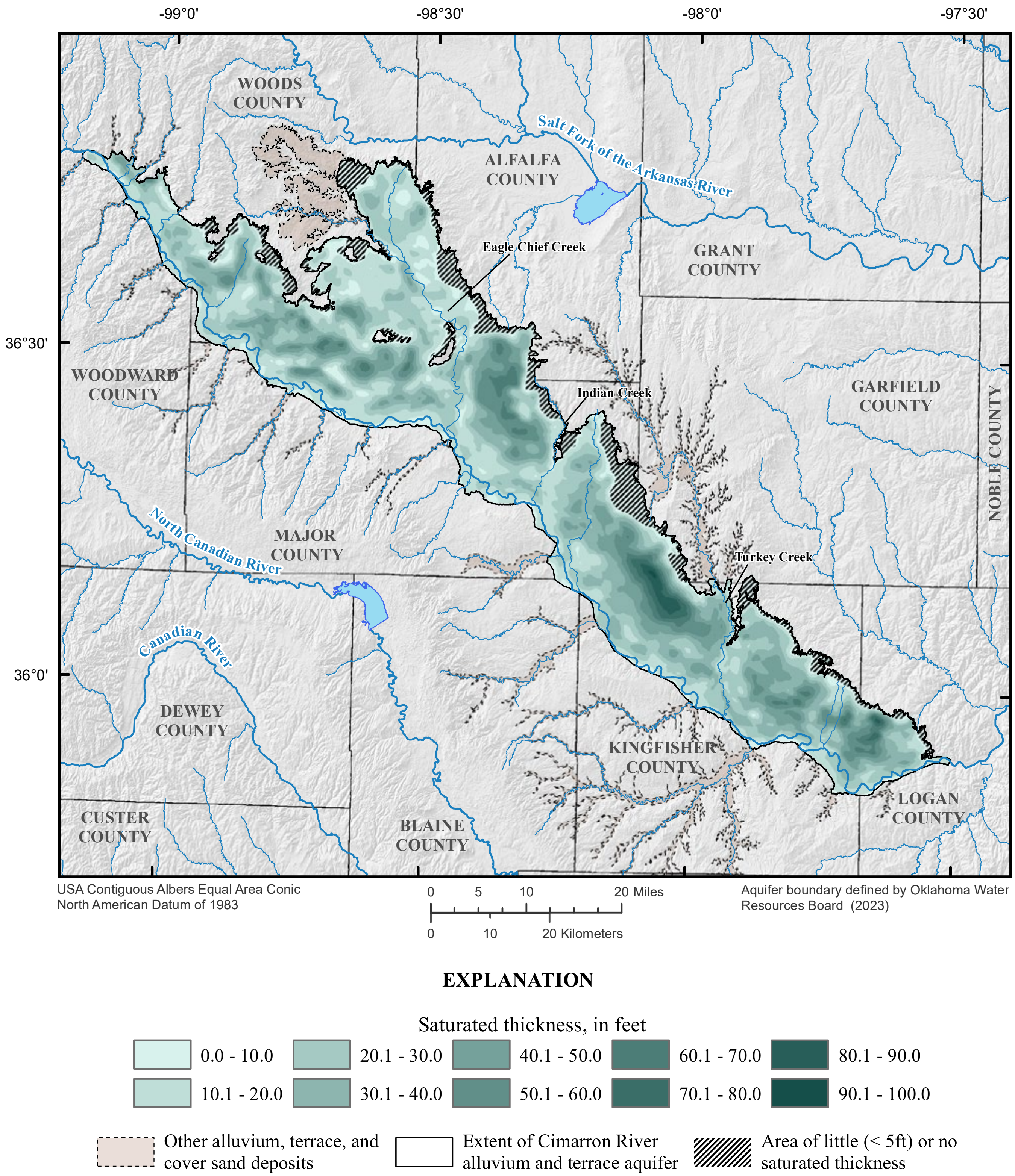


Figure 15. Saturated thickness of the Cimarron River alluvium and terrace aquifer, 2016

of record 1895–2023 (29.0 in/yr), the station-averaged mean recharge for the Cimarron River alluvium and terrace aquifer was about 3.2 inches per year (11.0 percent of mean annual precipitation) or about 218,283 acre-feet per year. Annual recharge estimates at individual continuous water-level recording wells ranged from 1.1 to 15.4 inches.

The normalized mean annual recharge rate estimated by the WTF method was compared to published estimates of mean annual recharge from other alluvium and terrace aquifers in western Oklahoma, which have similar climates to the study area. Ryter and Correll, (2015) estimated mean annual recharge rates of 3.14 and 3.08 inches per year, respectively, for reaches I and II of the Beaver-North Canadian River alluvial and terrace aquifer (study period 1980–2011). Ellis and others (2017) estimated a mean annual recharge rate of about 2.99 inches per year for reach I of the Canadian River alluvium and terrace aquifer (study period 1981–2013). Ellis and others (2020), estimated a mean annual recharge rate of 3.15 inches per year for the Washita River alluvium and terrace aquifer (study period 1980–2013). Mean annual recharge as a percentage of mean annual precipitation from these studies ranged from 8.0 to 14.0 percent. Based on the annual recharge estimates from these studies, the station-averaged mean annual recharge rate determined from the WTF method is representative of recharge to the aquifer.

Water Budget Method

The water budget method for recharge estimation requires several assumptions and simplifications that may not reflect actual field conditions. The method is based on the assumption that an aquifer is in hydrologic equilibrium, wherein the rate of recharge (R) is equal to the rate of discharge (Healy, 2010); the water budget equation can be written as:

$$R = Q_b + ET + Q_n + \Delta S \qquad (2)$$

where

- Q_b is baseflow discharge, in acre-feet per year;
- Q_n is net flux of groundwater entering or leaving the aquifer other than baseflow or precipitation, in acre-feet per year;
- ET is evapotranspiration, in acre-feet per year; and
- ΔS is change in storage, in acre-feet per year

Recharge was calculated by dividing the sum of the discharge components by the total contributing drainage area of the Cimarron River, defined as the aquifer area with a minimum saturated thickness of five feet at the time of the investigation with groundwater flow directed towards the Cimarron River and its major perennial tributaries. The total contributing drainage area was estimated to be approximately 1,137 square miles (727,372 acres) based on the potentiometric surface and saturated thickness maps (**Figures 13 and 15**). Areas along the northern edge of the aquifer where groundwater flow is directed out of the aquifer were considered non-contributing to baseflow in the Cimarron River. Areas with little to no saturated thickness were considered to have negligible flow; a saturated thickness of five feet was chose as a reasonable buffer between the saturated and unsaturated areas of the aquifer based on the smallest contour interval of ten feet and because the OWRB has historically considered areas with less than five feet of saturated thickness as not being part of a groundwater basin.

On a long-term basis, change in aquifer storage is generally considered negligible, except in circumstances where the rate of annual groundwater use exceeds the rate of annual recharge. The assumption of negligible storage change is reasonable for the Cimarron River alluvium and terrace aquifer (regionally) based on the relative changes in the altitude of the water table between 1986 and 2016 (Adams and Bergman, 1996; LePera and others, 2023) The assumption of negligible storage change may become inappropriate in the future as demands for groundwater in northwestern Oklahoma increase. Locally, annual groundwater use may exceed annual recharge.

Evapotranspiration is the process by which water is transferred to the atmosphere directly by evaporation from the soil and surface-water bodies and indirectly by transpiration from plants, generally from the soil-moisture (unsaturated) zone. These soil-moisture-zone and surface-water components of evapotranspiration were not considered part of the water budget because they occur before infiltrating precipitation has become groundwater recharge. For this analysis, evapotranspiration from the saturated zone was quantified for areas of the aquifer where the water table likely intersects with the plant root zone. The area where the water table intersects the plant root zone is small compared to the full aquifer area and is primarily confined to the wetland areas (land areas with frequently saturated or flooded soils) of the active alluvium (Qal, **Figure 5**) along the Cimarron River and its major tributaries. About 15,160 acres of the active alluvium were classified as wetland (riverine, freshwater emergent, and freshwater forested/shrub) by the National Wetlands Inventory (NWI; U.S. Fish and Wildlife Service, 2023).

A review of these areas using Google Earth satellite imagery indicated that the riverine wetland areas were nearly devoid of vegetation and the freshwater emergent wetland areas were sparsely vegetated, as indicated by exposed red- and tan-colored soils. The largest amount of vegetation was observed in the freshwater forested/shrub wetland areas. Therefore, only about 6,000 acres (40 percent) of the NWI wetland area was assumed to contribute to direct evapotranspiration from the saturated zone. An evapotranspiration rate of between 12.0–16.0 inches per year has been used for other alluvium and terrace aquifers in western Oklahoma (Rogers and others, 2023; Smith and others, 2021; Ellis and others, 2020; Ellis and others, 2017) based on a range estimated for undisturbed salt grass cover in southwestern Utah (White, 1932). Using a rate of 12 inches per year about 6,000 acre-feet per year is estimated to outflow from the saturated zone within the wetland areas of the Cimarron River alluvium and terrace aquifer.

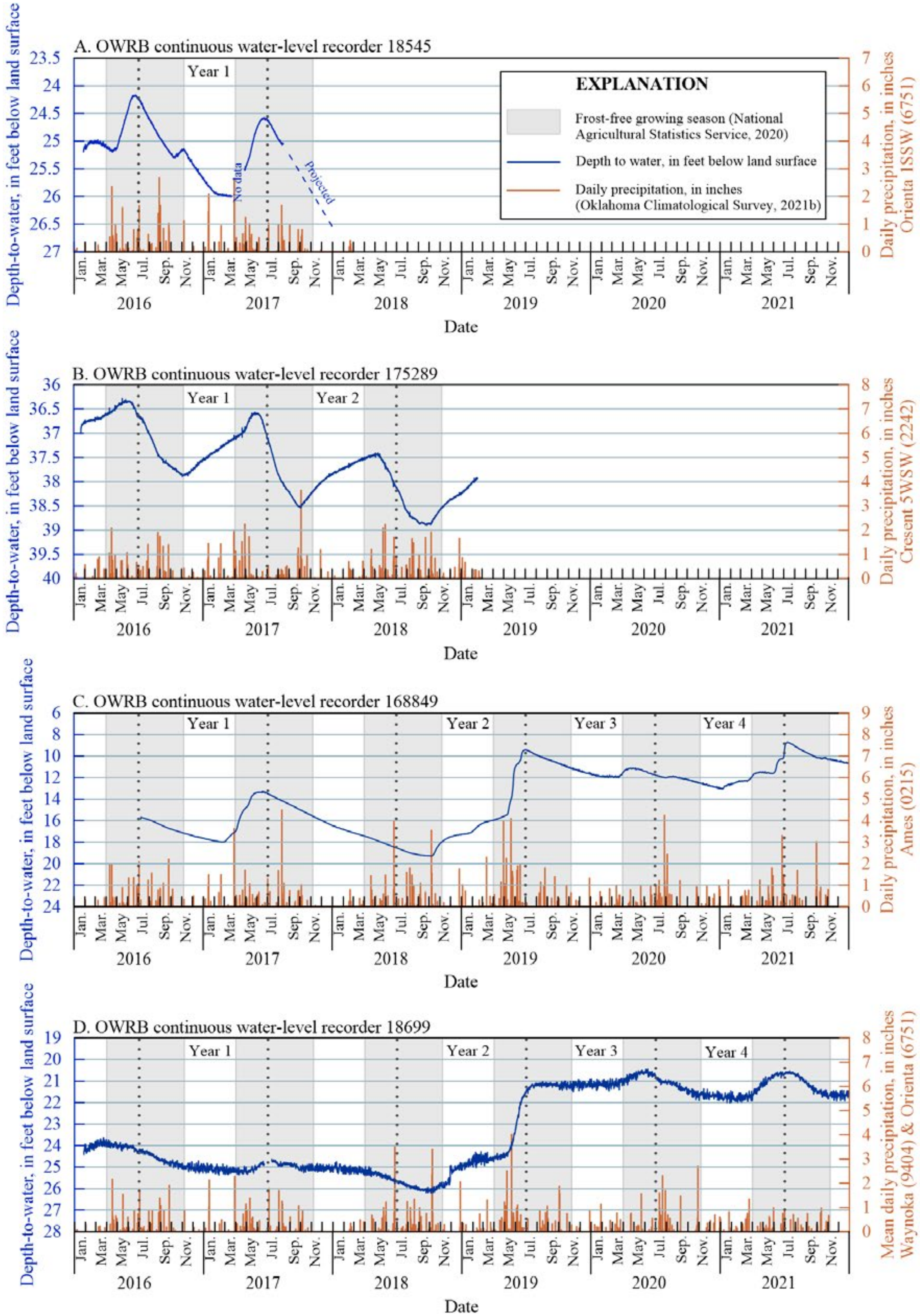


Figure 16. Daily precipitation and depth to water in four OWRB continuous water-level monitoring wells completed in the Cimarron River alluvium and terrace aquifer, 2016–2021, used for the Water-Table fluctuation method (WTF; Healy and Cook, 2002)

Table 10. Summary of recharge estimates using the Water-Table fluctation method (WTF; Healy and Cook, 2002) for the Cimarron River alluvium and terrace aquifer, 2016–2021.

[--, data not available or not applicable. Dates in MM-DD-YYYY format. Continuous recorder locations are shown in **Figure 1** and site details are listed in **Table 7.** Climate station locations are shown in **Figure 17** and station details are listed in **Appendix D**]

	OWRB continuous water-level recorder well				**Mean**
	18545	175289	18699	168849	
Mean annual precipitation, 1895–2023, in inches per year for selected counties in northwestern Oklahoma (Vose and others, 2014; Figure 3A)	29.0	29.0	29.0	29.0	--
Nearest Climate Station(s) (Figure 17)	6751	2242	9404 & 6751	0215	--
Estimated specific yield	0.13	0.13	0.13	0.13	--
Period: 07-01-2016 to 06-30-2017					
Annual pecipitation, inches	30.5	34.6	30.5	34.5	32.5
Sum of water-level rises, in feet	1.5	0.8	0.7	4.7	1.9
Estimated recharge, inches per year	2.3	1.3	1.1	7.4	3.0
Recharge, percent of annual precipitation	7.5	3.8	3.7	21.3	9.1
Normalized recharge, 1895–2023	2.2	1.1	1.1	6.2	2.7
Period: 07-01-2017 to 06-30-2018					
Annual precipitation, inches	--	31.7	25.3	31.1	29.4
Sum of water-level rises, in feet	--	1.1	--	--	--
Estimated recharge, inches per year	--	1.8	--	--	--
Recharge, percent of annual precipitation	--	5.6	--	--	--
Normalized recharge, 1895–2023	--	1.6	--	--	1.6
Period: 07-01-2018 to 06-30-2019					
Annual precipitation, inches	--	--	42.0	50.2	46.1
Sum of water-level rises, in feet	--	--	4.7	9.9	7.3
Estimated recharge, inches per year	--	--	7.3	15.4	11.4
Recharge, percent of annual precipitation	--	--	17.3	30.6	24.0
Normalized recharge, 1895–2023	--	--	5.0	8.9	7.0
Period: 07-01-2019 to 06-30-2020					
Annual precipitation, inches	--	--	22.9	23.3	23.1
Sum of water-level rises, in feet	--	--	1.1	0.9	1.0
Estimated recharge, inches per year	--	--	1.7	1.4	1.6
Recharge, percent of annual precipitation	--	--	7.5	6.0	6.8
Normalized recharge, 1895–2023	--	--	2.2	1.7	2.0
Period: 07-01-2020 to 06-30-2021					
Annual precipitation, inches	--	--	32.0	43.8	37.9
Sum of water-level rises, in feet	--	--	1.4	3.3	2.4
Estimated recharge, inches per year	--	--	2.2	5.1	3.7
Recharge, percent of annual precipitation	--	--	6.9	11.6	9.3
Normalized recharge, 1895–2023	--	--	2.0	3.4	2.7
Station-averaged mean annual recharge					**3.2**

A supplemental component of plant transpiration was estimated for forested areas within the active alluvium that were outside of the NWI-classified wetlands; the trees and shrubs in these forested areas were assumed to be phreatophytes (plants with root systems that draw water directly from the saturated zone or overlying capillary fringe [Robinson, 1958]) based on their relative density. The mean depth-to-water in these forested areas is about 12 feet below the land surface (based on drillers reports), with the highest tree densities occurring where the water table is shallowest and becoming sparser as depth-to-water increases. Approximately 5.6 percent of the aquifer area (45,835 acres) was classified as dedicated forest land (**Figure 2**; National Agricultural Statistics Service, 2021); of this, about 8,463 acres exist outside of the wetland areas within the active alluvium of the Cimarron River and its major tributaries.

Mogg and others (1960) estimated that the amount of groundwater used by cottonwoods and willows in a year would be about 5.4 acre-feet per acre if the tree density was 100 percent (no visible land between tree canopies); phreatophytes located in the North Canadian River valley were estimated to have a tree density of 70 percent. Similar types of phreatophytes exist within the study area but are generally less dense based on a visual comparison using the most recent (2020) Google Earth Imagery. Therefore, a 50 percent density estimate was adopted for this analysis, equating to a rate of about 2.7 acre-feet per acre per year. Based on the adopted consumptive rate, area of dedicated forest land, and tree density percentage, the mean annual transpiration from the aquifer was estimated to be about 22,850.1 acre-feet per year.

Leakage of groundwater from the aquifer to Permian-age geologic units occurs in limited areas along the northeastern boundary of the aquifer, where it often seeps through the Permian-age geologic units back to one of the three major Cimarron River tributaries (Eagle Chief, Indian, and Turkey creeks). The volume of leakage out of the aquifer in these areas is considered negligible. The flux of groundwater across the Permian-Quaternary boundary at the base of the aquifer is also considered negligible because of the relatively large difference in hydraulic conductivities of the unconsolidated alluvium and terrace deposits and the consolidated sandstones and shales of the bedrock units (Adams and Bergman, 1996).

For this analysis, the mean annual baseflow between the Waynoka and Dover Cimarron River gauge stations was used because the stream reach captures more than 70 percent of the drainage area of the aquifer. The contributing drainage area between the two gauge stations was about 850.6 square miles. As discussed in the Streamflow and Baseflow section of this report, the modified mean annual baseflow to the Cimarron River during the common period of record (1974–2023) was about 199.6 cubic feet per second (derived from data used to construct **Table 5**). An exact estimate of the mean annual baseflow contribution from tributaries draining Permian-age geologic units south of the Cimarron River could not be determined with the data available. However, streamflow synoptics conducted in 1986 by Adams and Bergman (1996) and in 2020 by the OWRB (**Table 6**) suggest that baseflow contribution to the Cimarron River from Permian-age geologic units and isolated terrace deposits ranges between 20–36 percent of total baseflow; using 25 percent, the modified mean annual baseflow estimate decreases to 149.7 cubic feet per second; this estimate reflects baseflow contribution to the Cimarron River from alluvium and terrace aquifer deposits. By linear extrapolation, mean annual baseflow from the total contributing drainage area of the basin was estimated to be 200.0 cubic feet per second or about 144,808 acre-feet per year.

The mean annual reported groundwater use for the period 1974–2023 was estimated to be about 32,418 acre-feet per year (estimates derived from values listed in **Table 8**). Mean annual reported groundwater and surface water use for irrigation over the same period were about 22,992 and 130 acre-feet per year, respectively. Assuming an irrigation return flow estimate of 12 percent (improved application efficiency), about 2,759 acre-feet per year was returned to the aquifer.

Based on the values of mean annual saturated zone ET, forest area transpiration, baseflow discharge, and groundwater use, the mean annual recharge to the Cimarron River alluvium and terrace groundwater basin area was estimated to be about 203,317 acre-feet per year or about 3.35 inches per year (10.8 percent of mean annual precipitation [30.98 in/yr]) for the period 1974–2023. The estimated recharge value is within the range determined for analogous alluvial and terrace aquifers in western Oklahoma. Based on the estimate rate of 3.35 inches per year, the mean annul recharge rate for the full 1,279 square mile aquifer area is about 228,783 acre-feet per year.

Soil-Water Balance Method

A modified Thornthwaite-Mather soil-water balance (SWB) code was used to estimate annual recharge to the Cimarron River alluvium and terrace aquifer for the period 1980–2020 (Westenbroek and others, 2010). The SWB code estimates spatial and temporal variations in recharge at the regional scale using tabular daily climate data (precipitation and minimum/maximum temperature), gridded landscape data (soil type, available soil-water capacity, and land use), and a properties matrix based on different combinations of soil type and land use (Westenbroek and others, 2010).

Tabular climate data was obtained for twelve Oklahoma Mesonet stations and eighteen cooperative observer (COOP) climate stations within and surrounding the defined aquifer boundary (Oklahoma Climatological Survey, 2025a and 2025b; **Figure 17**). A table listing the location details and periods of record for the thirty climate stations can be found in Appendix D. Hydrologic soil type data was derived from the Soil Survey Geographic Database (SSURGO; Natural Resources Conservation Service, 2016). Available soil-water capacity values were assigned based on soil texture, ranging from 1.20 inches per foot of thickness for sand to 3.60 inches per foot of thickness for clay (Westenbroek and others, 2010). Land-use data was derived from the National Agricultural

Statistics Service Cropland Data Layer program (CropScape; National Agricultural Statistics Service, 2021).

All geospatial datasets were resampled from their native resolutions to a common grid cell size of 100 by 100 meters (328 by 328 feet). The resampled datasets were all clipped to a single 146.2 by 119.8-kilometer fishnet grid that encompassed the aquifer and all the utilized climate stations. The soil-water balance code uses daily changes in soil moisture to estimate potential recharge at each grid cell in the model domain. Soil moisture is an iterative value estimated as the difference between daily precipitation infiltration and evapotranspiration (ET), wherein any excess water in the soil profile (surplus) is counted as recharge and any water loss (deficit) is calculated as a running sum during extended periods of insufficient precipitation. The amount of moisture retained at a specific time step is determined based on a soil-water-retention table (Thornthwaite and Mather, 1957). Soils were considered fully saturated when the soil moisture exceeded the soil's maximum water capacity; any additional water applied to the soil was converted to runoff and either routed to an adjacent downgradient grid cell or out of the model domain (Westenbroek and others, 2010). ET was computed in the SWB code using the Hargreaves-Samani method (Hargreaves and Samani, 1985) and runoff was estimated using the U.S. Department of Agriculture Natural Resources Conservation Service (NRSC) curve-numbers.

Root-zone values are classified based on land use and soil type and represent the depth to which different categories of vegetation will grow. Larger root-zone values, such as those used for forested wetlands and shrublands increase the uptake of soil moisture and decrease recharge, whereas smaller root-zone values, such as those used for unvegetated lands increase recharge. Because the default root-zone depths were developed for soils in northern Wisconsin where crops and native vegetation grow in soils overlying thick glacial till deposits, they generally need to be scaled for Oklahoma soils and vegetation (Dripps, 2003). Winter wheat and rye are the dominant crop types overlying the Cimarron River alluvium and terrace aquifer (**Figure 2**; National Agricultural Statistics Service, 2021). These two crops fall within the small grains (moderate-rooted agriculture) land-use category, which have default root-zone depths ranging from 2.00 to 3.33 feet. Although the maximum rooting depths for these two crops are around 4 to 5 feet, the bulk (greater than 60 percent) of the root biomass exists within the upper 1 to 2 feet of soil (Fan and others, 2016; Weaver 1926). To account for this bulk biomass depth range, the default root-zone values were scaled to 70 percent, resulting in a new depth range of 1.40 to 2.33 feet.

An initial SWB-estimated mean annual recharge of 2.3 inches per year (7.6 percent of the mean annual precipitation [30.4 inches]) was estimated for the Cimarron River alluvium and terrace aquifer for the period 1980–2023 using the default root zone depths. Using the scaled root-zone depths, the mean annual recharge increased to 3.13 inches per year (213,486 acre-feet per year) or about 10.3 percent of the mean annual precipitation [30.4 in/yr] for the period 1980–2023. Adams and Bergman (1996) reported a recharge rate of 2.3 inches per year (9 percent of mean annual precipitation [27.0 in/yr] for the period 1950–90) based on estimates of baseflow measured in February 1986 and mean annual water use, while Reed and others (1952) reported a recharge rate of 4.15 inches per year (14.4 percent of mean annual precipitation [28.8 in/yr] for the period 1895–1950) based on water level change data and a specific yield of 0.1. The maximum and minimum estimated annual recharge values for the period of analysis were 6.53 inches in 1993 and 0.22 inches in 2006 (**Figure 18**).

Spatially, mean annual recharge was greatest in areas with type A soils, specifically in parts of Kingfisher, Logan, south-central Alfalfa, and east Major Counties (**Figure 17**). Type A soils are characterized as having low runoff potential and high infiltration rates (low water retention ability) even when fully wetted. Type A soils consist chiefly of a mixture of sands, silts, and clays, wherein the sands compose 90 percent of the mixture and are generally coarse-grained (Natural Resources Conservation Service, 2009). Spatially, mean annual recharge was lowest in areas with type C soils, specifically along the Cimarron River in Woods County and along the northern edge of the aquifer in Kingfisher County (**Figure 17**). Type C soils are characterized as having moderately high runoff potential and low infiltration rates when thoroughly wetted. The transmission of water through type C soils is somewhat limited, being composed mainly of clay (20–40 percent) and fine- to very fine-grained loam material. Other observations were that mean annual recharge was greater in the southeastern region of the defined aquifer area than in the northwestern region for the same soil types and that there was little correlation between recharge and land use; Irrigation return flow (which is not accounted for in SWB model) would contribute to recharge in the cropland areas. Differences in mean annual recharge between regions can be attributed to differences in mean annual precipitation, with rates generally being about 10 inches per year greater in Logan County than Woods County (Oklahoma Climatological Survey, 2023a). Estimated monthly recharge ranged from 0.04 inches in July to 0.32 inches in March, with a mean of 0.19 inches per month.

Hydraulic Properties

Hydraulic properties of the Cimarron River alluvium and terrace aquifer determined as part of this investigation included hydraulic conductivity, transmissivity, and specific yield. Hydraulic conductivity (K) is a measure of a porous material’s capacity to transmit water and is defined as the rate of flow through a unit cross-sectional area of an aquifer under a unit hydraulic gradient (Lohman, 1972); K is expressed in units of length per unit time. Hydraulic conductivity varies depending on the physical properties of both the fluid (density and viscosity) and the porous material (permeability). Transmissivity (T) is the product of hydraulic conductivity and saturated thickness and is a measure of the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient (Lohman, 1972); T is

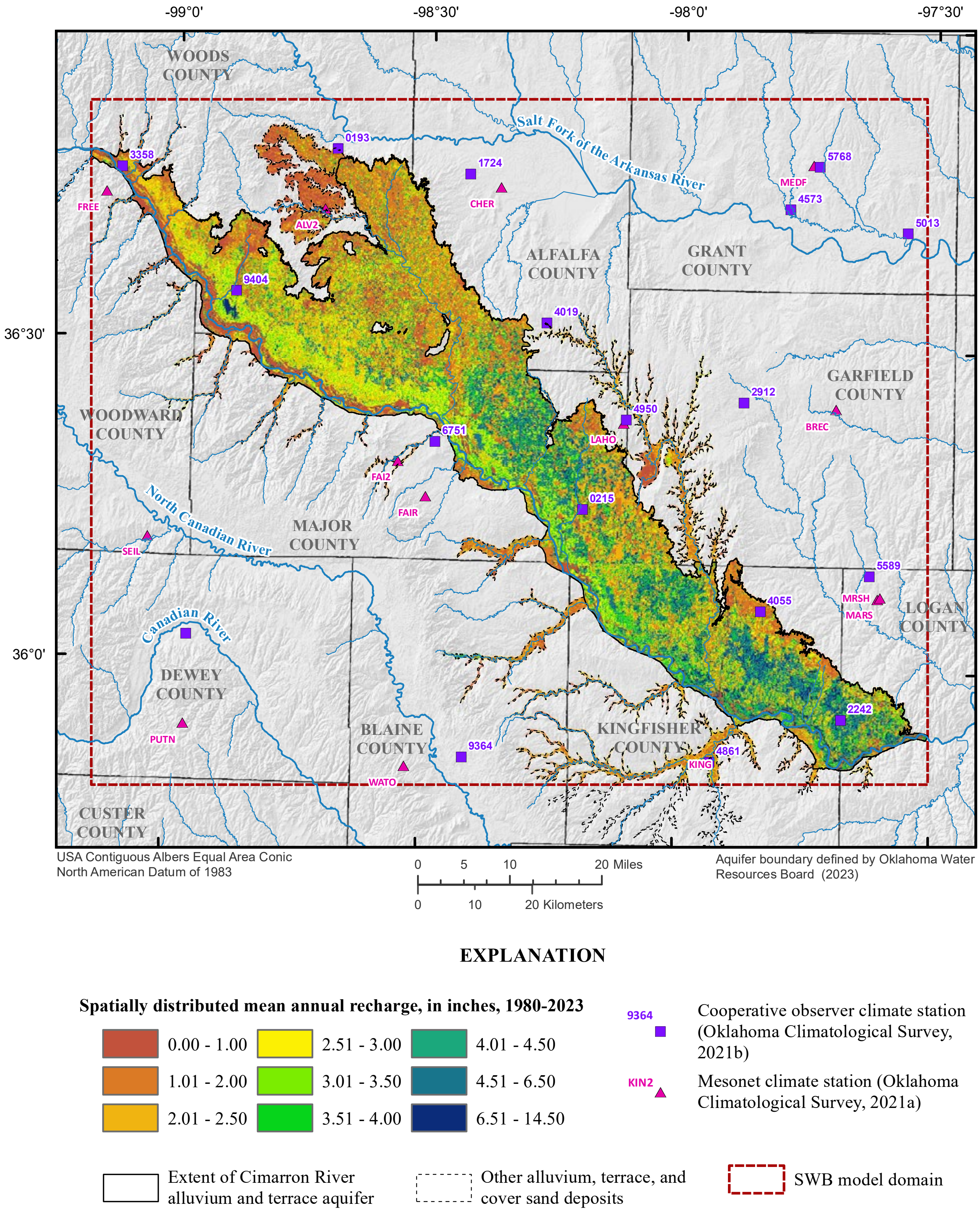


Figure 17. Spatially distributed mean annual recharge estimated using the Soil-Water-Balance code (SWB; Westenbroek and others, 2010) for the Cimarron River alluvium and terrace aquifer, 1980–2023.

expressed in units of length squared per unit time (Lohman, 1972). Specific yield (Sy) is a measure of the amount of water yielded by gravity drainage from an unconfined aquifer and is defined as the ratio of the volume of water released from storage to the total volume of the aquifer (Lohman, 1972); Sy is dimensionless.

The hydraulic properties were estimated using several methods. Hydraulic conductivity and transmissivity were estimated using slug tests, well drawdown specific capacity tests, two multi-well pumping tests, and the lithologic-log standardization method of Mashburn and others, (2013). The specific yield was estimated from two multi-well pumping test, the regional method of Christenson and others, (2011), and a non-linear relationship with hydraulic conductivity.

Groundwater wells completed in the alluvial and terrace deposits typically yield 30–250 gallons per minute (gal/min) but locally may yield less than 5 gallons per minute or more than 1,500 gallons per minute (Reed and others, 1952; Adams and Bergman, 1996; LePera and others, 2025). Well yields of differ considerably based on local variability in sediment grain size and sorting, which are related to the irregular depositional processes that occur in a fluvial environment; wells that intersect coarse-grained, well-sorted sediments usually have the highest yields.

Transmissivity, hydraulic conductivity, and specific yield determined or estimated from 29 aquifer tests conducted in the Cimarron aquifer by previous investigators are listed in **Table 11**. Tests conducted in terrace deposits were reported in Behnam Group (1982) and Reed and others (1952) while tests conducted in alluvial deposits were reported in Engineering Enterprises (1977). Values of hydraulic conductivity for alluvial deposits ranged from 100.9 to 501.2 feet per day with a mean of 253.8 feet per day and a median of 216.2 feet per day (**Table 11**). Values of hydraulic conductivity for terrace deposits ranged from 14.9 to 676.4 feet per day with a mean of 126.3 feet per day and a median of 96.4 feet per day (**Table 11**). The ratio of median hydraulic conductivities for the alluvial and terrace deposits was 2.2:1, meaning the alluvium is roughly two times as conductive to flow as the terrace deposits. Specific yield values from the pumping tests ranged from 1.3x10-7 to 1.2x100 (**Table 11**). The typical range for an unconfined aquifer is between 0.1 to 0.3 (Lohman, 1972; Fitz, 2002). Low estimates of specific yield in some tests were attributed to inadequate pumping periods (Benham group, 1982; Reed and others, 1952). If the unrealistic estimates were excluded from the statistics, the mean and median specific yield values from all aquifer tests would be 0.13 and 0.08, respectively.

Slug Tests

Slug tests are simple field experiments used to estimate the hydraulic properties of an aquifer within a short radius around a well; estimates of hydraulic properties derived from individual slug tests are site-specific and must be compared against other tests to produce ranges that are representative of the entire aquifer. Slug tests work by imposing hydraulic stress on an aquifer system in the form of a near-instantaneous change (rise or fall) in hydraulic head, which is measured through time until the water-level response returns to pre-test static conditions (Butler, 1998). Changes in hydraulic head can be induced by increasing or decreasing air pressure within the well casing or by rapidly introducing a solid object of known volume (slug) into the water column; solid PVC slugs were used in this investigation.

A total of 171 slug tests were conducted at 50 well sites across the defined aquifer area (**Figure 19**). Slug tests were performed according to standard guidelines and data were analyzed with the AQTESOLV software package (Duffield, 2007). The analyzed slug tests predominately displayed an overdamped response, with a few tests displaying a double straight-line effect. The double straight-line effect occurs when a well is screened across the water table, allowing for filter pack drainage during the test (Butler, 1998). The Bouwer-Rice solution for unconfined aquifers was used to estimate hydraulic conductivity at each well site (Bouwer and Rice, 1976). The Bouwer-Rice method involves calculating the slope of a straight line fit to the response data and using that value to estimate the hydraulic conductivity of the aquifer. The equation can be rearranged to solve for hydraulic conductivity as follows:

$$K = \frac{r_c^2 \, ln\left(\frac{R_e}{r_w}\right)}{2Lt} \, ln\frac{h_0}{h_t} \qquad (3)$$

where

r_c is the casing radius, in feet;
R_e is the effective radius of the test, in feet;
r_w is the well radius, in feet;
L is the screen length, in feet;
h_o is the initial displacement at t = 0, in feet;
h_t is displacement as a function of time, in feet; and
t is elapsed time since test initiation, in seconds

Of the 171 slug tests conducted, 69 had ratios of expected head to measured head that were considered unreliable; a ratio of 1.0 ± 0.3 was considered reliable. Slug tests that were deemed unreliable were excluded from the statistical analysis. Hydraulic conductivity estimates ranged from about 3.1 to 468.0 feet per day, with a mean of 110.5 feet per day and a median of 81.0 feet per day (**Table 12**). Two well sites were completed within alluvium deposits of the Cimarron River; the mean hydraulic conductivity for these two sites was 209.0 feet per day.

Well Drawdown Specific Capacity Test Analysis

Specific capacity test data compiled from 767 completion reports submitted to the OWRB for groundwater wells in the Cimarron River alluvium and terrace aquifer were used to estimate the hydraulic conductivity of aquifer materials locally around each well (**Figure 19**). Since none of the wells completed in the aquifer were fully penetrating (perforated over the entire saturated zone), values of hydraulic

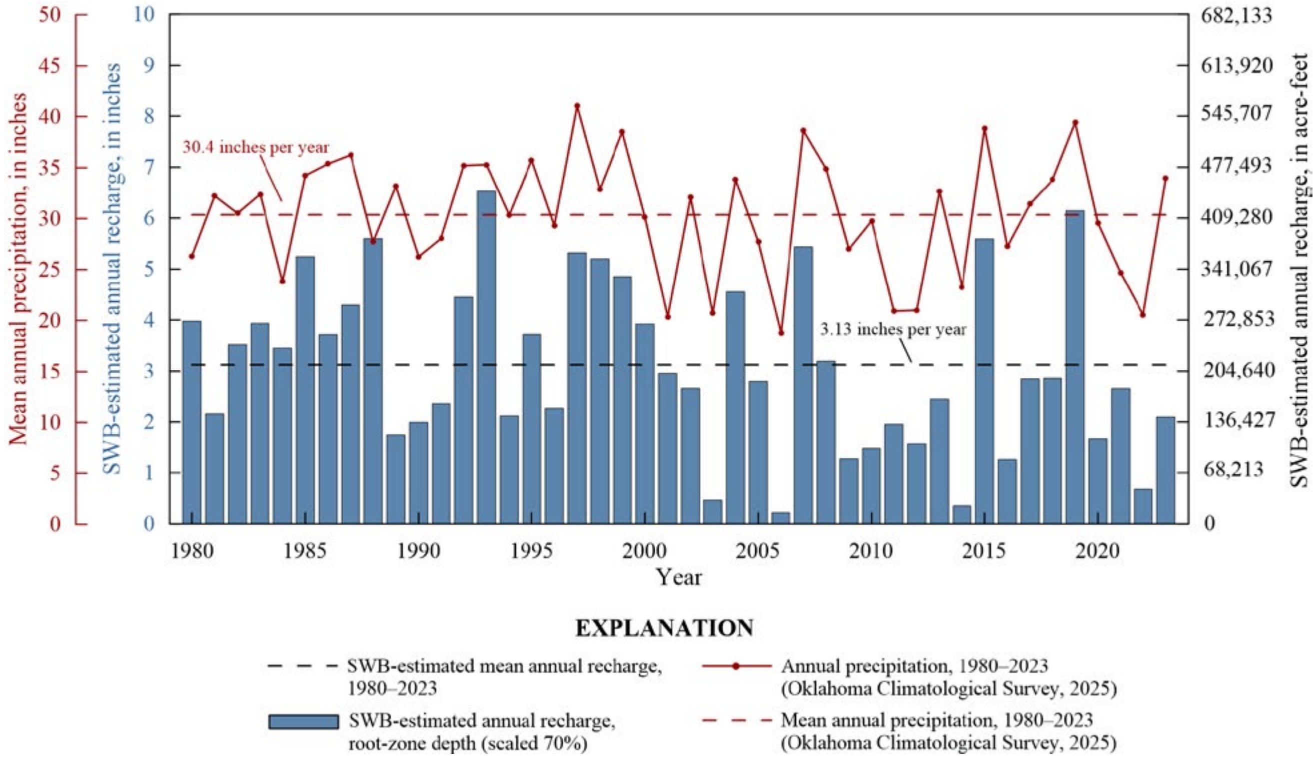


Figure 18. Mean annual precipitation and recharge estimated using the Soil-Water-Balance code (SWB;Westenbroek and others, 2010) for the Cimarron River alluvium and terrace aquifer, 1980–2023.

conductivity estimated from this method more appropriately reflect the aquifer material(s) within the perforation interval of each well, which is generally the most productive zone for the local area. Although there is no official best practice for this test in the Chapter 35 rules, many drillers have adopted the standard of spending at least as much time developing a well as drilling it (internal communication, OWRB well drillers section). Individual drilling firms, especially those that do a lot of irrigation or public supply wells likely have their own standard practices.

A specific capacity test is considered complete when the rate of influx into the well has reached equilibrium with the rate of pumping. Most (92 percent) of the wells used in this analysis were drilled for either irrigation, agriculture, or public supply use; the remaining wells were for domestic use. Most (97 percent) of the specific capacity tests were run for at least one hour, with several public supply and irrigation tests lasting longer than 24 hours. Although tests longer than 4-6 hours were preferred, a comparison of the time required to fully drain each well's casing (assuming a static volume) to the time duration of each test indicated that tests lasting one hour were achieving equilibrium.

The Neuman (1974) and Moench (1997) curve-matching solutions are most appropriate for an unconfined aquifer test but were unavailable for use in this analysis because continuous time-drawdown data was not collected. Instead, the Cooper and Jacob (1946) linear curve solution, which was derived from the Theis nonequilibrium method (Theis, 1935) was applied to each well. This solution is intended for the analysis of wells completed in a confined aquifer but is assumed by the researchers to provide a reasonable estimate of transmissivity in unconfined aquifers. The Cooper and Jacob equation is:

$$T = 0.183\frac{Q}{S_w}log\frac{2.25Tt}{r_w^2S} \qquad (4)$$

where

- Q is the discharge rate, in cubic feet per day;
- S_w is the total length of equilibrated drawdown, in feet;
- T is the transmissivity, in feet per day;
- S is the storativity of the aquifer [dimensionless];
- r_w is the well radius, in feet; and
- t is time, in days

Successive approximation was used to solve for transmissivity. In confined aquifers, storativity is equal to specific storage (a value related to aquifer compressibility) multiplied by the aquifer thickness. In unconfined aquifers, water released from storage by aquifer compression and water expansion is negligible compared to the amount of water released from storage by gravity drainage (specific yield). A specific storage value of 0.0001 has been used in numerical groundwater flow models for other alluvium and terrace aquifers in Oklahoma (Paizis and Trevisan, 2021; Ryter and Correll, 2016; Ellis and others, 2020). When multiplied by the mean saturated thickness, storativity for the Cimarron River alluvium and terrace aquifer was estimated to be about

Table 11. Estimates of transmissivity, hydraulic conductivity, and specific yield for the Cimarron River alluvium and terrace aquifer summarized from published studies.

[ft^2/day, square feet per day; ft/day, feet per day. Tests were originally presented in units of transmissibility (gallons per day per foot). They were converted to units of transmissivity by multiplying by the conversion factor 0.134 (Fetter, 1994). Sites with an asterisk (*) did not have a depth-to-base provided, so a value was assigned based on the nearest neighboring well(s) from the same report or OWRB database. Specific yield values highlighted in red are far outside of the typically range for an unconfined aquifer (0.1 to 0.3; Lohman, 1972). Specific yield statistics excluded values considered unrealistic]

	Site number	Transmissivity ft^2/day	Hydraulic conductivity ft/day	Specific yield
Benham Group	F-1	5,347.2	314.5	1.5×10^{-1}
	N-1	5,079.9	120.9	5.1×10^{-3}
	MN-1	4,010.4	97.8	3.8×10^{-4}
	P-6	7,887.2	239.0	2.6×10^{-3}
	O-7	1,871.5	60.4	4.3×10^{-5}
	B-4	3,342.0	92.8	1.3×10^{-7}
	E-5	828.8	20.7	7.5×10^{-3}
	H-4	1,604.2	41.1	6.0×10^{-3}
	M-3	601.6	28.6	1.0×10^{-4}
Reed and others	21N9W-28-1*	4,144.1	116.7	1.3×10^{-1}
	20N9W-6-2*	5,748.3	107.1	5.1×10^{-2}
	20N10W-12-3*	2,005.2	42.9	8.3×10^{-2}
	20N10W-12-5*	1,604.2	29.7	6.4×10^{-2}
	19N8W-27-1*	8,020.8	147.3	1.8×10^{-2}
	20N9W-5-6*	802.1	14.9	4.0×10^{-2}
	19N9W-10-1*	3,876.7	211.7	5.6×10^{-2}
	21N9W-20-2*	6,951.4	96.4	2.2×10^{-2}
	21N10W-16-1*	10,159.7	534.2	1.2×10^{-1}
Engineering Enterprises	G-43*	1,654.3	121.6	3.9×10^{-1}
	D-69*	9,729.0	421.1	2.2×10^{-1}
	E-78*	3,466.6	205.1	3.0×10^{-2}
	F-31*	4,758.2	240.3	7.0×10^{-2}
	CM-88*	3,114.0	216.2	2.8×10^{-1}
	CM-84*	1,538.4	142.4	2.1×10^{-1}
	CM-82*	806.6	152.2	2.8×10^{-1}
	CM-94*	5,293.8	398.0	4.8×10^{-3}
	CM-92*	1,176.4	101.4	1.6×10^{-3}
	CM-96	1,070.0	100.9	1.2×10^{0}
	CM-99*	7,919.1	501.2	8.0×10^{-2}
	CM-136*	5,881.9	384.4	2.7×10^{-3}
Alluvium	Mean	3,981.2	253.8	1.9×10^{-1}
	Median	3,466.6	216.2	2.1×10^{-1}
Terrace	Mean	4,031.6	126.3	7.0×10^{-2}
	Median	3,876.7	96.4	5.6×10^{-2}
All	Mean	4,009.8	181.5	1.3×10^{-1}
	Median	3,671.7	121.3	8.2×10^{-2}

0.0026. For this analysis, a specific yield value of 0.13 was utilized (see lithologic log standardization analysis). Once determined, transmissivity was calculated using:

$$T=Kb \qquad (5)$$

where

K is hydraulic conductivity, in feet per day; and

b is saturated thickness of the aquifer, in feet.

Hydraulic conductivities estimated from specific capacity tests for the Cimarron River alluvium and terrace aquifer using a specific yield of 0.13 ranged from 0.2 and 526.0 feet per day. The mean and median values were 34.2 and 19.2 feet per day, respectively (**Table 12**). Most of the estimated hydraulic conductivities were within the range of fine- to medium-grained sand (Domenico and Schwartz, 1989; **Figure 24**) and were consistent with reported lithologies. It should be emphasized that estimates of transmissivity and hydraulic conductivity estimated from this method will not be as accurate as those estimated from multi-well aquifer tests. Varying the Sy by ± 0.03 had minimal impact on the min, max, and mean hydraulic conductivities, with values differing by about 2.7 percent.

Multi-Well Aquifer Pumping Tests

The OWRB conducted four multi-well pumping tests as part of this investigation (**Figure 19**). The tests were performed on public water supply wells, three of which were owned by the city of Enid and one by the town of Okeene. Water-level recorders were installed in observation wells near each of the public supply wells and set to take a measurement every minute. Before each test was started, the public supply well pump was shut off for a few days to allow the water table to return to baseline (static) conditions; baseline water level measurements are collected to evaluate localized, regional, or seasonal trends that may alter or interfere with aquifer test interpretation. Once a pump was turned on, it was set to a constant rate and allowed to run for multiple days; the amount of time each site was able to run varied based on the available storage capacity of the associated municipal water districts' infrastructure. Each of the four sites faced unique problems during their respective monitoring periods ranging from surface disturbances to power loss and recharge. Although not ideal, the pump test data from the Ames #5 and Cleo Springs #6 test sites were used to estimate hydrologic properties of the aquifer. Data were analyzed using the AQTESOLV software package (Duffield, 2007).

The Ames #5 production well (OWRBID 184866) has a borehole diameter of 18 inches, a casing diameter of 12 inches, and was completed to a depth of 50 feet; the casing was slotted from 35 to 50 feet below the land surface. The observation well (OWRBID 184867) was located approximately 487 feet away from the production well and was completed to a depth of at least 49 feet, and was slotted from 48 to at least 49 feet below the land surface. The use of a downhole camera revealed that the base of the well was sanded in and only one foot of the original slotted interval was visible. Redevelopment of the observation well likely would have improved the accuracy of the test. Depth-to-base in this locality was about 53 feet below the land surface. Ames #5 was shut off six days prior to the start of the test on June 30, 2017. The production well was activated on July 5, 2017, at 10:30 a.m. and allowed to run for five days at a rate of 86 gallons per minute. The maximum observed water-level displacement was about 0.86 feet (**Figure 20A**). The production well was then shut off on July 10, 2017, at 8:30 a.m. and allowed to recover for five days before the water-level recorder was removed.

The unfiltered dataset on the water-level hydrograph shows semi-regular spikes in depth-to-water (**Figure 20A**). Each positive spike (decreased depth-to-water) only lasted for a few minutes and was immediately followed by a less severe negative spike (increased depth-to-water) that also only lasted for a few minutes. It was noted during the installation of the continuous water level recorder that the observation well was located less than 15 feet from a railroad track. A few minutes after the recorder was installed, a train was observed passing the observation well, which caused the ground to noticeably shake. The sudden, short-term changes in depth-to-water were likely related to aquifer loading caused by scheduled train activity. The well hydrograph also shows that the water level was still rising slightly when the test started and had equilibrated to a lower depth at the end of the test for the period of record. It is possible that if the continuous recorder was left in the observation well for an additional few days the water level would have eventually risen to the level observed at the start of the test. However, because the water level recovered to 95 percent of the initial water level, it was still considered a good pump test.

To minimize the potential impact of the aquifer loading on the aquifer model solution, a minimal lowess smoothing factor was applied to the dataset to effectively cut out the spikes without significantly altering the rest of the observations (Cleveland, 1979). The curve-matching solution that best fit the data was the Moench (1997) solution which was derived for unsteady flow to fully or partially penetrating wells in a homogeneous, anisotropic unconfined aquifer with a delayed gravity response. The best-fit model solution estimated a transmissivity of 2,000 feet squared per day and a specific yield of 0.084 (**Figure 20B**). Horizontal hydraulic conductivity (Kh) was calculated to be 56.6 feet per day (**Table 12**).

The Cleo Springs #6 production well (OWRBID 18655) has a borehole diameter of 16 inches, a casing diameter of 8 inches, and was completed to a depth of 48.7 feet; the casing was slotted from 35.7 to 45.7 feet below the land surface. The observation well (OWRBID 184869) was located approximately 116 feet away from the production well and was completed to a depth of 47 feet. Depth-to-base in this locality was about 42 feet below the land surface. Cleo Springs #6 was shut off ten days prior to the start of the test on December 5, 2017. The production well was activated on December 15, 2017, at 10:30 a.m. and allowed to run

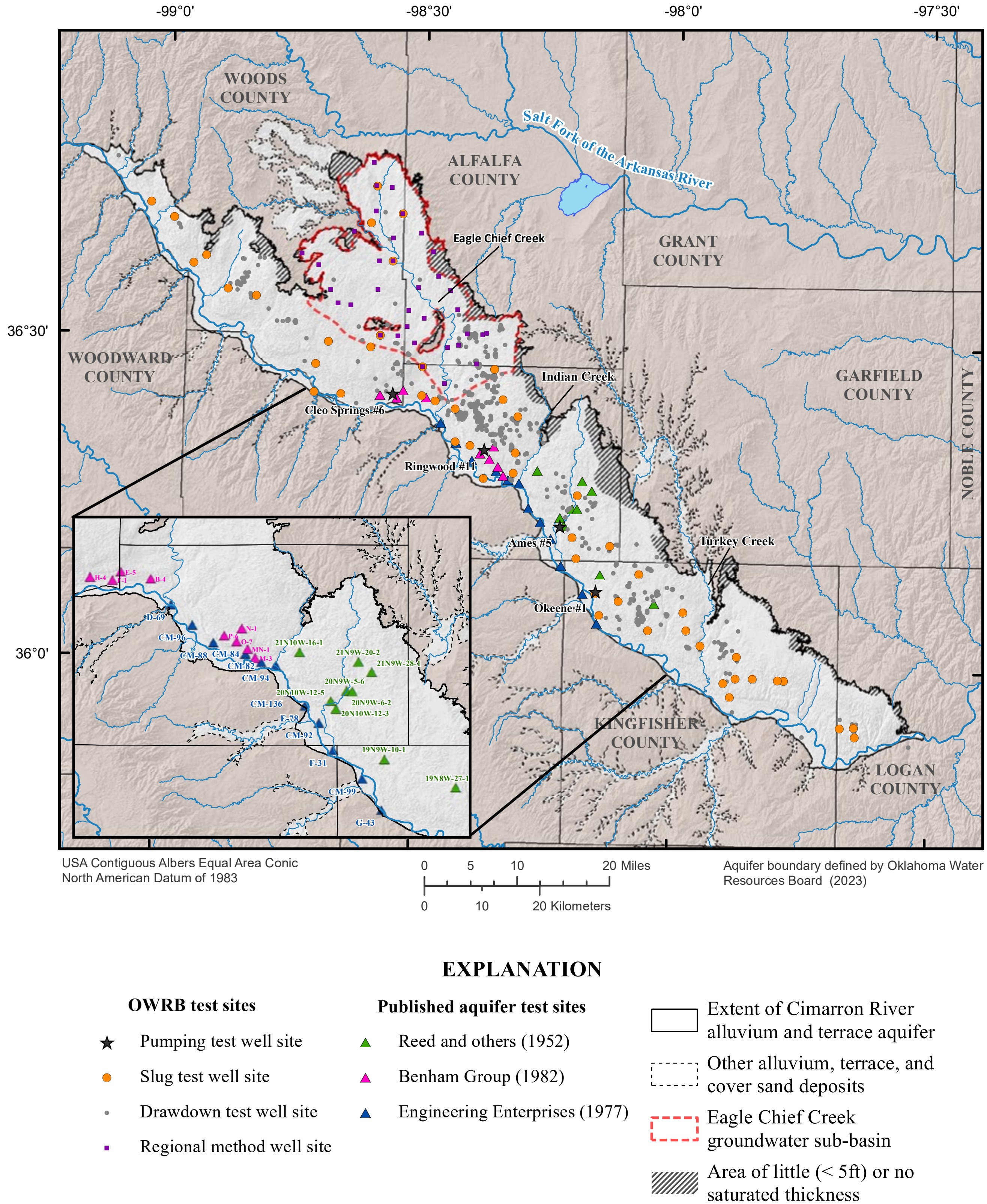


Figure 19. Spatial distribution of slug test sites, drawdown test sites, multi-well pumping test sites, and regional method well sites collected as part of this investigation as well as the locations of aquifer tests conducted in previous studies.

for twelve days at a rate of 100 gallons per minute. The maximum observed water-level displacement was about 1.94 feet (**Figure 21A**). The production well was then shut off on December 26, 2017, at 11:00 a.m. and allowed to recover for twelve days before the water-level recorder was removed.

The well hydrograph shows that water levels prior to and following the pump test were still rising, indicating that static conditions were not achieved during the period of record (**Figure 21A**). However, the effect of not achieving static conditions may not be significant because the water level at the end of the recovery phase was only about a tenth of an inch shallower than at the start of the drawdown phase, assuming the rising water level trend was only associated with a return to (non-pumping) equilibrium conditions. To minimize any potential impact of this difference on estimated aquifer properties, the water levels were adjusted using a linear time-dependent correction to make the water level at the end of the recovery phase equal to the water level at the start of the drawdown phase. The best-fit model solution (Moench, 1997) estimated a transmissivity of 2,850 feet squared per day and a specific yield of 0.138 (**Figure 21B**). Horizontal hydraulic conductivity (Kh) was calculated to be 106.2 feet per day (**Table 12**).

The Ringwood #11 observation well (OWRBID was excluded from analysis because the mid-test power loss (which lasted roughly six hours) was not compensated for by an increased pumping rate after the power was restored, such that the average pumping rate during the drawdown phase remained unchanged (**Figure 22A**).

The Okeene #1 observation well (OWRBID 184865) was excluded from the analysis because there was an insufficient period of record to adjust for the effect of recharge on the regional water level trend and pumping test measurements (**Figure 22B**). The well hydrograph shows that water levels were rising prior to and following the pump test, which is consistent with the water level trend observed in the nearest continuous water level recorded (168849; **Figure 1**). The Okeene #1 test site was located about halfway between the Fairview (FAIR) and Kingfisher (KIN2) Mesonet climate stations. Based on an average of the two climate stations, the test area received about 0.27 inches of precipitation on April 20, 2.05 inches on April 21, and 0.16 inches on April 26, 2017. Recharge associated with the April 20th and 21st precipitation events likely caused the slope of the drawdown recession curve to flatten, thereby reducing the maximum drawdown that would have occurred had there been no recharge. This effect was assumed based on the amount of drawdown that occurred during the pre-test period between April 18–19, 2017 (**Figure 22B**).

Regional Method for Estimating Specific Yield

The term “regional method” is used to describe a method of analysis of hydrologic data at basin-wide scales, as opposed to more localized methods such as slug tests and pumping tests. The regional method described in this section uses mean monthly baseflow data and monthly depth-to-water measurements to estimate a storage coefficient (specific yield) for the Eagle Chief groundwater sub-basin within the larger Cimarron River alluvium and terrace aquifer. The method assumes that if an aquifer is not being recharged during a set period, but is only draining, then the ratio of the volume of groundwater discharged to the volume change of the aquifer is the storage coefficient for that volume of the aquifer that was drained (Christenson and others, 2011). The regional method utilizes a modified version of the Healey and Cook (2002) equation for estimating recharge, based on the concept that baseflow can be considered a proxy for diffuse recharge in watersheds with gaining streams (Schilling, 2009). When there is little to no recharge during a set period, the baseflow that is measured in a stream is assumed to represent water being released from aquifer storage. If baseflow is substituted for recharge in equation (1), it can be rearranged to solve for specific yield, written as:

$$Sy = \frac{Q_b}{\Delta DTW} \qquad (6)$$

where

- Sy is the specific yield [dimensionless];
- Q_b is the amount of base flow, in cubic feet per second; and
- ΔDTW is the change in the depth-to-water over a set period of time (Δh/Δt), in feet.

Depth-to-water measurements were collected at 35 well sites spatially distributed across the sub-basin roughly every 30 days between September 22, 2016, and May 28, 2017 (**Figure 19**). Baseflow was estimated from daily streamflow measurements at the OWRB stream guage station near Cleo Springs (**Figure 1**) using the baseflow separation method of Rutledge (1998). Historically, the driest months in the study area are December, January, and February, with mean annual precipitations of 1.15, 0.91, and 1.16 inches, respectively for the period of record 1895–2023 (**Figure 4**). Precipitation data from the Alva (0193), Helena (4019), and Orienta (6751) cooperative observer climate stations (**Figure 17**) indicated that October, November, and December were the driest months during the 2016–17 measurement period.

There were no continous water level recorders located within the Eagle Chief Creek groundwater sub-basin; the hydrograph of nearest continuous recorder (18545) shows a slight rise in water level between September and October, 2016 and then a decline through March, 2017 (**Figure 8**). The water level changes at individual measurement sites were inconsistent during the measurement period with some sites showing small rises in water level and others showing small declines. Desipite this, the period between October and December 2016 was determined to be the most appropriate timeframe for this analysis. Heavy rains in mid January and late February, 2017 precluded the use of the December through March Period.

To maintain statisical consistency from month-to-month, only sites that had uniterrupted measurements over the full

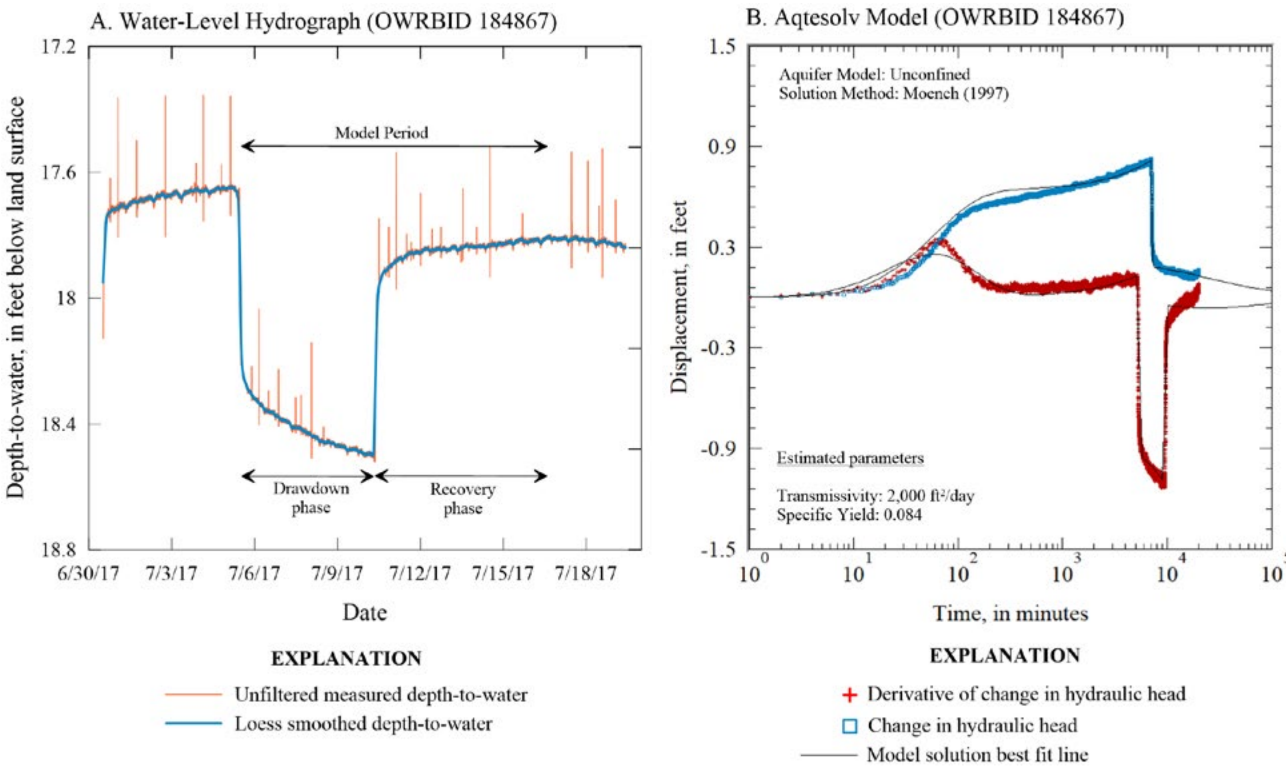


Figure 20. (A) Water-level hydrograph for Ames #5 aquifer pumping test observation well, June 30 – July 19, 2017. (B) Aqtesolv model with the best-fit curve matching solution for the Ames #5 aquifer pumping test observation well.

period of analysis were used; measurements marked as recently pumped or pumping were considered interruptions. Of the original 35 well sites, only 20 had uninterrupted measurements during the period of analysis. To estimate the total volume of groundwater gained or lost each month, the drainage area of the Eagle Chief Creek groundwater sub-basin (**Figure 19**) was delineated using a combination of the 2016 potentiometric surface and saturated thickness maps. Unsaturated areas were excluded from the sub-basin drainage area. The drainage area of the sub-basin was estimated to be approximately 282.2 square miles.

The volume change of the groundwater sub-basin was calculated as the monthly change in mean depth-to-water multiplied by the drainage area of the groundwater sub-basin. Estimates of mean monthly baseflow and volume change of the sub-basin were converted to units of acre-feet per day for use in equation 6. Estimates of specific yield determined from the regional method ranged from 0.04–0.11, with a mean of about 0.07 (**Table 12**). The specific yield range determined from this analysis is representative of a sandy clay or clayey sand within the zone of water level fluctuation.

Lithologic-Log Standardization Analysis

Approximately 3,650 well driller's logs were used to characterize the lithologic variability of the aquifer's alluvium and terrace deposits; the median total depth of the groundwater wells was 64 feet below the land surface and approximately 88 percent of the wells penetrated the base of the aquifer. Textural terms used in each lithologic log were standardized and converted to weighted percent-coarse values using the techniques described by Mashburn and others (2013). The weighted percent-coarse values were then used to estimate horizontal hydraulic conductivity and specific yield for the Cimarron River alluvium and terrace aquifer.

In the state of Oklahoma, there are no clearly defined standards for log descriptions. As a result, there is increased variability between well drillers, with some lithology descriptions being specific to localized areas. Lithologic logs with a single description, unnatural depths to bedrock, incomprehensible descriptions, or obvious "copy and paste" depth interval descriptions were discarded. Additionally, lithologic logs that predominantly consisted of bedrock units, such as those in the northwestern region of the aquifer were excluded; common lithologic descriptions of bedrock units included terms such as "shale," "siltstone," "gypsum," "sandstone," and "red bed." These terms were used as contact markers for determining aquifer thickness at each well location but were excluded from estimations of horizontal hydraulic conductivity and specific yield.

The lithologic logs were simplified by reducing the number of discrete log interval descriptions from about 2,400 unique textural terms to 252 standardized textural terms, characterized by color, grain size, and whether the lithologic material was consolidated or unconsolidated. Consolidated material was assumed to be bedrock. The

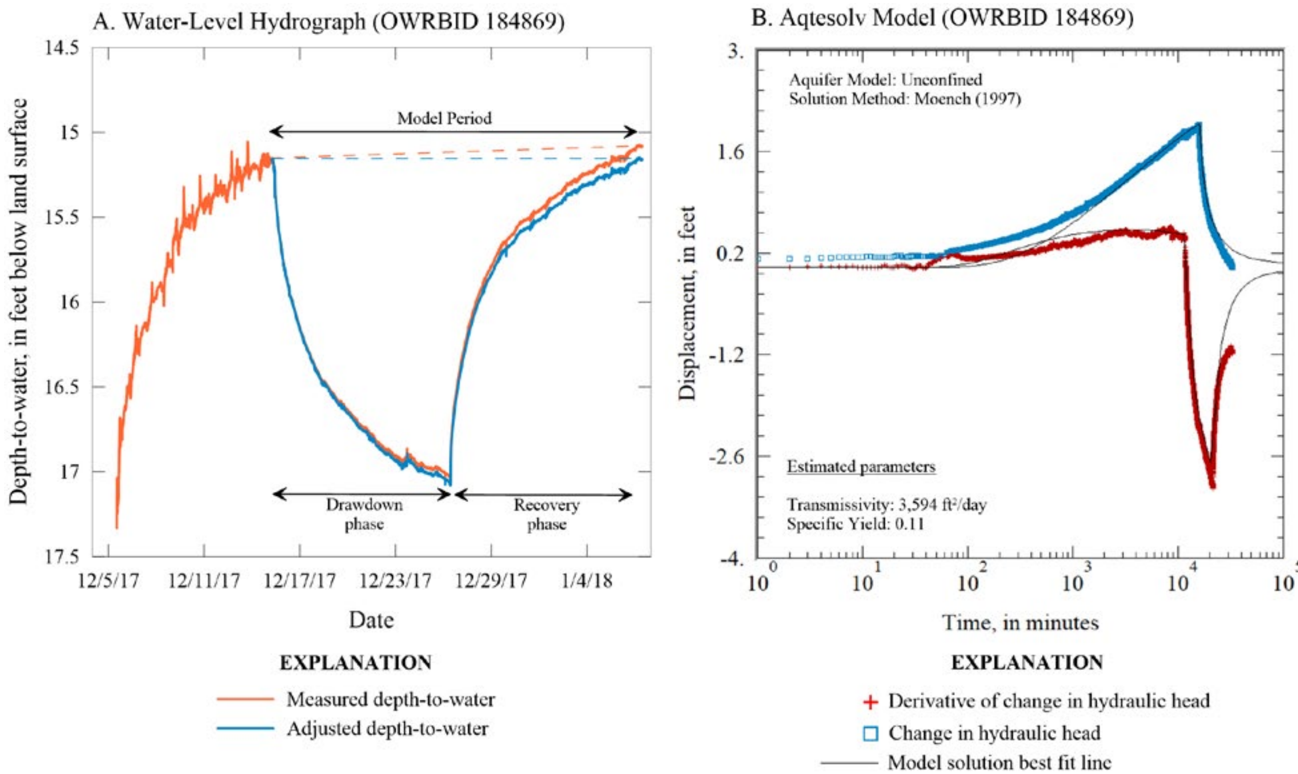


Figure 21. (A) Water-level hydrograph for Cleo Springs #6 aquifer pumping test observation well, December 15 – January 7, 2018. (B) Aqtesolv model with the best-fit curve matching solution for the Cleo Springs #6 aquifer pumping test observation well.

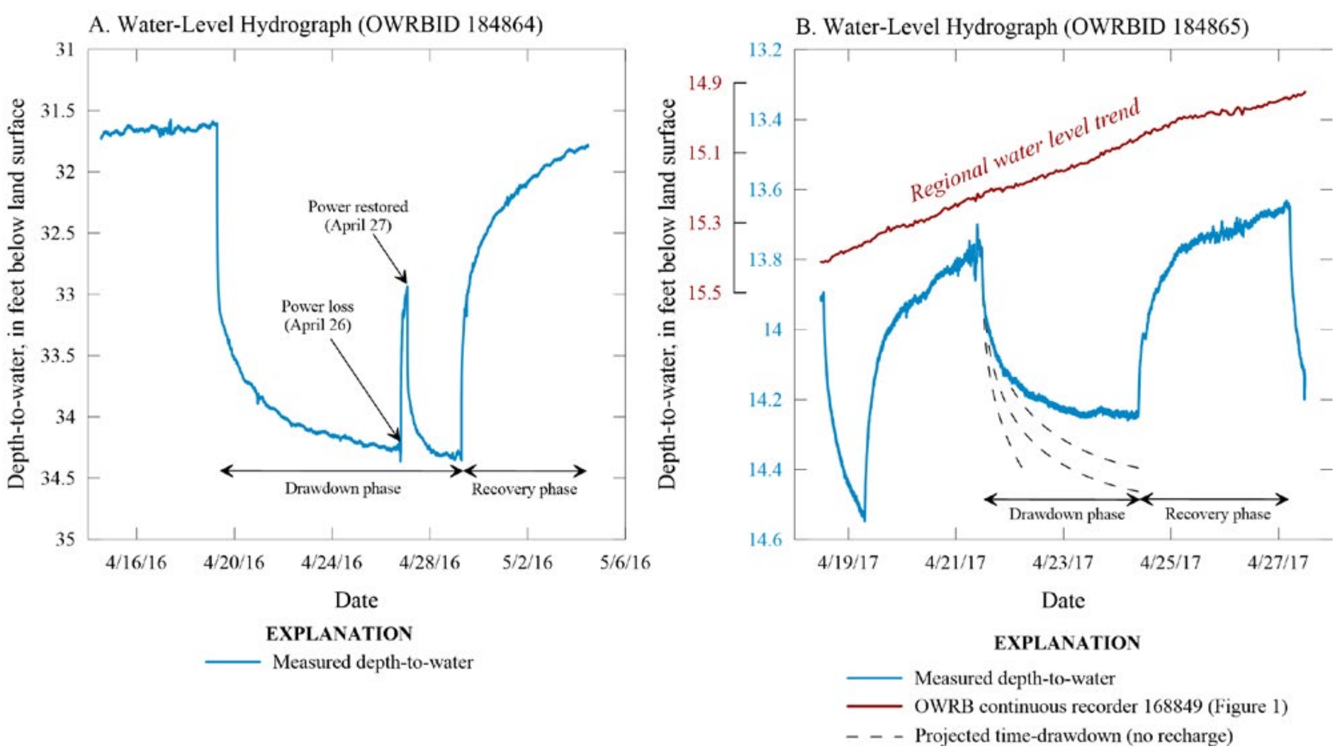


Figure 22. (A) Water-level hydrograph for Ringwood #11 aquifer pumping test observation well, April 14 – March 5, 2016. (B) Water-level hydrograph for Okeene #1 aquifer pumping test observation well, April 18 – April 27, 2017.

standardized descriptions were then classified into five generalized lithologic categories (clay/silt, fine sand, medium sand, coarse sand, and gravel), which were quantified as a continuous series of percent-coarse-material values from 0–100 percent. The ranges for each lithologic category were as follows: 0–5 percent (clay/silt), 5–10 percent (fine sand), 10–20 percent (medium sand), 20–60 percent (coarse sand), and 60–100 (gravel). All bedrock lithologies were assigned a percent-coarse-material value of 0.0 percent. The midpoint of each respective range (2.5, 7.5, 15.0, 40.0, or 80.0 percent) was then used as a multiplier (**Figure 23**) to convert each lithologic category to a thickness-weighted percent-coarse-material value (Pcm). The percent-coarse-material value for each lithologic log was computed as the sum of thickness-weighted percent-coarse material values divided by the total thickness of the unconsolidated lithologic material at each well site:

$$Pcm_{log} = \frac{\sum_{i=1}^{N} Pcm_i}{\sum_{i=1}^{N} b_i} \qquad (7)$$

$$Pcm_i = b_i m_i \qquad (8)$$

where

Pcm_{log} is thickness weighted percent-coarse-material value for each lithologic log;

b_i is the thickness of the discrete lithologic log interval, in feet; and

m_i is the midpoint lithologic category multiplier for the discrete lithologic log interval.

A horizontal hydraulic conductivity of 0.14 feet per day was assigned to the clay/silt lithologic category based on the mean of the Kh ranges for clay and silt from Domenico and Swartz (1998). A horizontal hydraulic conductivity of 540 feet per day was assigned to the gravel lithologic category based on the maximum Kh value estimated from the aquifer test of well 21N10W-16-1 (**Table 11**). By assuming that a horizontal hydraulic conductivity of 0.14 feet per day and percent-coarse multiplier of 2.5 is representative of the clay/silt lithologic category and that a horizontal hydraulic conductivity of 540 feet per day and percent-coarse multiplier of 80.0 is representative of the gravel lithologic category, and that the relationship is linear, mean horizontal hydraulic conductivity for each lithologic log was calculated using the equation:

$$Kh=(6.9659 \text{ x } Pcm_{log})-17.275 \qquad (9)$$

where

Kh is horizontal hydraulic conductivity in feet per day; and

Pcm_{log} is the thickness weighted percent-coarse material value for each lithologic log

Horizontal hydraulic conductivity for the Cimarron River alluvium and terrace aquifer estimated from the lithologic-log standardization method ranged from 0.14–515.3 feet per day with a mean and median of 58.4 and 40.9 feet per day, respectively (**Table 12**). The mean horizontal hydraulic conductivity of wells completed in alluvium deposits was 106.9 feet per day, while the mean horizontal hydraulic conductivity of wells completed in terrace deposits was 54.3 feet per day; wells were queried into either "alluvium" or "terrace" groups based on their mapped locations on the surface geology map (**Figure 5**). Kh estimates from this method were similar to the model-calibrated Kh estimates for alluvium (104.5 feet per day) and terrace deposits (47.5 feet per day) reported by Adams and others (1996). Further, the estimates are within the range of Kh values from aquifer tests completed in other alluvium and terrace aquifers in the state (Smith and others, 2017; Ryter and Correll, 2016).

The frequency distribution of horizontal hydraulic conductivities in the Cimarron River alluvium and terrace aquifer estimated from slug tests, drawdown tests, and lithologic-log characterization are shown in **Figure 24**. A log (base 10) scale was used for this graph to enhance the visual representation of the slug tests and drawdown tests which on a normal linear scale would be nearly imperceptible in contrast with the huge number of sites used in the lithologic-log characterization analysis.

The bedded character of the aquifer's alluvium and terrace deposits imparts a strong anisotropy such that horizontal hydraulic conductivity is much greater than vertical hydraulic conductivity (Benham Group, 1982). Vertical hydraulic conductivity was assumed to be between one-third and one-tenth of horizontal hydraulic conductivity; the 1:3 ratio was used by Ellis and others (2017) and Smith and others (2017) for the Canadian River alluvial and North Fork Red River aquifers, respectively. A 1:10 ratio was used by Ryter and Correll (2015) for the Beaver-North Canadian River alluvial aquifer.

Specific yield (Sy) values were calculated for each lithologic log using a non-linear equation derived from a relationship between weighted mean horizontal hydraulic conductivity and specific yield. The specific yield for each lithologic log represents the thickness-weighted mean of specific yield values assigned to the five lithologic categories. Specific yield values used to define the non-linear equation were 0.07 for clay/silt, 0.19 for fine sand, and 0.26 for gravel (Johnson, 1967; Morris and Johnson, 1967). The best-fit logarithmic coefficients were found, and the regression equation was determined to be:

$$Sy=0.0228 \ln(Kh)+0.1132 \qquad (10)$$

where

Sy is specific yield [dimensionless]; and

Kh is horizontal hydraulic conductivity, in feet per day.

The logarithmic (ln) regression had a correlation coefficient of 0.998. Using this method, the minimum, maximum, and mean Sy values for the Cimarron River alluvium and terrace aquifer were estimated to be 0.07, 0.26, and 0.20, respectively (**Table 12**). The Sy range and

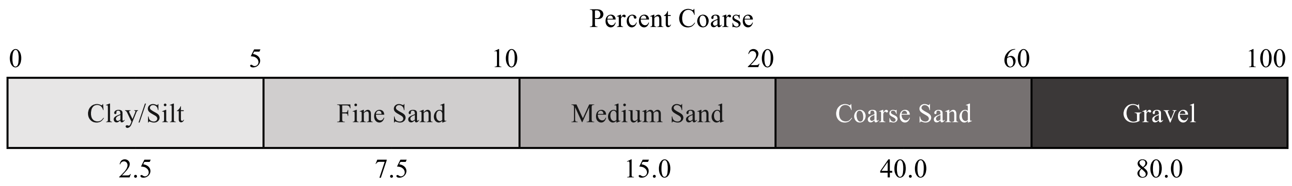


Figure 23. Generalized lithologic categories and percent-coarse multiplier values used to estimate horizontal hydraulic conductivity for the Cimarron River alluvium and terrace aquifer using the lithologic-log standardization method of Mashburn and others, 2014.

statistical values estimated from the non-linear relationship with Kh were dependent on the initial values of Sy assigned to the clay/silt, fine sand, and gravel lithologic categories. Although the values assigned were considered representative of the various aquifer sediments, values of Sy can vary by more than 10 percent for each lithologic category based on the shape, and sorting of sediment grains, which in turn affects the size and interconnectivity of sediment pore spaces (Harter, 2005).

Model-calibrated estimates of Sy for other alluvium and terrace aquifers in western Oklahoma ranged from 0.10 to 0.16 (Ellis and others, 2017; Smith and others, 2017; Ellis and others, 2020; Paizis and Trevisan, 2021). Based on the multi-well aquifer tests conducted in this investigation, the aquifer tests conducted by previous investigators in the study area, the regional method range, and the studies conducted for other alluvium and terrace aquifers in the state, a mean Sy value of 0.13 was estimated for the Cimarron River alluvium and terrace aquifer.

Groundwater Quality

The quality of groundwater from the Cimarron River alluvium and terrace aquifer is described as adequate for most purposes but is generally hard and can vary significantly over short distances (Reed and others, 1952). Natural factors that can affect groundwater quality include the lithologic and hydrological properties of the aquifer material, the amount and composition of recharge water, residence time, and various chemical processes occurring within the hydrogeologic system (Bartos and Ogle, 2002).

Agriculture is the predominant land-use type overlying the study area (**Figure 2**; National Agricultural Statistics Service, 2021). Agricultural activities are commonly associated with elevated concentrations of inorganic chemicals and organic pesticides within groundwater (Bohlke, 2002). Excess quantities of fertilizers, pesticides, and other additives used in agricultural practices can directly enter a groundwater system through dissolution and deep percolation. The introduction of high concentrations of inorganic constituents such as nitrate (NO_3^-), chloride (Cl), sulfate (SO_4^{2-}), calcium (Ca), magnesium (Mg), potassium (K), and arsenic (As) can also indirectly affect geochemical processes and water-rock interactions. For instance, recharge fluxes of ions like (NO_3^-) and H^+ can cause changes in mineral dissolution and ion exchanges in the subsurface, thereby indirectly altering the concentrations of natural constituents in groundwater (Bohlke, 2002).

Mineral Equilibrium Analysis

The Oklahoma Water Resources Board collected samples from 55 water-quality sites in 2001 as part of a preliminary study of the groundwater quality in the Cimarron River alluvium and terrace aquifer and from 32 water-quality sites in 2016 as part of the ongoing Groundwater Monitoring and Assessment Program (Oklahoma Water Resources Board, 2013). Water-quality data were imported into the modeling program PHREEQC, version 3.6 (Parkhurst and Appelo, 1999) to perform hydrogeochemical calculations capable of determining mineral saturation indices. The program is based on the concept of chemical equilibrium, which occurs when the concentrations and charges of reactants and products in an aqueous solution are balanced such that forward and reverse reactions occur at effectively equal rates (Hem, 1961). The saturation index (SI) is an indicator of the tendency of an aqueous solution to dissolve or precipitate a given mineral, calculated as the log of the ion activity product (IAP) of a solution divided by the solubility product (Ksp) of the mineral(s) being analyzed (Deutsch, 1997).

Minerals that are found to be in equilibrium with groundwater are assumed to be reactive in the environment and act as the controls on solution composition and ion concentration. A reactive mineral is in equilibrium when the saturation index is near zero (IAP = Ksp). When the ion activity product of a mineral is less than the solubility product, then the solution is undersaturated with respect to that mineral and the saturation index is negative ($SI < 0$). When the ion activity product is greater than the solubility product, then the solution is supersaturated with respect to the mineral and the saturation index is positive ($SI > 0$).

Groundwater that is undersaturated with respect to a particular mineral will dissolve that mineral until equilibrium is reached or the mineral completely dissociates. Groundwater that is supersaturated with respect to a particular mineral will precipitate that mineral until equilibrium is reached. As there are uncertainties inherent in the calculation of saturation indices such as the accuracy of chemical analysis and mineral equilibrium constants, a saturation index range between 0 ±

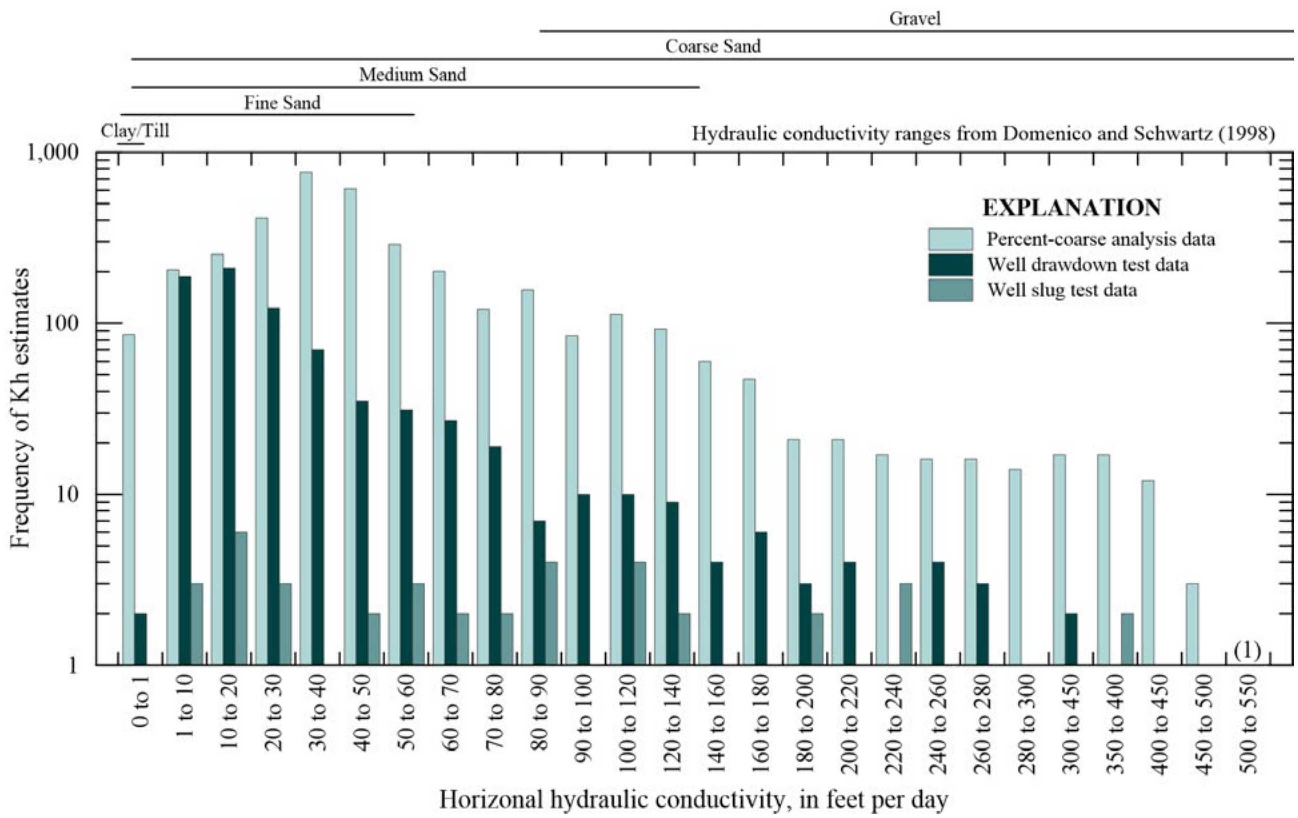


Figure 24. Frequency distribution of mean horizontal hydraulic conductivity values estimated from slug tests, well drawdown tests, and percent-coarse analysis for wells completed in the Cimarron River alluvium and terrace aquifer.

0.5 was considered within the equilibrium zone for a reactive mineral (Deutsch, 1997).

A necessary input parameter to run PHREEQC is redox potential. In aqueous solutions, redox potential is a measure of the tendency (or capacity) of the solution to oxidize or reduce a chemical species. Redox potential is represented in the program by the dimensionless quantity pE, which is calculated as the negative log of electron activity (Deutsch, 1997; Hiscock, 2005). For the 2016 sampling period, pE was derived from oxidation-reduction potential (ORP), measured in millivolts. Under standard conditions (25°C), ORP can be converted to Eh, by adding 200 millivolts to the ORP voltage and then dividing it by 59.2 millivolts (Deutsch, 1997). The oxidation-reduction potential was not measured during the 2001 sampling period, so the mean pE from the 2016 dataset (9.7 millivolts) was used for the 2001 water-quality samples.

Major cations (calcium, sodium, potassium, and magnesium) and major anions (bicarbonate, chloride, and sulfate) are the most abundant dissolved chemical constituents found in groundwater (Bartos and Ogle, 2002). Aqueous solutions are electrically neutral; however, analytical errors and unanalyzed constituents can cause electrical imbalances to be calculated for solutions. If a charge imbalance is calculated based on the initial input data, PHREEQC will attempt to reach electroneutrality by adjusting the pH or allowing for the addition, reduction, or removal of an element (Parkhurst and Appelo, 1999). The outputted charge-balance error (CBE) can be used to assess the quality of the analysis; a CBE of less than or equal to 15 percent is considered acceptable (Raymond Johnson, NGWA, oral communication, 2019).

Results from the hydrogeochemical analysis showed that eight of the 87 water quality sites sampled had charge-balance errors above 15 percent, six of which were from the 2001 dataset which had fewer measured chemical constituents and a constant pE. Reactive minerals identified by the analysis included calcite, dolomite, quartz, gypsum, and barite. Calcite (CaCO3) was found to be in equilibrium at 70 sites and undersaturated at 17 sites; the undersaturated sites were characterized by relatively low pH and alkalinity measurements. Calcium concentrations were also relatively low at the undersaturated sites. Calcite is assumed to be the principal reactive mineral in control of calcium and bicarbonate concentrations in the groundwater. The presence of calcite in the aquifer can be attributed to the reworking (erosion and weathering) of Permian-age bedrock units, where it has been found within small fractures and cavities in core samples and as thin veins in surface exposures (Reed and others, 1952). Calcite also acts as a type of cement holding the sediments of Permian-age bedrock units together.

Dolomite (CaMg(CO3)2) was found to be in equilibrium at 28 sites, mostly concentrated in the northwest region of the study area, but also present in a few sites as far east as Kingfisher County. All the remaining sites were

Table 12. Summary statistics for horizontal hydraulic conductivity and specific yield determined from slug tests, well drawdown tests, multi-wells aquifer tests, lithologic-log percent-coarse analysis, and the regional method.

[--, not available; ft/day, feet per day]

Statistic	Slug tests	Drawdown tests	Multi-well pump tests	Percent-coarse analysis	Regional method
Horizonal hydraulic conductivity (ft/day)					
Minimum	3.1	0.2	56.6	0.1	--
25th percentile	23.9	10.2	--	29.2	--
50th percentile	81.0	19.2	--	40.9	--
75th percentile	140.4	36.8	--	65.5	--
Maximum	468.0	526.0	106.2	515.3	--
Mean	110.5	34.2	81.4	58.4	--
Count	102.0	767.0	2.0	3,650.0	--
Specific yield (dimensionless)					
Minimum	--	--	0.08	0.07	0.04
Median	--	--	--	0.20	0.07
Maximum	--	--	0.14	0.26	0.11
Mean	--	--	0.11	0.20	0.07
Count	--	--	2.00	3,650.0	--

undersaturated with respect to dolomite. Dolomite is the only significant magnesium-bearing mineral in the aquifer and is likely the main control of magnesium concentrations in the groundwater. The only formation within the study area that is known to contain dolomite is the Permian-age Flowerpot Shale, which crops out in Woods County. The presence of dolomite in areas of the aquifer not underlain by the Flowerpot Shale is postulated herein to have come from reworked dolomite that was deposited along the banks of an ancient Cimarron River as it migrated southward.

Quartz (SiO2) was in equilibrium with groundwater in every sample collected during the 2016 period. Silica (Si) was not measured during the 2001 sampling period, so quartz could not be determined to be in equilibrium with groundwater for these samples. However, based on the 2016 results, it is assumed that quartz would be in equilibrium with groundwater at all the 2001 sampling sites. Quartz is an abundant mineral in siliclastic sedimentary rocks (sandstones, siltstones, and shales) and alluvium and terrace deposits.

Gypsum (CaSO4·2H2O) was in equilibrium with groundwater at three sites in Woods County along the edge of the aquifer boundary where terrace deposits lie directly adjacent to exposed Flowerpot Shale; gypsum can be found interbedded with shale in the upper 50 feet of the formation (Oklahoma Water Resources Board, 1975). Massive gypsum beds are also found in the Blaine Formation, which crops out northwest of the study area. Gypsum is a slightly soluble evaporitic mineral that is likely a source of sulfate in the groundwater system. All the remaining sites had a negative solubility index value indicating that gypsum if it was at one point present has since dissociated into its constituent ions.

Barite (BaSO4) was in equilibrium with groundwater at 24 of the 32 sites sampled in 2016. Barium (Ba) was not measured during the 2001 sampling period. Concentrations of barium in measured samples ranged from 11.3 to 1,360.0 micrograms per liter with a mean of 302.7 micrograms per liter. The specific origin of barium in the groundwater system is unclear, but may be related to the weathering barite concretions, veins, or disseminated grains in the underlying Permian-age Garber and Hennessey Formations (Ham and Merrit, 1944).

Water-Type Analysis

The ionic compositions of groundwater samples were used to classify water types based on ionic concentrations, expressed in millequivalents per liter (meq/L). If the ionic concentration of an individual cation or anion was greater than 50 percent of the total cation or anion concentration, then it was considered dominant (Adams and Bergman, 1996). If no cation or anion was dominant, then the water was classified as mixed and the two most prominent cations or anions in decreasing order of abundance were used to describe the water type (Bartos and Ogle, 2002).

The percentage concentration of major ions from groundwater samples collected in the Cimarron River alluvium and terrace aquifer by the OWRB is shown in **Figure 25** (Piper, 1944). Major cations are plotted in the left ternary diagram and major anions are plotted in the right ternary diagram. The diamond diagram represents a combination of the cation and anion ternary diagrams and is split into four quadrants; the top quadrant is calcium-sulfate (Ca-SO4) type, the left quadrant is calcium-bicarbonate (Ca-HCO3) type, the right quadrant is sodium-chloride (Na-Cl) type, and the bottom quadrant is sodium-bicarbonate (Na-HCO3) type.

Calcium was the predominant cation in the study area, with a total of 56 (out of 87) water quality sites exceeding 50 percent concentration. Sodium was dominant at three water quality sites and magnesium was not dominant at any of the sites. Potassium was negligible in all samples. The dominant anion in the study area was bicarbonate, with 60 sites having concentrations exceeding 50 percent. Sulfate was dominant at six sites and chloride was dominant at three sites.

The spatial distribution of classified water types is shown in **Figure 26**; Major-ion concentrations for select groundwater-quality sites are displayed as Stiff (1951) diagrams for better visualization of relative concentrations and mixing. Most of the water-quality sites were classified as either calcium-bicarbonate (Ca-HCO3) or mixed bicarbonate type. Water-quality sites located near outcropping Flowerpot shale were predominately calcium-sulfate (Ca-SO4) type. Two water-quality sites sampled from Cimarron River alluvium were sodium-chloride (Na-Cl) type and one was calcium-sulfate type. Nearly all the water-quality sites located in Kingfisher and Logan counties were of a mixed type, primarily Na-Ca-HCO3, Ca-Na-Cl, and Ca-Na-HCO3.

Sulfate concentration in the study area ranged from 10.1 to 1,440 milligrams per liter, with a mean of 143.0 milligrams per liter and a median of 50.1 milligrams per liter. The highest concentration of sulfate occurred in wells located in Woods and Alfalfa counties (**Figure 27A**); in this area, all six of the sulfate-dominant sites and three of the mixed-sulfate sites had concentrations exceeding the U.S. Environmental Protection Agency established secondary-drinking water standard of 250 milligrams per liter for sulfate (U.S. Environmental Protection Agency, 2020). Concentrations of sulfate in the more central and eastern regions of the study area rarely exceeded 50 milligrams per liter, with fewer than a dozen sites having a concentration between 50 to 100 milligrams per liter, and two sites having a concentration between 100 and 250 milligrams per liter (**Figure 27A**). The principal source of dissolved sulfate in the aquifer is from the dissolution of gypsum beds in the Flowerpot Shale.

Chloride concentrations in the study area ranged from 3.2 to 1,398.8 milligrams per liter, with a mean of 106.6 milligrams per liter and a median of 45.0 milligrams per liter. The only water quality sites that had chloride concentrations exceeding the drinking water standard (250 milligrams per liter) were those completed in the alluvium of the Cimarron River (**Figure 27B**). The high concentrations of dissolved chloride in the alluvium as well as the Cimarron River is associated with the dissolution of halite (NaCl), from salt beds in the underlying Permian-age bedrock. Brine formed from the dissolution of these salt beds produced the Big and Little salt plains located several miles upstream of the study area as well as the Okeene Salt Plain in Blaine County (Engineering Enterprises, 1977; Johnson, 2022).

Sodium concentration in the study area ranged from 10.4 to 956.5 milligrams per liter with a mean of 85.2 milligrams per liter and a median of 44.5 milligrams per liter. The water-quality sites with the highest concentrations of sodium corresponded with sites that had elevated concentrations of chloride and were likely of similar origin. Natural evaporite brines can migrate upward into the overlying alluvium and terrace deposits in areas where the hydrologic head is greater in the underlying bedrock (observed as saline springs along the edges of the aquifer), or in localized areas where groundwater pumping has induced upward flow.

A possible secondary source of dissolved sodium and chloride in the aquifer comes from oilfield operations. Oil and gas production and related service companies are the predominant industries in the study area (Masoner and Mashburn, 2004). Oil and gas production in the study area peaked around the 1950s and 1960s following the discovery of the Cresent-Lovell oilfield in the early 1930s and the Ringwood and Sooner Trend oilfields in the mid-1940s (Boyd, 2002; **Figure 25C**). A known historical source of oilfield contamination in the aquifer came from unlined brine evaporation pits (Oklahoma Water Resources Board, 1975). Other sources may include improperly constructed saltwater disposal wells and improperly plugged oil wells.

Major ion ratios have historically been used to distinguish between evaporite dissolution brines and oilfield brines (Richter and Kreitler, 1993). Leonard and Ward (1962), who examined waters in Kansas, Oklahoma, and Texas found that a Na/Cl ratio between 0.62 and 0.66 was typical for brines emerging from the dissolution of halite, whereas ratios between 0.45 and 0.59 were typical for oilfield brines. In general, a Na/Cl ratio below 0.6 is considered characteristic of oilfield brines. Further, brines emerging from the dissolution of gypsum can be distinguished from oilfield brines using a ratio of calcium to sulfate; Johnson (2022) found that salt dissolution brines from Permian-age bedrock generally have a Ca/SO4 ratio between 0.17 to 0.72, whereas oilfield brines have a ratio that is greater than 1.0, with most values being between 20 to 80.

Of the 87 water-quality sites samples by the OWRB, nineteen had Na/Cl and Ca/SO4 ratio values characteristic of oilfield brines; the Na/Cl ratio values ranged from 0.23 to 0.60, with a mean of 0.43 and the Ca/SO4 ratio values ranged from 1.53 to 4.55, with a mean of 2.84. The Ca/SO4 ratio values determined for the OWRB water-quality sites were much lower than the range postulated by Johnson (2022), who analyzed brine samples collected directly from production wells. Most (89 percent) of the sites fell within the Ringwood or Sooner Trend oilfields (**Figure 27C**). Four water quality sites had Na/Cl and Ca/SO4 ratio values characteristic of evaporite dissolution brines; the Na/Cl ratio values ranged from 0.68 to 0.70, with a mean of 0.69 and the Ca/SO4 ratio values ranged from 0.33 to 0.63, with a mean of 0.46. Unsurprisingly, the water quality sites that had Na/Cl and Ca/SO4 ratio values characteristic of evaporite dissolution

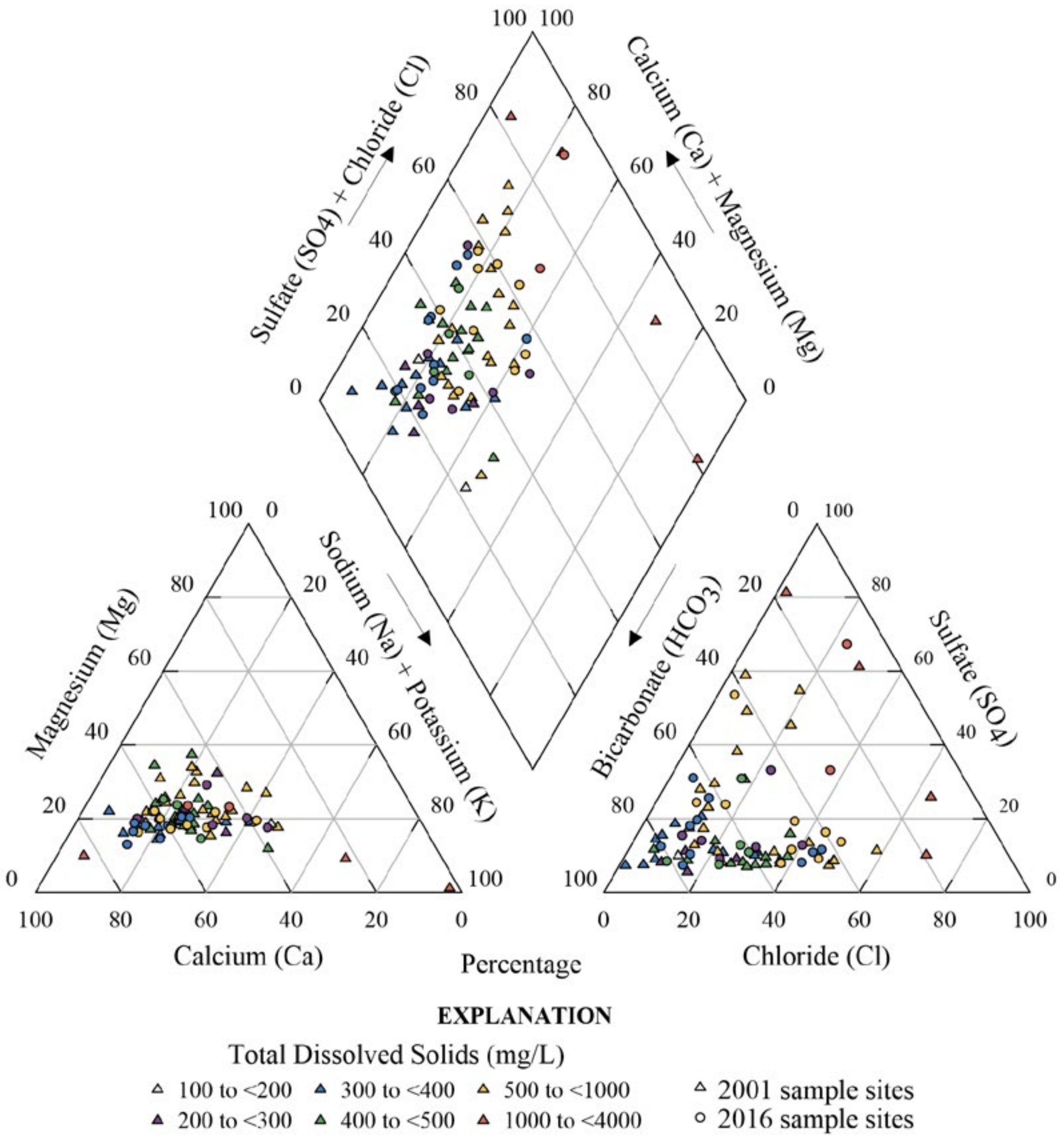


Figure 25. Piper (1944) diagram showing groundwater geochemistry for 55 samples collected in 2001 (triangle) and 32 samples collected in 2016 (circle) from the Cimarron River alluvium and terrace aquifer.

brines were located within alluvium and terrace deposits adjacent to the outcropping Flowerpot Shale (**Figure 27C**). Five additional sites in Woods County near the outcropping Flowerpot Shale had Ca/SO4 ratio values characteristic of evaporite dissolution brines (mean of 0.45; **Figure 27C**); all five sites had Na/Cl ratio values greater than 1.9. Chloride concentrations at the five sites ranged from 14.5 to 72.8 milligrams per liter with a mean of 31.1 milligrams per liter and sulfate concentrations ranged from 234.0 to 749.3 milligrams per liter with a mean of 407.1 milligrams per liter. Interestingly, the water quality site completed in alluvium about five miles downstream of the Okeene Salt Plain (**Figure 27B**) had a Na/Cl ratio value (0.91) that is quite a bit higher than that of pure halite (0.648) and a Ca/SO4 ratio value (0.1) that was quite a bit lower than pure gypsum or anhydrite (0.417). The elevated chloride concentrations in the Cimarron River and adjacent alluvium in this area are attributed to salt dissolution which has been shown to affect water quality several kilometers upstream and downstream of the salt plain (Engineering Enterprises, 1977; Johnson, 2022).

To further assess the utility of ion ratios for brine analysis, the water quality sites were plotted on the Hounslow (1995) brine differentiation plot (BDP) which uses molar Ca/(Ca+SO4) on the vertical axis and molar Na/(Na+Cl) on the horizontal axis. Most sites plotted in the upper left quadrant of the BDP with Na/(Na+Cl) and Ca/(Ca+SO4) ratio values greater than 0.5. Most (87 percent) of the water quality sites plotted within the oilfield brines and evaporites areas matched the determinations made using the Na/Cl and Ca/SO4 ratios; three sites characterized as oilfield brine impacted fell just outside of the oilfield brines area on the BDP (**Figure 28**). Four additional sites fell within the oilfield brines area and two fell within the evaporites polygon; all six sites had Na/Cl and Ca/SO4 ratio values that fell within the ranges of both oilfield and evaporite dissolution brines, suggesting potential mixing. The oilfield brine sites had a mean Na/Cl ratio value

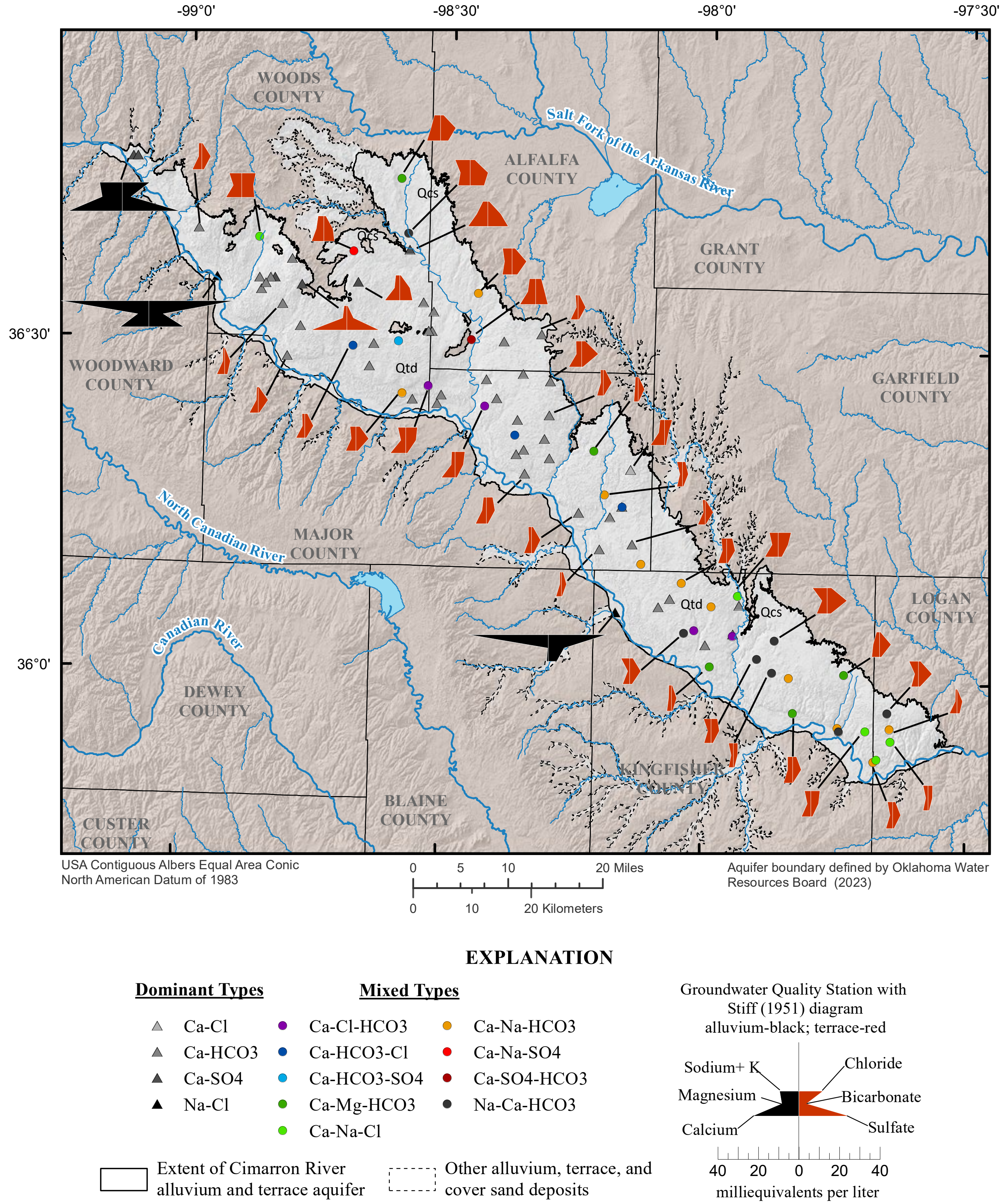


Figure 26. Spatial distribution of classified water types with stiff diagrams for selected water-quality sites. Red stiff diagrams represent wells completed in terrace deposits and black diagrams represent wells completed in alluvial deposits.

of 0.64 and mean Ca/SO4 ratio value of 3.08, while the evaporite dissolution brine sties had a mean Na/Cl value ratio of 0.55 and mean Ca/SO4 ratio value of 0.45.

Concentrations of total dissolved solids (TDS) in the study area ranged from 163.0 to 3,597.5 milligrams per liter, with a mean and median of 602.2 and 440.0 milligrams per liter, respectively. Of the 87 sites sampled, thirty-five (40 percent) had TDS concentrations that exceeded the secondary drinking water standard of 500 milligrams per liter (**Figure 27D**). Summary statistics for groundwater-quality constituents and properties for the 2001 and 2016 sampling periods in the Cimarron River alluvium and terrace aquifer are listed in **Tables 13 and 14**. Constituents that had data values reported as below the detectable limit were assigned a value of one-half the detectable limit.

Nitrate Analysis

Nitrate is a nutrient that is readily soluble and extremely mobile in the environment (Madison and Brunett, 1984). Nitrate concentrations in the subsurface can be derived naturally from processes such as nitrification, and organic matter mineralization (Bohlke, 2002), or from synthetic sources such as inorganic fertilizers and pesticides used on croplands. Additionally, point source contamination from leaky septic tanks and animal waste lagoons can artificially enhance nitrate concentrations in the subsurface locally. When concentrations of nitrate in the subsurface exceed the uptake ability of plants, the excess nitrate is leached from the root zone into groundwater. Nitrate concentrations greater than 3.0 milligrams per liter are generally considered the result of human activity (Mueller and others, 1995). Natural background concentrations tend to be less than 0.2 milligrams per liter (Madison and Brunett, 1984). Concentrations of nitrate between 0.2 and 3.0 milligrams per liter are considered transitional zones between natural sources and artificial enhancement.

Nitrate as nitrogen was detected in all 55 samples in the 2001 dataset and all 32 samples in the 2016 dataset; the detection limit was 0.05 milligrams per liter. Nitrate concentrations in the 2001 dataset ranged from 0.4 to 77.7 milligrams per liter with a median of 9.7 milligrams per liter (**Table 13**); none of the samples had nitrate concentrations less than 0.2 milligrams per liter, seven samples (13 percent) had nitrate concentrations between 0.2 and 3.0 milligrams per liter, and 48 samples (87 percent) had nitrate concentrations greater than 3.0 milligrams per liter. Nitrate concentrations in the 2016 dataset ranged from 3.0 to 35.9 milligrams per liter with a median of 10.7 milligrams per liter (**Table 14**); none of the samples had nitrate concentrations less than 0.2 milligrams per liter, two samples (6 percent) had nitrate concentrations between 0.2 and 3.0 milligrams per liter, and 30 samples (94 percent) had nitrate conditions greater than 3.0 milligrams per liter. In total, 27 samples (49 percent) from the 2001 dataset and 17 samples (53 percent) from the 2016 dataset had nitrate concentrations exceeding the U.S. Environmental Protection Agency's primary drinking water standard of 10 milligrams per liter (U.S. Environmental Protection Agency, 2019).

Land-use data from the National Land Cover Database was used to divide the land overlying the aquifer into two generalized categories (grassland/pasture and agriculture) to evaluate potential differences in nitrate concentration between intensely managed croplands and undisturbed rural land. Forestlands, shrublands, and barrenlands were grouped into the grassland/pasture area category, while the various cover crops were grouped into the agricultural area category. In total, 24 water quality sites were grouped into the grassland/pasture area category, and 63 sites were grouped into the agriculture area category. Well-construction details and assigned land-use classes are listed in **Tables AE1** and **AE2** in Appendix E.

A Wilcoxon rank-sum test was used to determine if there was a significant difference in nitrate concentrations between wells sampled in grassland areas and those sampled in agricultural areas during the two sampling periods. The Wilcoxon rank-sum test is a non-parametric test that evaluates the differences in distribution between two independent sample populations and measures the probability that the sample populations have a similar median (Helsel and Hirsch, 1992). The test hypothesis (Ha) is that median nitrate concentrations in the agricultural areas are much larger than in the grassland areas. The null hypothesis (Ho) is that median nitrate concentrations in the agricultural areas are smaller than or equal to the grassland areas. Since the sample populations of the two land-use categories are sufficiently large (greater than 10), the test statistic W1 is approximately normally distributed and can be standardized; the standardized test statistics Z1 (or Z-test statistic) can be calculated by the following equation:

$$Z_1 = \frac{W_1 - \left(\frac{n_1(n_1 + n_2 + 1)}{2}\right)}{\sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}} \qquad (12)$$

where

Z_1 is the standardized test statistic;
W_1 is the rank sum for the agricultural area category;
n_1 is the sample population of the agriculture area category; and
n_2 is the sample population of the grassland area category

The null hypothesis is rejected in favor of the test hypothesis if the Z-test statistic is greater than the z-critical value for the distribution; the z-critical value is the rejection region cut-off value of a normal distribution at a specific significance level (α-level). Using an α-level of 0.05 (95 percent confidence), the z-critical value for a right-tailed test is 1.65, as determined from a lookup table (Glen, 2021). For the 2001 dataset, the rank-sum value for agricultural areas was 1,357, resulting in a Z-test statistic of 3.59. For the 2016 dataset, the rank-sum value for agricultural areas was 407,

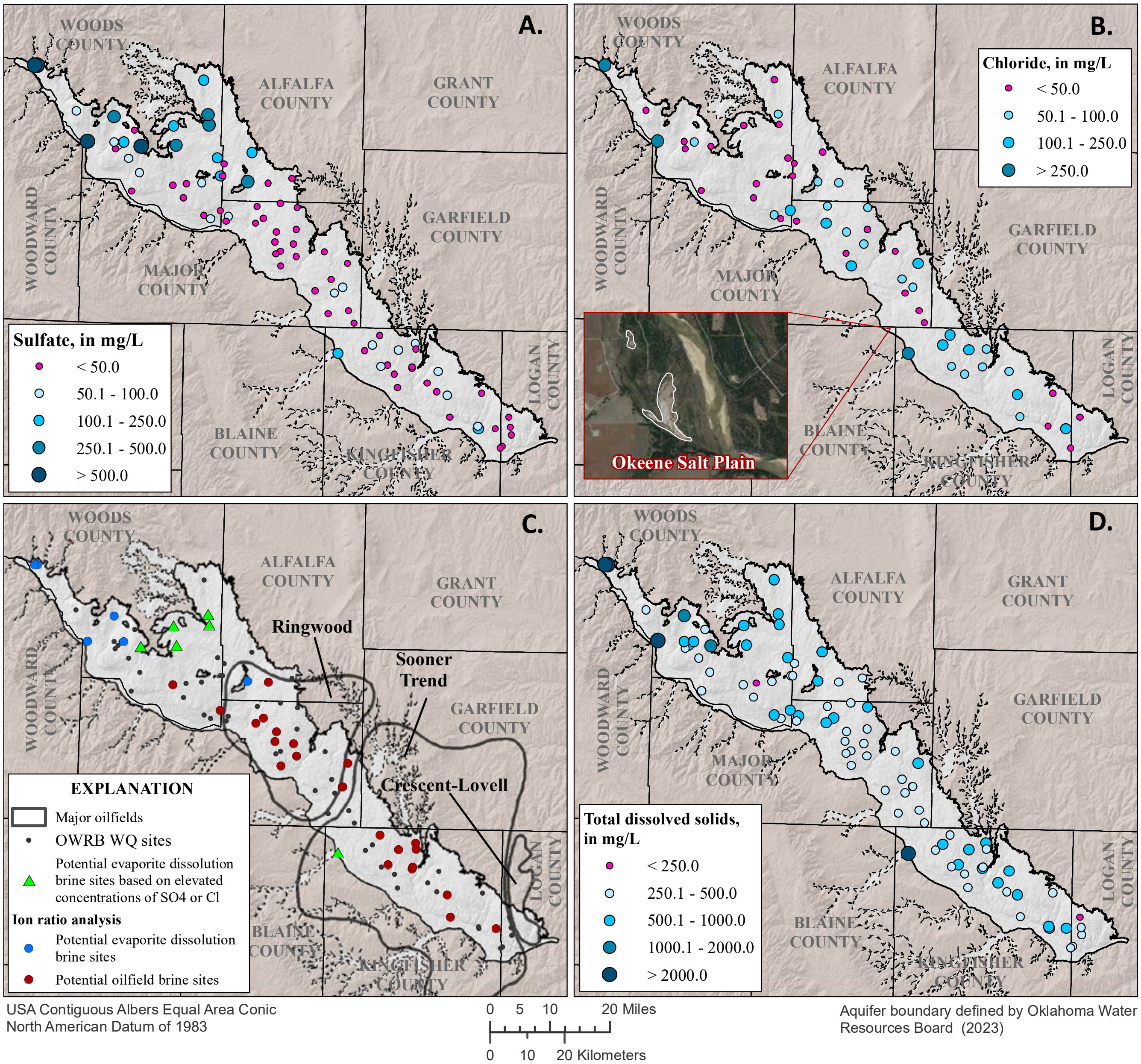


Figure 27. Spatial distributions of (A) sulfates, (B) Chlorides, and (D) total dissolved solids in concentrations of milligrams per liter from the Cimarron River alluvium and terrace aquifer. (C) Historical major oil fields (Boyd, 2002) and potential brine impacted water quality samples (Leonard and Ward, 1962; Johnson, 2022; Houslow, 1995).

resulting in a Z-test statistic of 2.38. For both datasets, the Z-test statistic was much greater than the z-critical value, therefore, the null hypothesis is rejected. The analysis indicates that the difference in median nitrate concentrations between agricultural areas and grassland areas is statistically significant. Nitrate concentrations in agricultural areas ranged from 0.95 to 77.71 milligrams per liter, with a median of 12.29 milligrams per liter, whereas nitrate concentration in grassland areas ranged from 0.43 to 15.90 milligrams per liter, with a median of 5.55 milligrams per liter. The spatial and statistical distribution of nitrate concentrations within the study area from water quality samples is shown in **Figure 29**. In total, three (3.5 percent) of the water quality samples collected from the grassland areas and forty (46.0 percent) of the water quality samples collected from the agricultural areas had nitrate concentrations exceeding the safe drinking water standard.

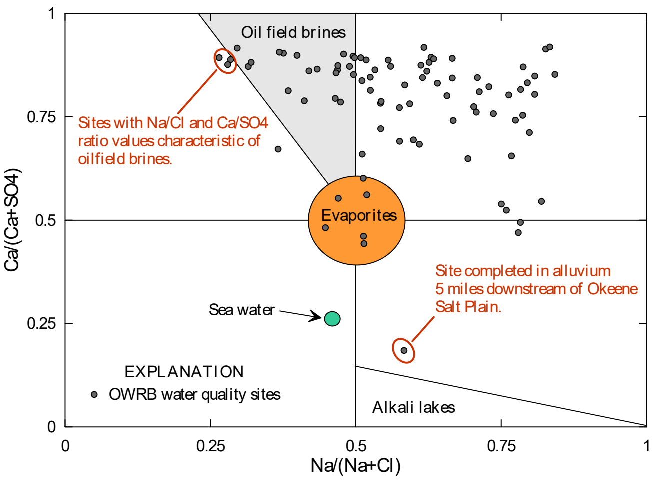


Figure 28. Brine differentiation plot (after Hounslow, 1995)

Summary

Oklahoma groundwater law (82 OK Stat §82-1020.5) requires the Oklahoma Water Resources Board to conduct hydrologic surveys and investigations of the state's aquifers to determine the maximum annual yield (MAY) and equal proportionate share (EPS) of each groundwater basin. At present (2025), the OWRB has not yet officially established a MAY or EPS for the Cimarron River alluvium and terrace aquifer. A proposed maximum annual yield of 835,200 acre-feet (EPS of 1.0 acre-foot/acre/year) was presented to the board for consideration in August 2000, but was not adopted; as such, the default EPS of 2.0 acre-feet/acre/year is currently in effect for the aquifer.

The purpose of this report is to provide an updated hydrogeologic framework for the Cimarron River alluvium and terrace aquifer, the properties of which will be used to define a maximum annual yield for the groundwater basin. Specific objectives of the hydrologic investigation included: (1) estimate mean annual recharge to and discharge from the basin, (2) estimate the hydraulic properties of the basin, specifically hydraulic conductivity, and specific yield, (3) estimate the quantity of water in storage in the basin, and (4) describe the type and quality of water in the basin. The geographic scope of the hydrologic investigation is the extent of alluvium and terrace deposits that compose the Cimarron River alluvium and terrace aquifer; the aquifer resides within the geographic area between Freedom and Guthrie, Oklahoma. The extent of the Cimarron River alluvium and terrace aquifer as presented in this investigation is about 1,279 square miles, of which, 1,137 square miles was defined as the contributing drainage area of the Cimarron River.

Recharge to the Cimarron River alluvium and terrace aquifer primarily occurs through the deep percolation of precipitation. Irrigation return flow was considered the second largest source of recharge to the aquifer, and potentially the only source of recharge during extended dry periods within cropland areas; using a return flow rate of 12 percent, the mean annual return flow was estimated to be approximately 2,621 acre-feet per year for the period 1967–2023. Recharge to the aquifer was estimated using the water table fluctuation method, a simple water budget method, and the soil-water balance method.

Table 13. Summary statistics for groundwater-quality data for 55 wells completed in the Cimarron River alluvium and terrace aquifer, 2001.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; pH in standard units]

Water-quality constituent	Units	Mean	Minimum	Percentile			Maximum
				25	50	75	
Specific conductance	µS/cm	980.0	229.0	603.0	769.0	1,079.0	5,640.0
pH	standard	6.9	6.1	6.8	7.0	7.1	7.9
Temperature	°C	17.0	15.4	16.4	16.8	17.2	19.9
Total dissolved solids	mg/L	630.6	163.0	391.8	457.0	688.8	3,597.5
Alkalinity as CaCO3	mg/L	225.3	80.0	177.3	202.1	281.3	440.4
Nitrate as N	mg/L	11.9	0.4	4.4	9.7	15.3	77.7
Sodium	mg/L	85.1	10.4	30.7	47.8	68.9	956.5
Potassium	mg/L	1.6	0.5	1.0	1.4	1.9	4.6
Sulfate	mg/L	117.0	10.1	26.9	37.9	82.8	1,184.8
Calcium	mg/L	106.4	17.2	74.9	87.5	115.8	459.3
Magnesium	mg/L	26.1	4.8	15.2	21.3	30.4	102.5
Chloride	mg/L	107.1	3.2	25.4	51.2	95.7	1,398.8
Bicarbonate	mg/L	279.0	100.7	219.9	254.3	346.3	543.8

Table 14. Summary statistics for groundwater-quality data for 32 wells completed in the Cimarron River alluvium and terrace aquifer, 2016 as part of the OWRB GMAP program.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; pH in standard units; <, less than analytical detection limit; --, could not be determined]

Water-quality constituent	Units	Mean	Minimum	Percentile			Maximum
				25	50	75	
Specific Conductance	µS/cm	845.8	430.4	514.3	712.1	937.2	3,687.9
Temperature	°C	20.1	16.9	18.4	19.4	20.9	28.1
pH	standard	7.1	6.4	6.9	7.1	7.4	7.5
Hardness	mg/L	311.8	129.0	203.8	258.5	314.5	1,541.0
Total Dissolved Solids	mg/L	553.5	268.0	340.5	403.0	562.0	3,088.0
Alkalinity as CaCO3	mg/L	185.3	84.0	129.5	190.5	228.0	293.0
Calcium	mg/L	95.8	36.8	61.9	79.2	101.3	478.2
Magnesium	mg/L	21.6	7.0	11.6	15.7	22.8	128.6
Sodium	mg/L	52.1	12.0	26.1	38.2	58.3	250.4
Potassium	mg/L	1.5	0.5	1.1	1.3	1.8	3.6
Bicarbonate	mg/L	224.4	102.0	158.3	229.0	276.8	357.0
Sulfate	mg/L	103.9	15.3	27.5	37.5	65.2	1,440.00
Chloride	mg/L	73.7	7.8	24.2	42.8	99.0	365.0
Fluoride	mg/L	--	<0.2	--	--	0.3	0.6
Silica as Si	mg/L	11.6	8.3	10.4	11.5	13.0	14.6
Nitrate as N	mg/L	11.7	3.0	8.1	10.7	13.8	35.9
Phosphorous	mg/L	0.1	<0.02	0.0	0.1	0.1	0.1
Aluminum	µg/L	--	<5.0	--	--	--	--
Arsenic	µg/L	1.5	<1.0	1.1	1.3	1.8	4.1
Barium	µg/L	302.7	11.3	168.5	217.5	423.5	1,360.0
Bromide	µg/L	--	<250.0	--	--	360.5	541.0
Boron	µg/L	--	<500.0	--	--	--	--
Cadmium	µg/L	--	<1.0	--	--	--	--
Chromium	µg/L	--	<1.0	--	--	--	1.7
Copper	µg/L	2.4	<1.0	0.5	1.2	3.0	16.9
Iron	µg/L	--	<100.0	--	--	--	--
Lead	µg/L	--	<1.0	--	--	--	1.7
Manganese	µg/L	--	<1.0	--	--	--	5.1
Molybdenum	µg/L	--	<1.0	--	--	--	1.8
Uranium	µg/L	2.4	<1.0	--	2.0	2.8	10.3
Vanadium	µg/L	5.0	2.0	3.3	3.9	6.3	13.0
Zinc	µg/L	--	<100.0	--	--	--	367.0

- Estimates of annual recharge derived from the WTF method ranged from 1.1 to 15.4 inches, with mean annual values of 3.0 inches during 2016–17, 11.4 inches during 2018–19, and 1.6 inches during 2019–20, and 3.7 inches during 2020–21. The 2017–18 estimated annual recharge was 1.8 inches near well 175289. When normalized by the mean annual precipitation for the period of record 1895–2023 (29.0 inches), the station-averaged mean recharge for the Cimarron River alluvium and terrace aquifer was about 3.2 in/year (11.0 percent of mean annual precipitation).
- Estimated mean annual recharge derived from the water budget equation was about 203,317 acre-ft/year or about 3.35 in/year (10.8 percent of mean annual precipitation [30.98 in/yr]) for the period 1974–2023. Based on the estimate rate of 3.35 inches per year, the mean annul recharge rate for the full 1,279 square mile aquifer area is about 228,783 acre-feet per year.
- Estimates of annual recharge derived from the SWB code (using scaled root-zone depths) ranged from 0.22 inches in 2006 to 6.53 inches in 1993, with a mean of 3.13 inches per year (213,486 acre-ft/year) for the period 1980–2023, equating to 10.3 percent of mean annual precipitation (30.4 inches) for the period 1980–2023.
- Assuming recharge as a percentage of precipitation is 10.5 percent, then the estimated mean annual recharge to the study area is about 3.05 in/year (207,689 acre-ft/year) for the period of record 1895–2023. In Woods County, the mean annual recharge would be about 2.7 in/year and in Kingfisher County would be about 3.1 in/year. Discharge from the Cimarron River alluvium and terrace aquifer primarily occurs through baseflow discharge, evapotranspiration, and groundwater use.
- Mean annual baseflow discharge from the aquifer was estimated to be about 200.0 cubic feet per second (144,808 acre-ft/year) for the period 1974–2023.
- Mean annual reported groundwater use from the aquifer was estimated to be about 30,814 acre-ft/year for the period 1974–2023, of which about 9 percent (2,621 acre-ft/year) infiltrated back into the aquifer as irrigation return flow.
- Mean annual evapotranspiration from the saturated zone was estimated to be about 6,000 acre-ft/year and a supplemental component of plant transpiration was estimated to be 22,850.1 acre-ft/year for forested areas within the active alluvium of the Cimarron River and associated tributaries.

Hydraulic properties of the Cimarron River alluvium and terrace aquifer determined as part of this investigation included horizontal hydraulic conductivity, transmissivity, and specific yield. Horizontal hydraulic conductivity (Kh) and transmissivity were estimated using slug tests, well drawdown specific capacity tests, multi-well pumping tests, and a lithologic-log standardization method. Specific yield (Sy) was estimated from multi-well pumping tests, a regional method, and a non-linear relationship between hydraulic conductivity and specific yield.

- Estimates of Kh determined from slug tests ranged from 3.1–468.0 ft/day, with a mean of 110.5 ft/day and a median of 81.0 ft/day.
- Estimates of Kh determined from well drawdown specific capacity tests (using and specific yield of 0.13) ranged from 0.2–526.0 ft/day, with a mean of 34.2 ft/day and a median of 19.2 ft/day. Varying the Sy by ± 0.03 had minimal impact on the min, max, and mean hydraulic conductivities, with values differing by about 2.7 percent.
- Estimated Kh determined from two multi-well pumping tests conducted as part of this investigation ranged from 56.6 to 106.2 ft/day, with a mean of 81.4 ft/day. Estimated Sy from the two pumping tests ranged from 0.08 to 0.14, with a mean of 0.11.
- Estimates of Kh determined from the litho-log standardization method range from 0.14–515.3 ft/day with a mean of 58.4 and median of 40.9 ft/day. The mean horizontal hydraulic conductivity of wells completed in alluvium deposits was 106.9 ft/day, while the mean horizontal hydraulic conductivity of wells completed in terrace deposits was 54.3 ft/day.
- Estimates of Kh from published multi-well aquifer tests ranged from 14.9 to 534.2 ft/day, with a mean and median of 181.5 and 121.3 ft/day, respectively. The ratio of median hydraulic conductivities for the alluvial (216.2 ft/day) and terrace deposits (96.4 ft/day) was 2:1, meaning the alluvium is roughly two times as conductive to flow as the terrace deposits.
- Estimates of specific yield determined from the regional method ranged from 0.04–0.11, with a mean of 0.07.
- Estimates of specific yield from published multi-well aquifer tests ranged from 1.3x10-7 to 1.2x100. Low estimates of specific yield in some tests were attributed to inadequate pumping periods. If the unrealistic estimates are excluded from the statistics, the mean and median specific yield values from all aquifer tests would be 0.13 and 0.08, respectively.
- Estimates of Sy derived from the non-linear relationship with Kh ranged from 0.07–0.26, with a mean of 0.20. Because values of Sy can vary by more than 10 percent for each lithologic category, the mean Sy estimate was not considered to representative of the aquifer material.

Model-calibrated estimates of Sy for other alluvium and terrace aquifers in western Oklahoma ranged from 0.10 to 0.16. Based on the multi-well aquifer tests conducted in this investigation, the aquifer tests conducted by previous investigators in the study area, the regional method range, and the studies conducted for other alluvium and terrace aquifers in the state, a mean Sy value of 0.13 was estimated for the Cimarron River alluvium and terrace aquifer. The specific yield likely varies locally from less than 0.1 to more than 0.25 depending on the size and sorting of the aquifer sediments.

The saturated thickness of the Cimarron River alluvium and terrace aquifer was estimated by subtracting the altitude of the aquifer base from the 2016 potentiometric surface. The saturated thickness of the aquifer ranges from less than 5 feet to 93 feet, with a mean of about 26 feet.

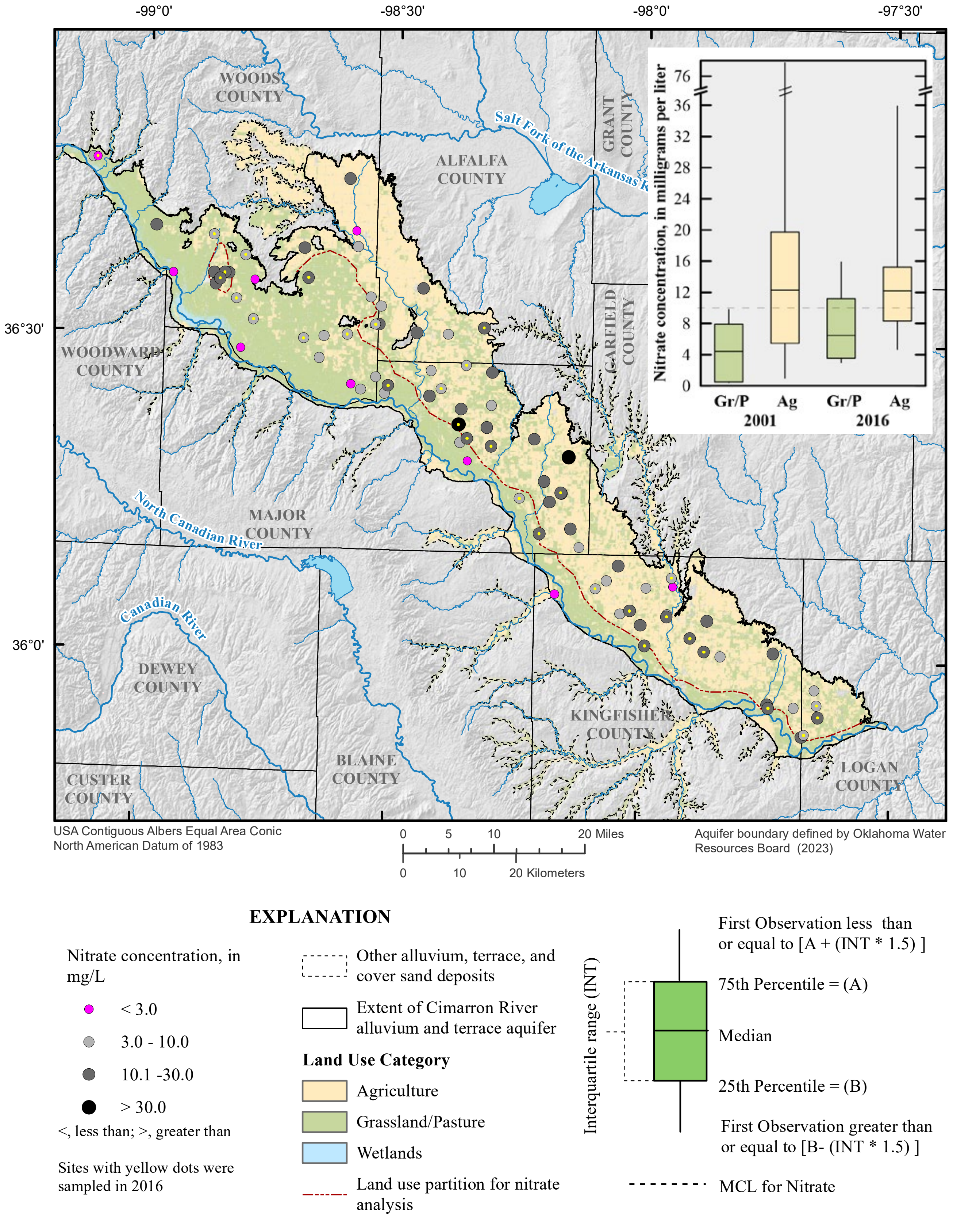


Figure 29. Spatial and statistical distribution of Nitrate concentrations (mg/L) from water quality samples collected by the OWRB in 2001 and 2016.

The amount of groundwater in storage in the Cimarron River alluvium and terrace aquifer was estimated to be about 2.77 million acre-feet, based on the aquifer area of 1,279 square miles (818,478 acres), the mean saturated thickness of 26 feet, and the specific yield value of 0.13. Varying the specific yield by ± 0.03 resulted in groundwater storage estimates of 2.13 and 3.40 million acre-feet, respectively. These estimations were considered rough approximations of groundwater in storage because they were based on mean saturated thickness.

The quality of groundwater from the Cimarron River alluvium and terrace aquifer is adequate for most purposes but is generally hard. Calcium-bicarbonate is the dominant water type in the aquifer, with higher concentrations of sulfate in Woods County, higher concentrations of sodium in Kingfisher County, and higher concentrations of chloride in the Cimarron River alluvium deposits. Concentrations of total dissolved solids ranged from 163.0 to 3,579.5 mg/L with a median around 430.0 milligrams. Concentrations of Nitrate (as nitrogen) in the Cimarron aquifer ranged from 0.4–77.7 mg/L. Nitrate concentrations greater than 3.0 mg/L are generally considered the result of human activity; of the 87 water quality samples collected, 78 had nitrate concentrations greater than 3.0 mg/L. None of the samples collected had nitrate concentrations below 0.2 mg/L, which is generally considered the cutoff for natural background conditions. Results of a Wilcoxon rank-sum test indicated that the difference in nitrate concentrations between areas classified as grasslands/pasture and areas classified as agricultural lands was statistically significant; the median nitrate concentration of samples collected from agricultural areas (12.29 mg/L) was twice as high as the median nitrate concentration of samples collected from grassland areas (5.55 mg/L).

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Appendix A. Detailed Boundary Description of the Cimarron River Alluvium and Terrace Aquifer

The extent of the Cimarron River alluvium and terrace groundwater basin is defined by the geologic contact between quaternary-age Cimarron River alluvium and terrace deposits and Permian-age bedrock from Township 27N, Range 18WI in Woods County to Township 17N, Range 03WI in Logan County. The groundwater basin area defined as part of this investigation reflects the geographical extent of alluvium and terrace deposits as shown on published OGS geology maps, including Buffalo 30' by 60' Quadrangle (Stanley and Suneson, 2002), the Alva 30' by 60' Quadrangle (Miller and Stanley, 2003), the Fairview 30' by 60' Quadrangle (Stanley and others, 2002), the Enid 30' by 60' Quadrangle (Stanley and Miller, 2008), and the Oklahoma City North 30' by 60' Quadrangle (Stanley, 2021) as well as considerations for hydrologic connectivity and saturated thickness. The eastern and western boundaries of the basin were picked where the alluvium deposits significantly narrowed and the terrace deposits became more isolated or were absent.

The groundwater basin area defined in this report is similar to the one defined in Adams and Bergman (1996), which was based on several hydrologic atlases published by the OGS. This unofficial basin boundary was presented to the OWRB Board in 2000 as part of the maximum annual yield process but was never adopted. However, the unofficial boundary has been used for the administration of groundwater permits. The most notable changes between the unofficial boundary and the boundary defined in this investigation were:

(1) The expansion of terrace deposits and cover sand in parts of Townships 19–20N, Ranges 06–07WI, Township 24N, Ranges 10–11WI, Township 20N, Range 18WI, and Township 25N, Range 12WI. Most of these areas were depicted as outcropping bedrock in surface geology maps. The inclusion of these deposits in the new basin boundary is based primarily on their apparent connection with the main body of the basin. The saturated thickness in these areas is generally less than five feet.

(2) The exclusion of all tributary alluvium deposits on the south side of the Cimarron River; although the alluvium of these tributaries is hydrologically connected with the alluvium of the Cimarron River, their contributions to the main body of the groundwater basin was considered minimal. Given the hydrologic connectivity of the deposits, it is possible for there to be some amount of flux between the tributary alluvium and the Cimarron River alluvium. However, given the average saturated thicknesses of these tributary deposits, it is likely that groundwater that is not discharged as baseflow to these tributaries and eventually transported out of the study area by the Cimarron River is held in storage. The decision to exclude these alluvium deposits was also based on groundwater use. Of the more than 800 historical groundwater permits assigned to the Cimarron River alluvium and terrace aquifer, only a single permit was in the alluvium of one of these tributaries.

(3) The exclusion of terrace deposits and cover sand in parts of Township 25N–27N, Ranges 14–15WI in south central Woods County (**Figure 5**). The deposits form several lobes varying in size from 2.5–18.0 square miles and together cover an area of approximately 39.0 square miles. The lobes are largely isolated from the main body of the groundwater basin because of the downcutting of Eagle Chief Creek and one of its tributaries. The deposits in 27N, 14–15WI lacked sufficient thickness to be included as part of the groundwater basin; most well logs indicated bedrock at the surface.

(4) The modification of the outcrop area of Permian-age bedrock in parts of Woods and Alfalfa counties was based on well driller's lithologic logs, satellite imagery, lidar, and field observations. Along much of Eagle Chief Creek's valley, well logs showed as much as 40 feet (20 foot average) of sand, silt, and gravel with a characteristic fining upward sequence. The cross-sectional area of the incised channel into the underlying Cedar Hills Sandstone was relatively narrow based on depth-to-base picks from bordering groundwater wells. For this reason, OWRB staff geologists opted to forgo the visual representation of exposed bedrock along the stream channel as done previously on the hydrologic atlases and quadrangle surface geology maps of the area. In Township 23N–24N, Range 12WI, the extent of exposed bedrock was reduced and reshaped based on wells logs near the town of Aline and a land surface topography map. The extent of exposed bedrock in Township 25N, Ranges 14–15WI along the south side of Eagle Chief Creek was defined using nine well logs and a land surface topography map; the OWRB defined extent resembles the extent mapped by Miser, 1954.

For the matter of determining the Maximum Annual Yield of fresh groundwater from the alluvium and terrace deposits of the Cimarron River in Woods, Alfalfa, Major, Garfield, Blaine, Kingfisher, and Logan Counties, the extent of the Cimarron River aquifer covers all or parts of Township 16N, Ranges 03WI, 04WI, and 05WI, and Township 17N, Ranges 03WI, 04WI, 05WI, 06WI, and 07WI, and Township 18N, Ranges 04WI, 05WI, 06WI, 07WI, 08WI, and 09WI, and Township 19N, Ranges 06WI, 07WI, 08WI, 09WI, and 10WI, and Township 20N, Ranges, 06WI, 07WI, 08WI, 09WI, and 10WI, and Township 21N, Ranges 08WI, 09WI, 10WI, 11WI, and 12WI, and Township 22N, Ranges 09WI, 10WI, 11WI, 12WI, 13WI, and 14WI, and Township 23N, Ranges 10WI, 11WI, 12WI, 13WI, 14WI, 15WI, and 16WI, and Township 24N, Ranges 10WI, 11WI, 12WI, 13WI, 14WI, 15WI, and 16WI, and Township 25N, Ranges, 12WI, 13WI, 14WI, 15WI, 16WI, and 17WI, and Township 26N, Ranges 12WI, 13WI, 14WI, 15WI, 16WI, 17WI, and 18WI, and Township 27N, Ranges 13WI, 14WI, 17WI, and 18WI.

Appendix B. Land Cover Class Descriptions for Mapping Year 2020

Table AB1. Descriptions and percent of total land coverage for land use categories overlying the Cimarron River alluvium and terrace aquifer.

Category[1]	Description[2]	Percentage
	Water/Wetlands	
Open Water	Areas of open water, generally with less than 25% cover of vegetation or soil.	1.18
Woody Wetlands	Areas where forest of shrubland vegetation accounts for greater than 20% of vegetative cover and the soil is periodically saturated or covered with water.	0.14
Herbaceous Wetlands	Areas where perennial gerbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.	0.89
	Developed	
Developed, Open Space	Areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas are most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aestheric purposes.	3.10
Developed, Low Intensity	Impervious surfaces account for 20% to 49% of total cover.	0.67
Developed, Medium Intensity	Impervious surfaces account for 50% to 79% of total cover.	0.27
Developed, Open Space	Highly developed areas where people reside or work in high numbers. Impervious surfaces account for 80% to 100% of total cover.	0.05
	Barren	
Barren	Areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits, and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.	0.32
	Forest	
Deciduous Forest	Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.	4.72
Evergreen Forest	More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.	0.82
Mixed Forest	Neither deciduous nor evergreen species are greater than 75% of total tree cover.	0.06
	Shrubland	
Shrubland	Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.	0.18
	Grassland/Pasture	
Grassland/pasture	Areas dominated by herbaceous vegetation, grasses, or legumes, generally greater than 80% of total vegetation. Pasture/hay vegetation accounts for greater than 20% of total vegetation. These areas are not subject to intensive management such as tilling but can be utilized for grazing.	41.45
	Cultivated Crops	
Cultivated Crops	Areasused for the production of annual crops, such as corn, soybeans, vegetatables, tobacco, and cotton, and also perennial woody crops such as orchards. Crop vegetation accounts for greater than 20% of total vegetation. This class includes all land being actively tilled.	46.14

[1] Land-use categories come from the U.S. Department of Agriculture National Agriculture Statistics Service CropScape product.

[2] Land cover desciptions come from the annual National Land Cover Database, a collaborative product of the USGS and Multi-Resolution Land Characteristics Consortium.

Appendix C. Location Details and Periods of Record for Mass Measurement Sites Used for the Groundwater-level Fluctuation Analysis

Table AC1. Period of record and location data for 72 selected mass measurement sites collected as part of the OWRB groundwater monitoring and assessment program (GMAP) used for groundwater-level fluctuation analysis in the Cimarron River alluvium and terrace aquifer. Well sites are shown in **Figure 1**, and annual fluctuations are shown in **Figure 3C**.

Station number	Agency	County	Period of record[1]	Number of years[2]	Latitude	Longitude
92698	OWRB	Woods	2009–2023	13	36.50803	-98.78258
9857	OWRB	Woods	1975–2020	41	36.61148	-98.83898
9852	OWRB	Woods	1977–2023	44	36.53556	-98.67528
9859	OWRB	Woods	1983–2023	35	36.65238	-98.59409
9849	OWRB	Woods	1983–2023	39	36.49399	-98.58558
9853	OWRB	Woods	1983–2023	38	36.57924	-98.56595
9861	OWRB	Woods	1983–2023	37	36.73927	-98.62977
9855	OWRB	Woods	1983–2023	38	36.57885	-98.85984
9854	OWRB	Woods	1983–2023	39	36.57934	-98.59203
9851	OWRB	Woods	1983–2003	20	36.53035	-98.74514
9850	OWRB	Woods	1983–2023	39	36.51350	-98.67599
9862	OWRB	Woods	1983–2023	37	36.76871	-98.65265
9848	OWRB	Woods	1975–2021	43	36.46588	-98.62282
9523	OWRB	Kingfisher	1974–1985	12	36.03038	-97.85076
9527	OWRB	Kingifsher	1974–2007	30	36.06161	-97.83202
9512	OWRB	Kingfisher	1974–1923	49	35.95715	-97.72085
9139	OWRB	Kingfisher	1991–2023	33	36.04551	-97.99998
27647	OWRB	Kingfisher	1992–2023	31	36.11727	-98.10647
9528	OWRB	Kingfisher	1951–2008	39	36.08876	-97.98611
9517	OWRB	Kingfisher	1974–1995	22	35.96962	-97.78357
9515	OWRB	Kingfisher	1975–1999	24	35.96391	-97.89202
9532	OWRB	Kingfisher	1951–1999	48	36.15816	-98.03456
9522	OWRB	Kingfisher	1951–2007	55	36.01590	-97.94905
9520	OWRB	Kingfisher	1974–1989	16	35.99950	-97.86443
9516	OWRB	Kingfisher	1974–1989	16	35.96289	-97.90902
9512	OWRB	Kingfisher	1974–2023	49	35.95815	-97.91381
9530	OWRB	Kingfisher	1974–2014	41	36.11621	-98.07505
9529	OWRB	Kingfisher	1969–2023	53	36.09124	-98.03522
9519	OWRB	Kingfisher	1974–1988	15	35.98619	-97.87275
9513	OWRB	Kingfisher	1974–1989	15	35.95706	-97.80154
9510	OWRB	Kingfisher	1974–1990	15	35.94233	-97.78191
9525	OWRB	Kingfisher	1978–2011	31	36.04245	-98.01465
9526	OWRB	Kingfisher	1974–2023	45	36.05512	-97.87492
9511	OWRB	Kingfisher	1974–2023	50	35.95113	-97.88967

[1] Period of record may not be continuous

[2] Reflects only the number of discrete water-level measurements between January-March of each year at each well site.

Table AC1. Period of record and location data for 72 selected mass measurement sites collected as part of the OWRB groundwater monitoring and assessment program (GMAP) used for groundwater-level fluctuation analysis in the Cimarron River alluvium and terrace aquifer. Well sites are shown in Figure 1, and annual fluctuations are shown in Figure 3C — continued

Station number	Agency	County	Period of record[1]	Number of years[2]	Latitude	Longitude
9531	OWRB	Kingfisher	1974–1989	15	36.13113	-98.14945
9524	OWRB	Kingfisher	1974–2023	50	36.04352	-97.85774
9521	OWRB	Kingfisher	1974–2014	41	36.00055	-97.88281
360237097490401	USGS	Kingfisher	1974–1985	12	36.04393	-97.81922
360651097560001	USGS	Kingfisher	1974–1986	13	36.11615	-97.93589
360059097520001	USGS	Kingfisher	1974–1986	13	36.01782	-97.86867
360649098062501	USGS	Kingfisher	1951–1974	22	36.11309	-98.10506
9563	OWRB	Logan	1974–1987	12	35.90132	-97.62067
9567	OWRB	Logan	1974–1992	19	35.94307	-97.61645
9564	OWRB	Logan	1974–2004	30	35.91305	-97.61221
9562	OWRB	Logan	1974–2006	33	35.89889	-97.67535
9561	OWRB	Logan	1983–1999	17	35.88728	-97.65284
9566	OWRB	Logan	1974–1989	16	35.93567	-97.65876
9567	OWRB	Logan	1974–1992	19	35.94307	-97.61645
9581	OWRB	Major	1974–2016	41	36.34735	-98.31281
9582	OWRB	Major	1950–1986	36	36.34648	-98.40057
9579	OWRB	Major	1951–1993	24	36.29068	-98.28023
9586	OWRB	Major	1983–2023	36	36.44856	-98.32309
9576	OWRB	Major	1974–1992	38	36.27417	-98.20187
9575	OWRB	Major	1950–2023	61	36.24581	-98.15796
9584	OWRB	Major	1983–2011	26	36.40713	-98.36949
9583	OWRB	Major	1974–2023	48	36.36976	-98.33717
9587	OWRB	Major	1974–2023	49	36.45518	-98.40854
9578	OWRB	Major	1950–2023	68	36.27542	-98.26695
9574	OWRB	Major	1950–1993	38	36.23297	-98.19248
18630	OWRB	Major	2000–2023	23	36.43099	-98.52887
26152	OWRB	Major	2000–2023	23	36.28438	-98.17458
9580	OWRB	Major	1976–2023	42	36.31925	-98.21096
9577	OWRB	Major	1950–1995	44	36.27589	-98.17724
9573	OWRB	Major	1978–2023	45	36.21764	-98.22059
361108098074901	USGS	Major	1951–1963	13	36.18559	-98.13062
361938098062201	USGS	Major	1951–1983	18	36.32726	-98.10645
9413	OWRB	Garfield	1950–2011	42	36.28972	-98.09380
9412	OWRB	Garfield	1954–2014	37	36.28205	-98.10430
361655098061301	USGS	Garfield	1950–1990	13	36.28198	-98.10395
361907098053801	USGS	Garfield	1950–1984	30	36.31865	-98.09423
361514098052501	USGS	Garfield	1951–1966	15	36.25392	-98.09062
9004	OWRB	Alfalfa	1983–2002	18	36.49840	-98.42605

[1] Period of record may not be continuous

[2] Reflects only the number of discrete water-level measurements between January-March of each year at each well site.

Appendix D. Location Details and Periods of Record for Climate Stations Used for the Soil-Water Balance Method

Table AD1. Period of record and location data for National Weather Servce (NWS) Cooperative Observer Program and Oklahoma Mesonet Climate stations used for the Soil-Water Balance method in the Cimarron River alluvium and terrace aquifer (Figure 17)

Station number	Station name	County	Period of record[1]	Number of years[2]	Latitude	Longitude
Cooperative Observer Program climate stations (Oklahoma Climatological Survey, 2021b)						
3358	Freedom	Woods	1948–2015	67	36.76447	-99.11278
9404	Waynoka	Woods	1938–2023	86	36.57583	-98.87972
0193	Alva 1W	Woods	1894–2023	130	36.80139	-98.68778
1724	Cherokee 4W	Alfalfa	1915–2014	100	36.76722	-98.42444
4019	Helena 1SSE	Alfalfa	1906–2023	118	36.53806	-98.26611
6751	Orienta 1SSW	Major	1956–2023	68	36.34861	-98.48083
4950	Lahoma RSCH STN	Major	2003–2023	21	36.38944	-98.10611
0215	Ames	Major	1896–2023	128	36.24833	-98.18833
4055	Hennessey 4ESE	Kingfisher	1915–2013	98	36.09417	-97.83500
4861	Kingfisher	Kingfisher	1897–2023	127	35.85833	-97.92944
1724	Crescent 5WSW	Logan	1940–2023	84	35.92694	-97.67417
5589	Marshall	Logan	1951–2023	73	36.15222	-97.62250
8708	Taloga	Dewey	1900–2017	118	36.03806	-98.95917
5768	Medford 1S	Grant	1981–2023	43	36.78944	-97.73333
4573	Jefferson	Grant	1900–2023	124	36.72222	-97.79028
5013	Lamont	Grant	1993–2023	31	36.68778	-97.55722
2912	Enid	Garfield	1900–2023	124	36.41944	-97.87472
9364	Watonga	Blaine	1902–2023	122	35.85778	-98.41389
Oklahoma Mesonet climate stations (Oklahoma Climatological Survey, 2021a)						
116	Alva 7.2 SSW (ALV2)	Woods	1999–2023	25	36.70823	-98.70974
083	Seiling 7.0 WNW (SEIL)	Woodward	1994–2023	30	36.19033	-99.04030
039	Freedom 3.0 SSW (FREE)	Woodward	1994–2023	30	36.72562	-99.14234
025	Cherokee 0.5 SSW (CHER)	Alfalfa	1994–2023	30	36.74813	-98.36274
014	Breckinridge 3.0SE (BREC)	Garfield	1994–2023	30	36.41201	-97.69394
037	Fairview 1.0 W (FAIR)	Major	1994–2023	30	36.26353	-98.49766
145	Fairview 5.0 NW (FAI2)	Major	2023–2023	1	36.31719	-98.55225
055	Lahoma 1.0 WSW (LAHO)	Major	1994–2023	30	36.38435	-98.11139
054	Kingfisher 2.0 NE (KING)	Kingfisher	1994–2009	16	35.88050	-97.91121
133	Kingfisher 1.0 W (KIN2)	Kingfisher	2009–2023	15	35.85431	-97.95442
063	Medford 1.0 SW (MEDF)	Grant	1994–2023	30	36.79242	-97.74577
060	Marshall 3.0 SSE (MARS)	Logan	1994–2003	10	36.11860	-97.60140
125	Marshall 4.0 SSE (MRSH)	Logan	2003–2023	21	36.11685	-97.60685
078	Putnam 3.0 N (PUTN)	Dewey	1994–2023	30	35.89904	-98.96038
100	Watonga 7.0 W (WATO)	Blaine	1994–2023	30	35.84185	-98.52615

[1] Period of record may not be continuous

[2] May not be full years as stations can be retired or be down for extended periods of time (months) for maintenance

Appendix E. Supplemental Tables for Nitrate Analysis Land-use Classifications in the Cimarron River Alluvium and Terrace Aquifer

Table AE1. Well site construction details and assigned land use class for 55 water quality sites sampled in 2001.

Well number	OWRB ID	County	Well depth (feet)	Aquifer base (feet)	Perf interval (feet)	Date measured (M/D/Y)	Land use
1	7672	Kingfisher	60	57	50 to 60	10/18/2001	Agriculture
2	7718	Kingfisher	102	95	86 to 101	10/23/2001	Agriculture
3	7733	Kingfisher	82	81	72 to 82	10/23/2001	Agriculture
4	17901	Alfalfa	56	45	45 to 50	10/17/2001	Agriculture
5	17908	Alfalfa	60	50	45 to 55	10/25/2001	Agriculture
6	18105	Major	57	53	50 to 57	10/24/2001	Agriculture
7	18113	Major	65	61	59 to 65	10/23/2001	Agriculture
8	18362	Major	82.7	95	67 to 80	10/10/2001	Grassland
9	18426	Major	62	59	56 to 61	10/10/2001	Agriculture
10	18528	Major	73.5	67	57 to 71	10/10/2001	Grassland
11	18536	Major	43	40	33 to 43	10/10/2001	Agriculture
12	18610	Major	58	54	52 to 58	10/10/2001	Agriculture
13	18656	Woods	69.4	62	53 to 66	10/10/2001	Grassland
14	18707	Woods	90	83	75 to 90	10/17/2001	Grassland
15	18782	Woods	65	60	45 to 60	10/8/2001	Grassland
16	18786	Woods	58	>58	45 to 55	10/9/2001	Agriculture
17	18807	Woods	33	26	25 to 30	10/9/2001	Agriculture
18	18832	Woods	44	35	30 to 40	10/9/2001	Agriculture
19	24536	Woods	50	36	35 to 40	10/9/2001	Grassland
20	25288	Woods	46	>46	30 to 35	10/8/2001	Agriculture
21	27581	Woods	27	26	18 to 27	10/9/2001	Grassland
22	27685	Alfalfa	49	40	10 to 49	10/9/2001	Agriculture
23	27928	Woods	49	40	20 to 40	10/8/2001	Agriculture
24	27982	Alfalfa	70	65	55 to 65	10/11/2001	Agriculture
25	28750	Kingfisher	32	30	17 to 32	10/24/2001	Grassland
26	29472	Major	60	58	54 to 59	10/10/2001	Agriculture
27	29903	Woods	43	25	35 to 40	10/17/2001	Agriculture
28	30810	Kingfisher	76	74	15 to 75	10/16/2001	Agriculture
29	31250	Major	54.9	50	45 to 55	11/5/2001	Agriculture
30	32482	Kingfisher	84	80	74 to 84	11/5/2001	Agriculture
31	32596	Major	76.7	>77	67 to 77	10/18/2001	Agriculture
32	36066	Kingfisher	61	57	12 to 61	10/16/2001	Agriculture
33	36071	Kingfisher	52	42	41 to 46	10/16/2001	Agriculture
34	36092	Kingfisher	42	40	27 to 56	10/24/2001	Agriculture
35	36705	Major	68	66	58 to 68	10/23/2001	Agriculture
36	37626	Woods	25	17	15 to 25	10/11/2001	Grassland

Table AE1. Well site construction details and assigned land use class for 55 water quality sites sampled in 2001 — continued

Well number	OWRB ID	County	Well depth (feet)	Aquifer base (feet)	Perf interval (feet)	Date measured (M/D/Y)	Land use
37	37634	Woods	50	31	28 to 32	11/06/2001	Agriculture
38	38188	Alfalfa	92	75	72 to 92	10/18/2001	Agriculture
39	38763	Kingfisher	57	36	17 to 37	11/05/2001	Agriculture
10	38850	Major	58	50	28 to 48	10/25/2001	Agriculture
41	38852	Major	60	58	40 to 60	10/18/2001	Agriculture
42	39030	Woods	40	28	21 to 32	10/25/2001	Agriculture
43	39041	Woods	75	69	59 to 67	10/08/2001	Grassland
44	39073	Woods	40	35	30 to 40	10/09/2001	Agriculture
45	39602	Woods	53	47	42 to 48	10/11/2001	Grassland
46	44695	Kingfisher	59	58	49 to 59	10/24/2001	Agriculture
47	44816	Logan	75	71	65 to 75	10/24/2001	Agriculture
48	45285	Major	75	71	60 to 75	10/18/2001	Agriculture
49	50110	Kingfisher	51	47	41 to 51	11/05/2001	Agriculture
50	50655	Kingfisher	40	37	20 to 40	10/16/2001	Agriculture
51	52820	Kingfisher	68	>66	61 to 66	10/16/2001	Agriculture
52	56217	Major	40	30	18 to 28	10/17/2001	Grassland
53	59145	Major	31	25	19 to 29	10/10/2001	Grassland
54	59942	Major	100	92	90 to 100	10/17/2001	Agriculture
55	61968	Kingfisher	73	68	59 to 73	10/16/2001	Agriculture

Table AE2. Well site construction details and assigned land use class for 32 water quality sites sampled in 2016.

Well number	OWRB ID	County	Well Depth (feet)	Aquifer Base (feet)	Perf Interval (feet)	Date measured (M/D/Y)	Land Use
1	18635	Major	68	61	49 to 65	7/19/2016	Grassland
2	18699	Woods	70	66	50 to 70	7/20/2016	Grassland
3	18819	Woods	60	50	15 to 55	7/27/2016	Grassland
4	23484	Major	65	>69	10 to 65	7/18/2016	Grassland
5	23683	Woods	100	88	40 to 100	7/19/2016	Grassland
6	28463	Woods	35	32	20 to 35	7/19/2016	Agriculture
7	29904	Woods	70	60	50 to 60	7/26/2016	Agriculture
8	31231	Major	60	56	52 to 60	7/18/2016	Agriculture
9	45074	Logan	75	75	65 to 75	8/8/2016	Agriculture
10	80288	Major	65	61	57 to 61	7/20/2016	Agriculture
11	80969	Major	38	>38	27 to 35	7/26/2016	Grassland
12	82080	Kingfisher	62	58	46 to 61	7/25/2016	Agriculture
13	82119	Kingfisher	25	>25	15 to 25	7/18/2016	Agriculture
14	92697	Woods	50	50	30 to 50	7/26/2016	Grassland
15	96372	Woods	30	30	20 to 30	7/20/2016	Grassland
16	99966	Woods	70	70	60 to 70	7/26/2016	Agriculture
17	112824	Kingfisher	40	>40	20 to 40	7/19/2016	Agriculture
18	112887	Logan	62	>62	42 to 62	7/18/2016	Agriculture
19	115206	Woods	40	40	20 to 40	7/27/2016	Grassland
20	123303	Logan	72	>72	52 to 72	7/18/2016	Agriculture
21	125787	Kingfisher	61	58	41 to 61	7/26/2016	Agriculture
22	129972	Kingfisher	65	60	45 to 65	7/19/2016	Agriculture
23	130032	Major	83	79	62 to 82	8/10/2016	Agriculture
24	134489	Major	76	72	55 to 75	7/18/2016	Agriculture
25	143065	Woods	45	25	10 to 25	7/26/2016	Grassland
26	147793	Major	85	80	64 to 84	7/27/2016	Agriculture
27	154463	Major	79	76	56 to 76	7/19/2016	Agriculture
28	158109	Kingfisher	47	40	30 to 40	7/19/2016	Agriculture
29	158905	Kingfisher	47	40	30 to 40	7/20/2016	Agriculture
30	160161	Woods	78	72	55 to 75	7/27/2016	Grassland
31	162874	Alfalfa	75	>75	55 to 75	7/19/2016	Agriculture
32	175292	Kingfisher	76	74	66 to 76	7/25/2016	Agriculture

Appendix F. Cimarron River Alluvium and Terrace Aquifer Reach Analysis

The purpose of this supplemental analysis was to assess a split of the Cimarron River alluvium and terrace aquifer into two reaches demarcated by Indian Creek. There are no significant hydrologic or geologic barriers to flow in the alluvium and terrace deposits, so dividing the basin into two subbasins would be for administrative or groundwater-flow modeling purposes. The structure of this appendix will be similar to the main report with added figures and tables as needed; caption numbering for figures and tables created for this analysis will include "AF" to differentiate them from figures and tables referenced from the main report.

Location and Area

As discussed in the Description of Study Area section of the main report, the Cimarron River alluvium and terrace aquifer underlies approximately 1,279 square miles of land along approximately 115 miles of the Cimarron River between Freedom and Guthrie. Reach I includes alluvium and terrace deposits of the Cimarron River from an area roughly 3.5 miles upstream of the town of Freedom in Woods County to Indian Creek in Major County (**Figure AF1**). The area of Reach I is approximately 734 square miles (469,758 acres). Reach II includes alluvium and terrace deposits of the Cimarron River from Indian Creek to an area roughly 6.0 miles upstream of U.S. Highway 77, north of the City of Guthrie in Logan County (**Figure AF1**). The area of Reach II is approximately 545 square miles (348,720 acres).

Land Use

Generalized land cover and crop cover over the defined aquifer area are shown in **Figure 2**. In 2020, the land use in Reach I was about 51.0 percent grasslands/pastures, 38.1 percent cultivated croplands, 4.2 percent developed and barren lands, 3.9 percent dedicated forest lands, 2.6 percent wetlands/open water, and 0.20 percent shrublands (National Agricultural Statistics Service, 2021). Winter Wheat composed 69.4 percent of cultivated crops in Reach I in 2020, with rye being a distant second at 11.0 percent. Crops that cover between 1.6–4.3 percent of the cultivated lands include alfalfa, herbs, corn, soybeans, and triticale; these crops collectively made up about 13.5 percent of the cultivated land. Various vegetables, nuts, and fruits collectively made up 6.1 percent. The land use in Reach II was about 56.9 percent cultivated croplands, 28.6 percent grasslands/pastures, 7.9 percent dedicated forest lands, 4.7 percent developed and barren lands, 1.7 percent wetlands/open water, and 0.17 percent shrublands (National Agricultural Statistics Service, 2021). Rye composed 54.5 percent of cultivated crops in Reach II in 2020, with winter wheat being a close second at 34.7 percent. Crops that cover between 0.5–2.4 percent of the cultivated lands include alfalfa, herbs, corn, soybeans, and triticale; these crops collectively made up about 7.2 percent of the cultivated land. Various vegetables, nuts, and fruits collectively made up 3.6 percent.

Climate

As discussed in the Climate section of the main report, mean annual precipitation and temperature vary across the study area. Climate data summarized by county could not be used for this analysis because both reaches included part of Major County. Instead, long-term precipitation and temperature trends in the two reaches were analyzed using 26 climate stations in and around the defined aquifer boundary (**Figure AF1**). **Table AF1** lists the periods of record, mean annual precipitation, and mean annual temperature estimates for the climate stations used in the analysis.

Data gaps in the climatological time series of each climate station were addressed using the informal "3/5 rule" which qualifies that if more than three consecutive daily values are missing or more than five daily values in total in a given month are missing, the monthly mean should not be computed and the year-month mean should be considered missing (World Meteorological Organization, 1989). The 3/5 rule was not applied to daily precipitation data. Instead, if the number of missing non-consecutive daily values was less than fifteen percent of the total number of days in a given month, the monthly total was calculated as the total of the observed daily values multiplied by a ratio of the total days in the month over the number of days with daily values; if the number of missing non-consecutive daily values was greater than fifteen percent, the monthly total was not calculated.

Annual statistics for each climate station were only calculated for years with 12 complete months of data. The climate statistics were not considered period-of-record normals if three or more consecutive annual means or 20 percent or more of the annual means were missing from a period of record (World Meteorological Organization, 2017). To minimize spatial bias, stations with common periods of record that were near (less than five miles) to each other were averaged; the cooperative observer climate stations were excluded from the annual statistics after the mesonet climate stations became active, unless a mesonet station was missing an annual mean estimate.

The common period of record 1950–2023 was chosen for this analysis because it ensured a relatively even distribution of climate stations across the study area for each year; this distribution was necessary to capture localized variations in precipitation across the study area. Because temperature variations are more regional, having at least three active climate stations for each year in each reach was considered sufficient to calculate mean annual estimates. Mean annual temperature in Reach I was 59.2°F and in Reach II was 60.4°F. Mean annual precipitation was 28.2 inches per year in Reach I and 32.4 inches per year in Reach II (**Table AF1**; **Figure AF2**). Mean annual precipitation increases across the study area from about 27.3 inches per year in Woods County to about 32.7 inches per year in eastern Kingfisher County, when analyzed over the common period of record. A 5-year weighted moving average was used to delineate periods of

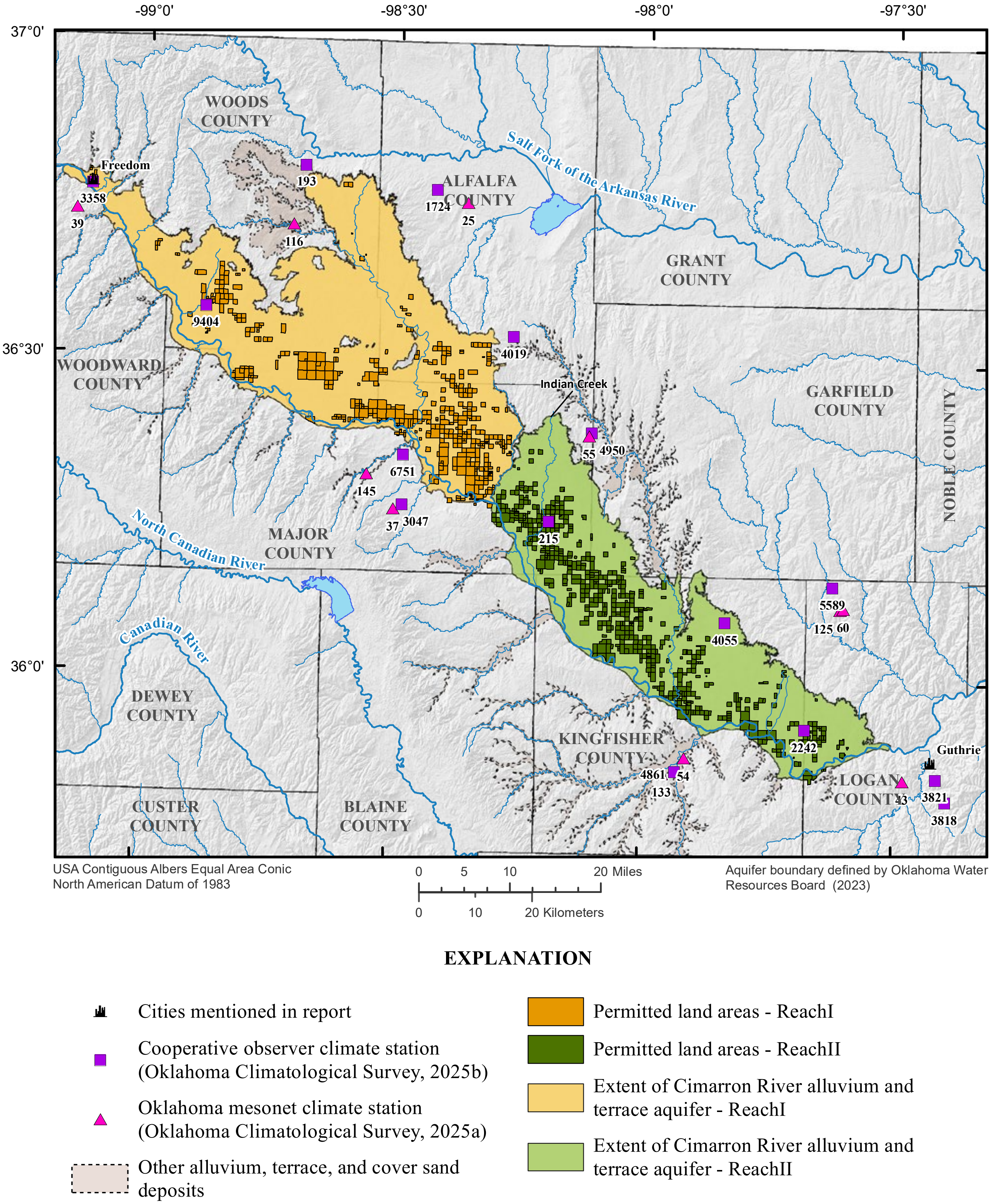

Figure AF1. Locations of the Cimarron River alluvium and terrace aquifer reaches, climate stations, and cities, northwestern Oklahoma.

Table AF1. Periods of record, mean annual precipitation, and mean annual temperature for thirteen climate stations in the Cimarron River alluvial and terrace aquifer study area used for Reach analysis.

[Percentages listed in parenthese represent data coverages for each climate element at each climate station. Stations names with an (M) are mesonet stations; all others are cooperative observer stations. Annual statistics with an astericks (*) are not considered period-of-record climate normals. Data coverage is an approximation of the completeness of each climate elements dataset (daily values). Data coverage gives a general idea of how continuous a period of record is, with higher percentages meaning fewer gaps in each dataset (National Center for Environmental Information, 2023)]

Station number	Station name	County	Period of record[1]	Mean annual precipitation, in inches per year	Mean annual temperature, in degrees Farenheit
3358	Freedom	Woods	1948–2015	25.2* (97.1%)	57.9* (93.3%)
0039	Freedom 3.0 SSW (M)	Woods	1994–2023	25.8 (99.7%)	59.1 (89.3%)
9404	Waynoka	Woods	1938–2023	27.8* (98.9%)	59.2* (97.4%)
0193	Alva 1W	Woods	1894–2023	29.1* (86.0%)	59.3* (74.4%)
0116	Alva 7.2 SSW (M)	Woods	1994–2023	27.7* (81.8%)	59.1* (83.2%)
1724	Cherokee 4W	Alfalfa	1915–2014	28.7* (79.1%)	59.6* (73.5%)
0025	Cherokee 0.5 SSW (M)	Alfalfa	1994–2023	28.1 (98.7%)	59.3 (89.2%)
4019	Helena 1SSE	Alfalfa	1906–2023	30.7* (73.2%)	58.1* (57.6%)
6751	Orienta 1SSW	Major	1956–2023	28.8* (97.6%)	-- (00.0%)
3047	Fairview	Major	1933–1976	28.6 (95.7%)	61.2* (75.7%)
0037	Fairview 1.0 W (M)	Major	1993–2023	28.9 (98.8%)	60.3 (87.9%)
0145	Fairview 5.0 NW (M)	Major	2023–2023	Merged	Merged
Reach I		--	1950–2023	28.2 --	59.2 --
4950	Lahoma RSCH STN	Major	2003–2023	32.4* (94.9%)	60.4* (32.6%)
0055	Lahoma 1.0 WSW (M)	Major	1994–2023	30.4 (99.7%)	59.4 (89.0%)
0215	Ames	Major	1896–2023	31.3* (22.5%)	-- (02.0%)
4055	Hennessey 4ESE	Kingfisher	1895–2013	31.3* (83.3%)	60.1* (82.3%)
4861	Kingfisher	Kingfisher	1897–2023	32.5 (98.6%)	60.5* (87.2%)
0054	Kingfisher 2.0 NE (M)	Kingfisher	1994–2009	32.2 (99.9%)	60.6 (99.2%)
0133	Kingfisher 1.0 W (M)	Kingfisher	2009–2023	33.9 (98.6%)	60.3 (78.1%)
5589	Marshall	Logan	1951–2023	33.1 (98.5%)	-- (00.0%)
0060	Marshall 3.0 SSE(M)	Logan	1994–2003	33.0* (97.7%)	60.5* (66.9%)
0125	Marshall 4.0 SSE (M)	Logan	2003–2023	33.0 (99.6%)	60.1 (99.6%)
2242	Crescent 5WSW	Logan	1940–2023	34.6* (64.1%)	61.5* (17.8%)
0043	Guthrie 4.0 WSW (M)	Logan	1994–2023	35.2 (98.5%)	61.3 (89.1%)
3821	Guthrie 5S	Logan	1894–2015	34.5* (92.2%)	60.9* (92.4%)
3818	Guthrie Airport	Logan	1998–2023	28.9 (99.0%)	61.9 (98.9%)
Reach II		--	1950–2023	32.4 --	60.4 --

[1] Period of record may not be continuous

above- and below-mean annual precipitation and temperature for the study area (**Figure AF2**); minor differences between the reaches negated the need to delineate periods for each.

Groundwater Use

As of the end of the calendar year 2023, the number of active long-term groundwater permits within the defined aquifer boundary was 578; 348 temporary, and 230 prior rights. Of the 578 active permits, 235 were located in Reach I and 343 were located in Reach II. Annual groundwater use was summarized for the period 1967–2023 based on self-reported use estimates from 656 historical long-term permits; all other permits either never reported any water use or lacked documentation within the OWRB database. Total annual reported groundwater use for the Cimarron River alluvium and terrace aquifer reaches is shown in **Figure AF3** and mean annual use statistics are listed in **Table AF2**. Mean annual groundwater use for the period 1967-2023 in Reach I was estimated to be 14,518 acre-feet per year with a median of 12,358 acre-feet. Mean annual groundwater use in Reach II was higher for the same period of record with an estimated value of 16,296 acre-feet per year, and a median value of 13,799 acre-feet. The highest and lowest annual reported groundwater use in Reach I were 28,698 acre-feet in 2023 and 5,788 acre-feet in 1967, respectively. The highest and lowest

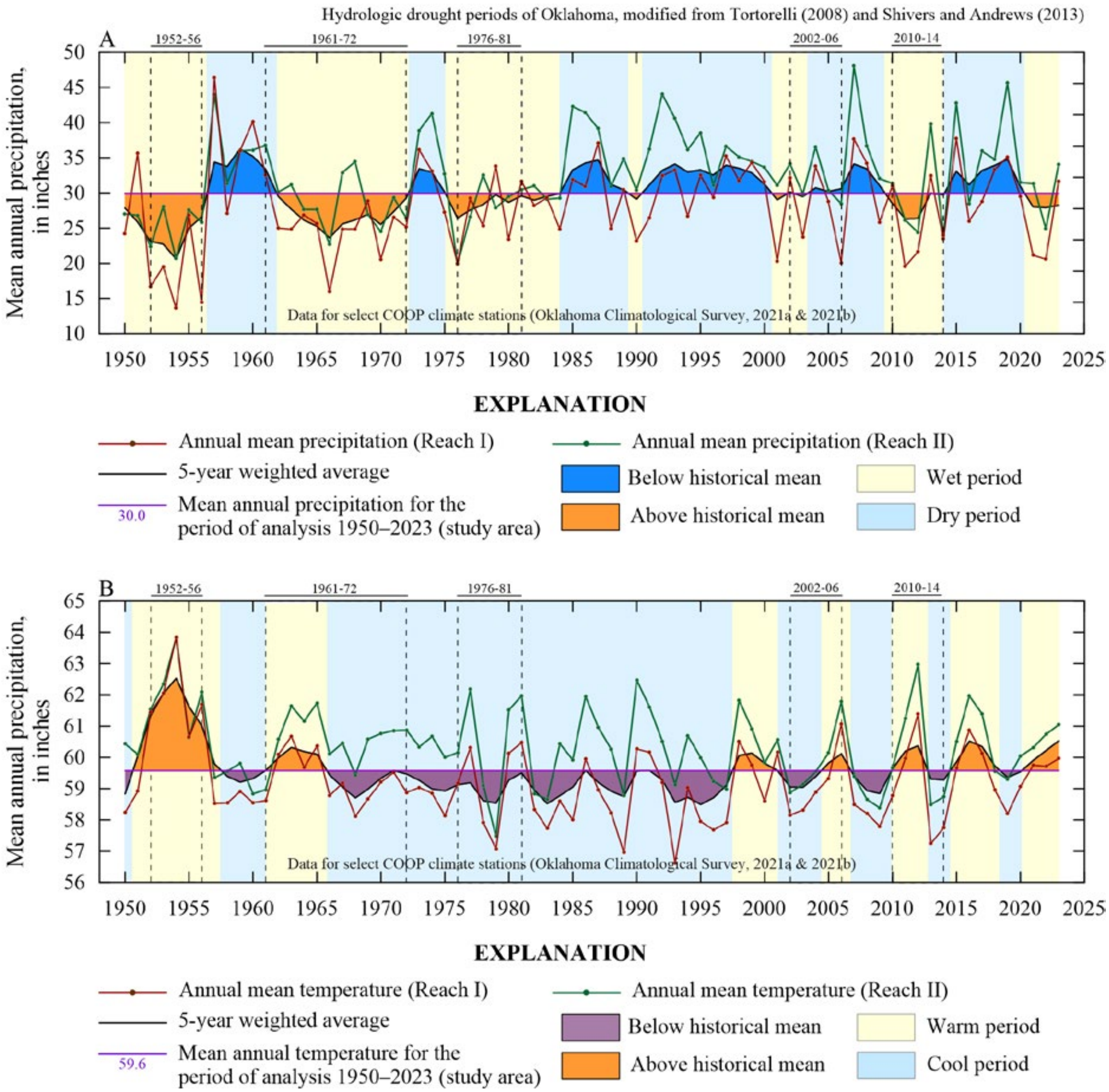

Figure AF2. Annual precipitation (A),and annual temperature (B) for Reaches I and II of the Cimarron River alluvium and terrace aquifer, northwestern Oklahoma for the period 1950–2023.

annual reported groundwater use in Reach II were 34,493 acre-feet in 1978 and 7,088 acre-feet in 1993, respectively (**Table AF2**).

Before 1980, groundwater use for irrigation was estimated using a sliding scale based on the number of acres irrigated and the number of times the crop was irrigated. Since 1980, permit holders have been required to also include the average amount of water (in inches) used during each application, which allowed irrigation volumes to be calculated directly, thereby reducing uncertainty in the annual estimates. The other water use categories (public supply; commercial; industrial; mining; agriculture; power; and recreation fish and wildlife) generally report annual groundwater usage in gallons based on either pumping rate multiplied by time pumped or electronic metering. In some cases, annual groundwater use for agriculture is reported as the number of cattle; annual use was calculated as the number of cattle multiplied by an average consumptive rate of 12 gallons per day for beef cows (Spencer and others, 2017).

Three periods were identified for detailed analysis based on trends in total reported groundwater use: 1970–1980, 1981–2009, and 2010–2023. The period 1970–80 is characterized by high annual water use, particularly in Reach II (**Figure AF3**). The increased annual water usage during this period corresponds with an increase in the number of active groundwater permits across both reaches from 144 in 1970 to 266 in 1980, which may have been the result of water availability concerns stemming from the prolonged periods

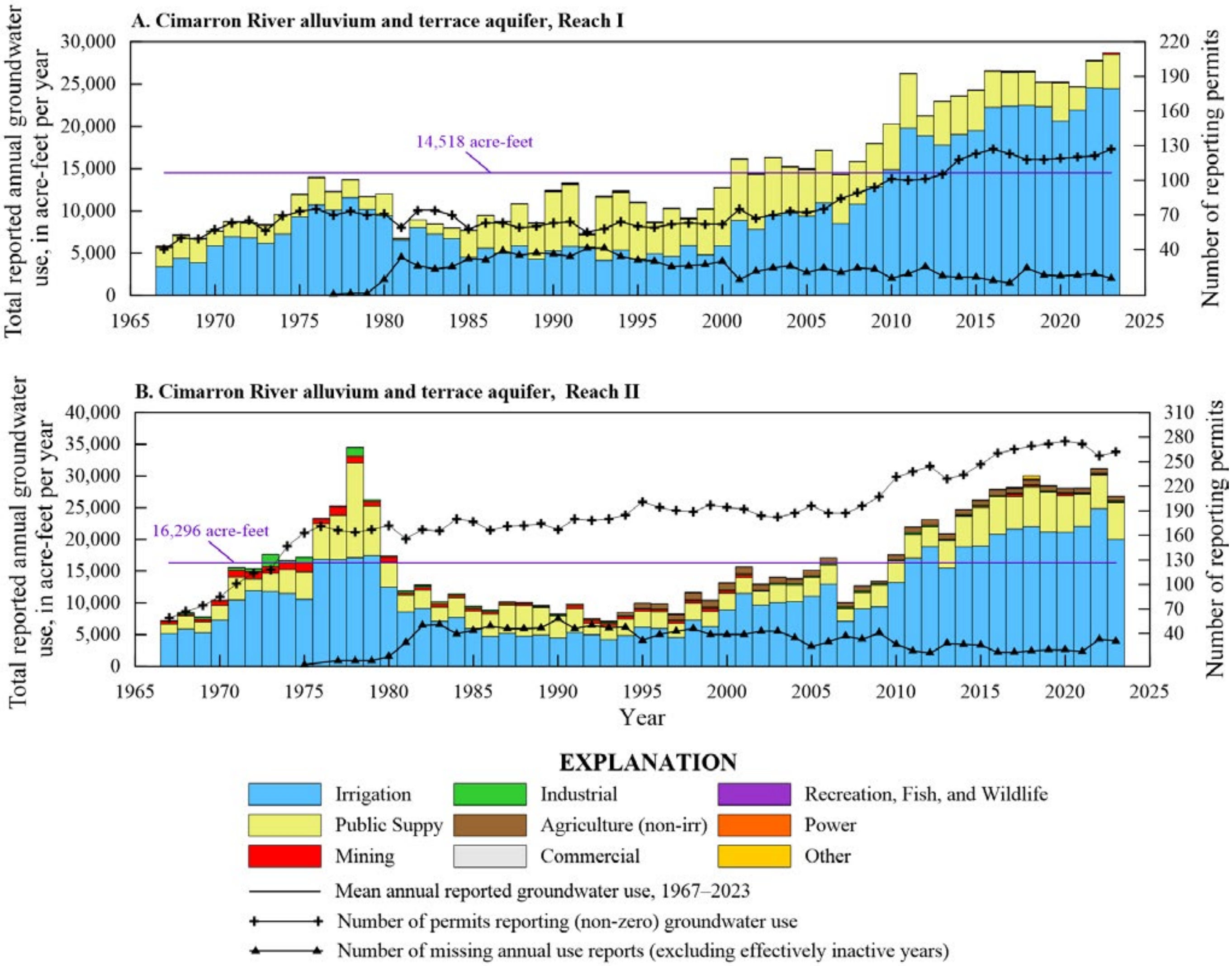

Figure AD3. Total reported annual groundwater use by water demand category, 1967–2023 for A. Reach I and B. Reach II of the Cimarron River alluvium and terrace aquifer, northwestern Oklahoma.

of below-average precipitation associated with the 1961–72 and 1975–81 hydrologic droughts (Shivers and Andrews 2013). Mean annual groundwater use for the period 1970–80 in Reach I was about 10,783 acre-feet per year, with a median of 11,696 acre-feet. Mean annual groundwater use for Reach II during the same period was about 19,953 acre-feet per year, with a median of 17,387 acre-feet (**Table AF2**).

The period 1981-2009 is characterized by relatively low irrigation usage in both reaches, with reported annual usage averaging 6,870.0 acre-feet per year in Reach I (about a 20 percent decline from the 1970–80 period [8,584 acre-feet per year]) and 7,306 acre-feet per year in Reach II (about a 44 percent decline from the 1970–80 period [13,113 acre-feet per year]). The decline in mean annual irrigation usage may have been related to the waning drought conditions across the state beginning in the mid-1980s and the start of an extended wet period between 1985–2002 (**Figure AF3**). Some of the decline in annual groundwater use during this period may be related to the number of missing annual use reports, which averaged about 29 per year in Reach I and 42 per year in Reach II. Mean annual groundwater use for the 1981-2009 period in Reach I was about 11,705 acre-feet per year, with a median of 11,057 acre-feet. Mean annual groundwater use for Reach II over the same period was about 11,141 acre-feet per year, with a median of 10,214 acre-feet (**Table AF2**).

The period 2010–23 is characterized by above-average annual water use in both reaches. During the five years of the 13-year period, groundwater use steadily increased in both reaches as the state entered into a 239-week-long drought period that lasted from November 2, 2010, until May 26, 2015—the most severe period of drought occurred in September 2011, when 80 percent of the state was enduring extreme drought conditions (National Integrated Drought Information System, 2020). Groundwater use peaked at 28,698 acre-feet in 2023 in Reach I and 31,146 acre-feet in 2022 in Reach II and was primarily the result of increased irrigation usage (**Figure AF3**). Mean annual groundwater use for the 2010–23 period in Reach I was about 24,978 acre-feet per year, with a median of 25,220 acre-feet. Mean annual groundwater use for Reach II over the same period was about

Table AF2. Summary statistics of total annual reported groundwater use from reaches I and II of the Cimarron River alluvium and terrace aquifer, 1967–2023.

[All units are in acre feet per year]

Period of record	Annual reported groundwater use			
	Mean	Median	Minimum	Maximum
Reach I				
1970–1980	10,783	11,696	7,631	13,986
1981–2009	11,705	11,057	6,748	17,965
2010–2023	24,978	25,220	20,269	28,698
1967–2023	14,518	12,358	5,788	28,698
Reach II				
1970–1980	19,953	17,387	10,423	34,493
1981–2009	11,141	10,214	7,088	17,084
2010–2023	25,928	27,361	17,549	31,146
1967–2023	16,296	13,799	7,088	34,493

25,928 acre-feet per year, with a median of 27,361 acre-feet (**Table AF2**). The relatively high volume of groundwater use during the 2010–23 period was in part attributable to an increase in the number of reporting permits from 376 in 2010 (across both reaches) to 439 in 2021. This period is also characterized by an overall decline in the number of missing annual use reports compared to the preceding three decades.

Irrigation is the predominant water-use category in both reaches, constituting 72.1 percent of mean annual groundwater use in Reach I and 69.8 percent in Reach II for the period 1967–2023 (**Figure AF4**; **Table AF3**). Public water supply was the second highest water-use category in both reaches, constituting 27.5 percent of mean annual groundwater use in Reach I and 23.5 percent in Reach II for the same period (**Figure AF4**; **Table AF3**). All other water-use categories collectively constituted about 0.4 percent of mean annual groundwater use in Reach I and 6.7 percent in Reach II. **Table AF3** lists reported mean annual groundwater use for selected periods by water-use category in the Cimarron River alluvium and terrace aquifer, 1967–2023.

The industrial, mining, recreation, and agriculture (non-irrigation) water-use categories were all greater in Reach II. Annual industrial use was greatest during the 1970–80 period, specifically the years 1973–75 and 1978 (**Figure AF3**); total mean annual industrial use was 551.8 acre-feet during 1970-80, 204.0 acre-feet during 1981–2009, and 178.4 acre-feet during 2010–23 (T**able AF3**). Annual mining use was greatest during the 1970-80 period (**Figure AF3**); total mean annual mining use was 1,027.9 acre-feet during 1970–80, 277.2 acre-feet during 1981–2009, and 127.2 acre-feet during 2010–23 (**Table AF3**). The decline in groundwater use for mining (most notable after 2001) can be attributed to the transition from long-term permits to provisional temporary permits by affiliates of the oil and gas industry (**Figure AF3**). The rise of non-irrigation agriculture groundwater use in the mid-1990s and onward can be attributed to the development of confined animal feeding operations within the study area, with most occurring in Reach II (**Figure AF3**); mean annual agriculture use was 452.3 acre-feet during 1981–2009, and 750.2 acre-feet during 2010–23 (**Table AF3**).

Baseflow Discharge

The lack of a stream gauging station near the confluence of Turkey Creek and the Cimarron River precluded direct estimations of mean annual baseflow for each reach using the baseflow separation method. Instead, baseflow discharge was approximated for each reach using a contributing area ratio discharge calculation, which was based on the assumption that baseflow discharge was proportional to the contributing area of each reach. As discussed in the Water Budget Method section of the main report, the mean annual baseflow from the total contributing area of the aquifer (1,137 square miles) was estimated to be about 200.0 cubic feet per second or about 144,808 acre-feet per year for the period 1974–2023. Using the contributing areas of the two reaches (see Recharge subsection), the mean annual baseflow was estimated to be

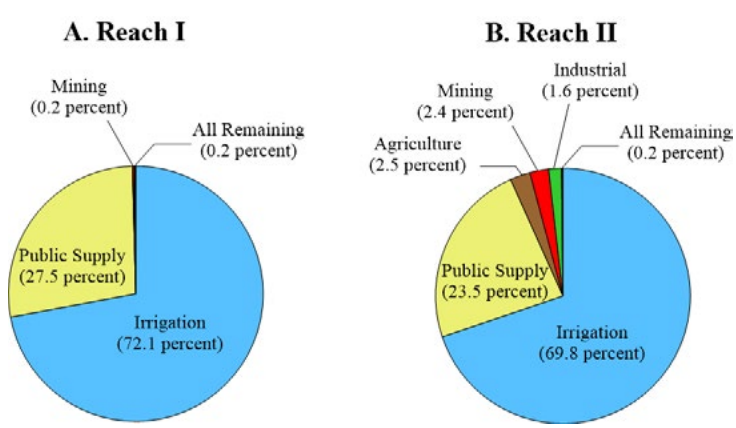

Figure AF4. Distribution of mean annual groundwater use for 1967–2023 by percentage for water demand categories for A. Reach I and B. Reach II of the Cimarron River alluvium and terrace aquifer, northwestern Oklahoma.

Table AF3. Mean annual reported groundwater use by water-use category from reaches I and II of the Cimarron River alluvium and terrace aquifer, 1967–2023.

[PWS, public water supply. All groundwater use estimates are in acre feet per year. Values in parenthesis are percentages of total mean annual groundwater usage]

Period of record	Water-use category								
	Irrigation	PWS	Industrial	Mining	Agriculture	Commercial	Power	Recreation	Other
Reach I									
1970–1980	8,583.5 (79.6)	2,158.8 (20.0)	8.3 (0.1)	25.1 (0.2)	6.1 (0.1)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	1.0 (0.0)
1981–2009	6,870.0 (58.7)	4,767.8 (40.7)	0.2 (0.0)	12.2 (0.1)	0.9 (0.0)	36.5 (0.3)	0.0 (0.0)	17.5 (0.1)	0.0 (0.0)
2010–2023	20,786.7 (83.2)	4,137.2 (16.6)	7.0 (0.0)	44.4 (0.2)	2.2 (0.0)	0.2 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
1967–2023	10,462.4 (72.1)	3,993.5 (27.5)	3.4 (0.0)	28.7 (0.2)	2.2 (0.0)	18.6 (0.1)	0.0 (0.0)	8.9 (0.1)	0.2 (0.0)
Reach II									
1970–1980	13,112.5 (65.7)	5,253.5 (26.3)	551.8 (2.8)	1,027.9 (5.2)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	7.4 (0.0)	0.0 (0.0)
1981–2009	7,305.9 (65.6)	2,889.8 (25.9)	204.0 (1.8)	277.2 (2.5)	452.3 (4.1)	0.0 (0.0)	0.0 (0.0)	10.6 (0.1)	0.7 (0.0)
2010–2023	19,717.3 (76.0)	5,069.9 (19.6)	178.4 (0.7)	127.2 (0.5)	750.2 (2.9)	0.2 (0.0)	0.0 (0.0)	39.3 (0.2)	45.3 (0.2)
1967–2023	11,376.1 (69.8)	3,822.6 (23.5)	264.3 (1.6)	389.7 (2.4)	414.4 (2.5)	0.1 (0.0)	0.0 (0.0)	16.9 (0.1)	11.5 (0.1)

about 84,978.5 acre-feet per year for Reach I and 59,829.5 acre-feet per year for Reach II.

Hydraulic Properties

As discussed in the Hydraulic Properties section of the main report, estimates of hydraulic conductivity and transmissivity were determined using slug tests, well drawdown specific capacity tests, a single multi-well pumping test, and the lithologic-log standardization method, while estimates of specific yield were determined from two multi-well pumping test, the regional method, and a non-linear relationship with hydraulic conductivity.

Hydraulic conductivity (K) is a measure of a porous material's capacity to transmit water and is defined as the rate of flow through a unit cross-sectional area of an aquifer under a unit hydraulic gradient (Lohman, 1972). Hydraulic conductivity varies depending on the physical properties of both the fluid (density and viscosity) and the porous material (permeability). Transmissivity (T) is the product of hydraulic conductivity and saturated thickness and is a measure of the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient (Lohman, 1972). Specific yield (Sy) is a measure of the amount of water yielded by gravity drainage from an unconfined aquifer and is defined as the ratio of the volume of water released from storage to the total volume of the aquifer (Lohman, 1972).

Of the 50 total sites visited as part of this investigation, 28 were located in Reach I and 22 were located in Reach II (**Figure 19**); multiple slug tests were conducted at each site. Estimated horizontal hydraulic conductivity (Kh) from 77 slug tests conducted in Reach I ranged from 2.8 to 468.0 feet per day, with a mean of 90.6 feet per day and a median of 52.8 feet per day (**Table AF4**). Estimated Kh from the 59 slug tests conducted in reach II ranged from 11.2 to 373.6 feet per day, with a mean of 131.9 feet per day and a median of 88.7 feet per day (**Table AF4**).

Of the 764 specific capacity test sites used for this investigation, 563 were located in Reach I and 201 were located in Reach II (**Figure 19**); most of the test sites were clustered within terrace deposits between Eagle Chief Creek and Indian Creek in Major County. Estimated Kh from specific capacity tests conducted in Reach I ranged from 0.8 to 473.4 feet per day, with a mean of 34.3 feet per day and a median of 17.6 feet per day, based on a Sy of 0.13 (**Table AF4**). Estimated Kh from specific capacity tests conducted in Reach II ranged from 0.2 to 525.9 feet per day, with a mean of 34.2 feet per day and a median of 21.7 feet per day based on a Sy of 0.13 (**Table AF4**).

Of the four pumping tests conducted in the aquifer, only Ames #5 and Cleo Springs #6 had testing conditions and results that were deemed reasonable. The Cleo Springs #6 pump test site is located in Reach I, about 6.2 miles west of the town of Cleo Springs, and the Ames #5 pump test site is located in Reach II, about 2.7 miles southwest of the town of Ames (**Figure 19**). The two pumping tests yielded transmissivity estimates of 2,000–2,850 feet squared per day and specific yield estimates of 0.08–0.14 (**Table 12**). Kh was estimated to be 56.5 feet per day at the Ames #5 site and 106.2 feet per day at the Cleo Springs #6 site. Both tests were conducted in terrace deposits of the Cimarron River. The regional method consisted of 35 well sites spatially distributed across the Eagle Chief sub-basin in Reach I. Monthly estimates of specific yield ranged from 0.04–0.11, with a mean of 0.07 (**Table 12**).

Of the 3,650 drillers logs used for the lithologic log standardization method, 1,579 were located in Reach I and 2,071 were located in Reach II. Horizontal hydraulic conductivity for all 3,650 wells ranged from 0.14 to 515.3 feet per day, with a mean of 58.4 feet per day and a median of 41.0 feet per day (**Table 12**). Kh for wells in Reach I ranged from 0.14 to 481.6 feet per day, with a mean of 61.2 feet per day and a median of 41.9 feet per day (**Table AF4**). Kh for wells in Reach II ranged from 0.14 to 515.3 feet per day, with a mean of 56.4 feet per day and a median of 40.69 feet per day (**Table AF4**). Estimates of horizontal hydraulic conductivity from slug tests, specific capacity tests, and the lithologic log standardization method were locally variable, with a mean of about 62 feet per day in reach I and about 75 feet per day in reach II. **Figure AF5** shows a spatially interpolated map of horizontal hydraulic conductivity for wells used in the lithologic log standardization method that fully penetrated (completed below the Qauternary-Permian contact) the aquifer; mean horizontal hydraulic conductivity in both reaches is about 60 feet per day from raster statistics.

Based on the nonlinear relationship with hydraulic conductivity (equation 10 in the main report; page 53), the estimated specific yield for all 3,650 wells ranged from 0.07 to 0.26, with a mean of 0.20 (**Table 12**). However, an estimated specific yield value of 0.13 was considered more appropriate for the aquifer based on values estimated from the multi-well aquifer tests conducted as part of this investigation, the multi-well aquifer tests conducted by previous investigators (**Table 11**), and the model-calibrated specific yield values for other alluvium and terrace aquifers in western Oklahoma. The specific yield values in both reaches were nearly identical, ranging from 0.05 to 0.17 when scaled to the aquifer mean of 0.13. However, spatially, the lowest specific yield values occurred along the northwestern edge of the aquifer boundary and in parts of Woods and Alfalfa counties. These areas are generally very thin, with little saturated thickness and generally more clay content. **Figure AF6** shows a spatially interpolated map of specific yield values for wells used in the lithologic log standardization method that fully penetrated the aquifer.

Estimates of horizontal hydraulic conductivity and specific yield were based on min-max ranges derived from published studies and aquifer tests conducted during the 2016–2023 period of investigation and were interpolated using the distance-weighted method of Shepard (1968). The interpolated hydraulic property maps represent mean horizontal hydraulic conductivity and specific yield for the vertical profile of sediments at each well, which vary in thickness. Because of this variability, wells that have a thick zone of coarse-grained sediments relative to the total thickness of the aquifer will appear to have a greater horizontal hydraulic conductivity value than wells that have a similarly thick zone of coarse-grained sediments but a greater aquifer thickness. To more accurately show how hydrologic properties vary with depth across the study area, horizontal hydraulic conductivity and specific yield should be interpolated spatially at equal depth intervals. However, it was beyond the scope of this hydrologic investigation to define such intervals.

Table AF4. Summary statistics for horizontal hydraulic conductivity and specific yield determined from slug tests, well drawdown tests, and the lithologic-log percent-coarse analysis, subdivided by reach in the Cimarron River alluvium and terrace aquifer.

[All units in feet per day]

Statistic	Slug tests		Drawdown tests		Percent-coarse analysis	
	Reach I	Reach II	Reach I	Reach II	Reach I	Reach II
Horizonal hydraulic conductivity (ft/day)						
Minimum	2.8	11.2	0.8	0.2	0.14	0.14
25th percentile	13.3	58.4	9.4	12.0	27.8	29.9
50th percentile	52.8	88.7	17.6	21.7	41.9	41.9
75th percentile	112.3	191.4	38.1	35.8	68.2	63.5
Maximum	468.0	373.6	473.4	525.9	481.6	515.3
Mean	90.6	131.9	34.3	34.2	61.2	56.4
Count	77.0	59.0	563.0	201.0	1,579.0	2,071.0

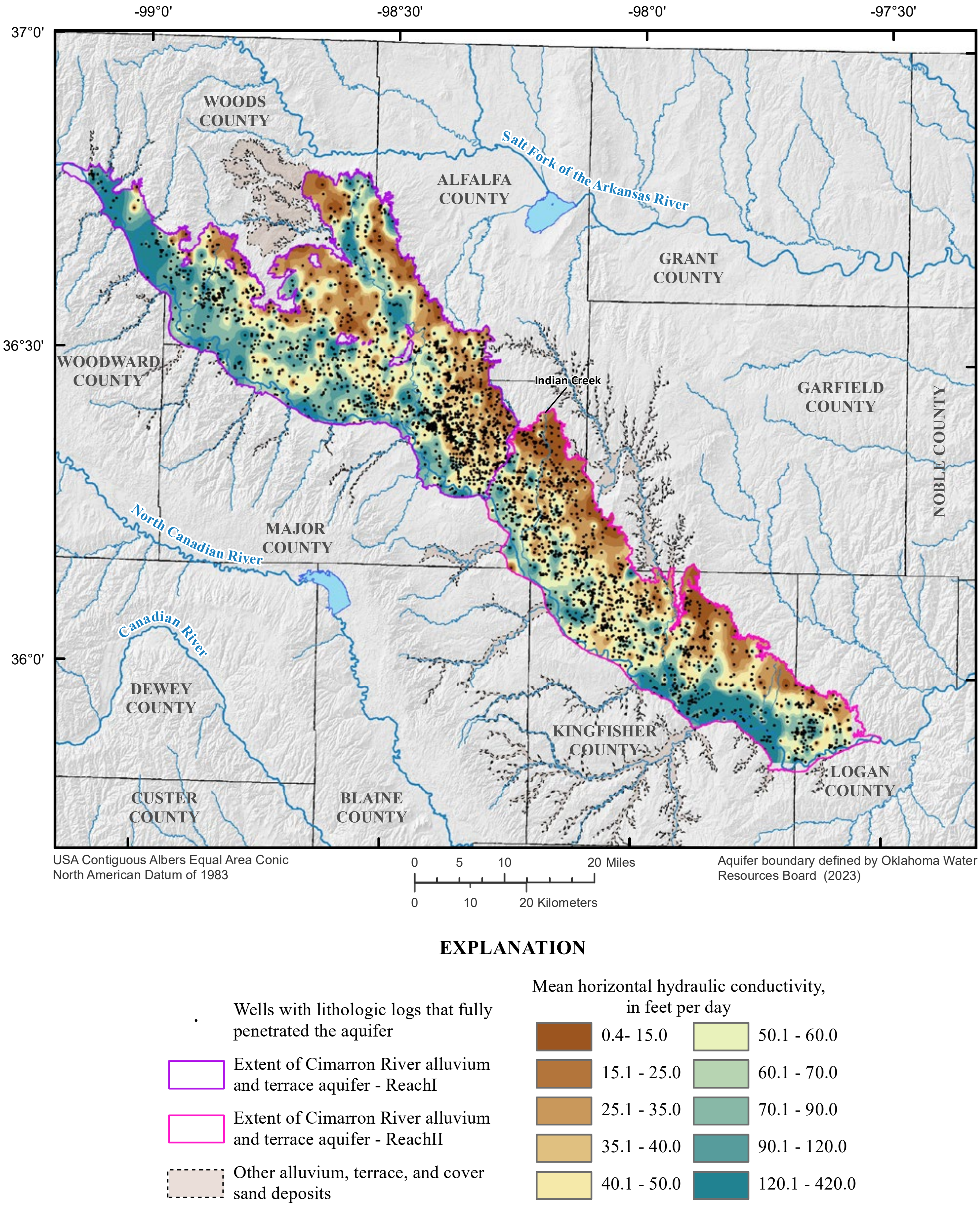

Figure AF5. Spatially interpolated mean horizontal hydraulic conductivity for the Cimarron River alluvium and terrace aquifer, northwestern Oklahoma, from the lithologic log standardization method of Mashburn and others (2013)

Saturated Thickness

As discussed in the Aquifer Saturated Thickness section of the main report, the saturated thickness of the Cimarron River alluvium and terrace aquifer was determined by subtracting the base altitude map (**Figure 13**) from the 2016 (**Figure 12**) potentiometric surface altitude map. The thickest areas occur in the central regions of the aquifer. Saturated thickness thins outward from these central regions toward the edges of the aquifer and the three major tributaries (Eagle Chief Creek, Indian Creek, and Turkey Creek) draining the aquifer (**Figure 14**). Saturated thickness along the three major tributaries ranges from 5–25 feet but averages less than 20 feet. The saturated thickness in Reach I ranged from less than 5 feet to 69 feet with a mean of 23 feet; in total, about 60 square miles had a saturated thickness of five feet or less. The saturated thickness of Reach II ranged from less than 5 feet to 93 feet with a mean of 29 feet; in total, about 50 square miles had a saturated thickness of five feet or less.

Recharge

As discussed in the Groundwater Recharge section of the main report, recharge is defined as the process by which surface water infiltrates the subsurface and becomes part of the groundwater flow system. Recharge to the Cimarron River alluvium and terrace aquifer primarily occurs through the deep percolation of precipitation, with irrigation return flow being considered the second largest source of recharge. Irrigation return flow as a percentage of withdrawn groundwater was not included as recharge but was instead deducted from mean annual irrigation use. The rate of recharge is difficult to quantify because it cannot be measured directly. For this reason, recharge is often estimated by multiple methods and the results are compared. Recharge to the two aquifer reaches was estimated using a water-budget method and a soil-water-balance method.

As discussed in the Water-Budget-Method section of the main report the water budget method is based on the assumption that an aquifer is in hydrologic equilibrium, wherein the rate of recharge is equal to the rate of discharge (Healy, 2010). Recharge was calculated by dividing the sum of the discharge components (evapotranspiration, baseflow discharge, and groundwater use) in each reach by the contributing drainage area of each reach. The total contributing drainage areas of Reach I and Reach II were estimated to be approximately 667 square miles (426,848 acres) and 470 square miles (300,524 acres), respectively, based on the potentiometric surface (**Figure 12**) and saturated thickness maps (**Figure 14**).

Evapotranspiration (ET) is the process by which water is transferred to the atmosphere directly by evaporation from the soil and surface-water bodies and indirectly by transpiration from plants, generally from the soil-moisture (unsaturated) zone. These soil-moisture-zone and surface-water components of ET were not considered part of the water budget because they occur before infiltrating precipitation has become groundwater recharge. For this analysis, ET from the saturated zone was quantified for areas of the aquifer where the water table likely intersects with the plant root zone. The area where the water table intersects the plant root zone is probably small compared to the full aquifer area and is primarily confined to the wetland areas along the Cimarron River and its major tributaries. About 7,510 acres of the active alluvium in Reach I and 7,650 acres in Reach II were classified as wetland (riverine, freshwater emergent, and freshwater forested/shrub) by the National Wetlands Inventory (NWI; U.S. Fish and Wildlife Service, 2023). Based on the 39 percent estimate for vegetation coverage used for the full aquifer, only about 2,972 acres in Reach I and 3,028 acres in Reach II were assumed to contribute to direct evapotranspiration from the saturated zone. Using an ET rate of 12 inches per year (Smith and others, 2021; Ellis and others, 2020), the vegetated wetland areas in each reach would correspond with annual outflows of 2,972 and 3,028 acre-feet per year, respectively, from the saturated zone.

A supplemental component of plant transpiration was estimated for forested areas within the active alluvium that were outside of the NWI-classified wetlands. The mean depth to water in these forested areas is about 12 feet below the land surface (based on drillers reports), with the highest tree densities occurring where the water table is shallowest and becoming more sparse as depth to water increases. Approximately 5.6 percent of the aquifer area (45,835 acres) was classified as dedicated forest land (**Figure 2**; National Agricultural Statistics Service, 2021); of this, about 2,154 acres in Reach I and 6,308 acres in Reach II exist outside of the wetland areas within the active alluvium of the Cimarron River and its major tributaries. Mogg and others (1960) estimated that the amount of groundwater used by cottonwoods and willows in a year would be about 5.4 acre-feet per acre if the tree density was 100 percent (no visible land between tree canopies). Based on the consumptive rate of 2.7 acre-feet per acre per year used for the full aquifer, the mean annual transpiration from forested areas in Reaches I and II were estimated to be about 5,816 and 17,032 acre-feet per year, respectively.

The mean annual reported groundwater use for the 1974–2023 period of record was estimated to be about 15,488 acre-feet per year in Reach I and 16,930 acre-feet per year in Reach II. Mean annual groundwater use for irrigation over the common period was about 11,177 acre-feet per year in Reach I and 11,816 acre-feet per year in Reach II. Assuming an irrigation return flow estimate of 12 percent (improved application efficiency), about 1,341 acre-feet per year in Reach I and 1,418 acre-feet per year in Reach II are returned to the aquifer.

Based on the values of mean annual saturated zone ET, forest area transpiration, baseflow discharge, and groundwater use, the mean annual recharge to the contributing area of Reach I was estimated to be about 107,914 acre-feet per year or about 3.03 inches per year (10.5 percent of mean annual precipitation [28.9 inches per year]) for the period 1974–2023; mean annual recharge is about 118,762 acre-feet

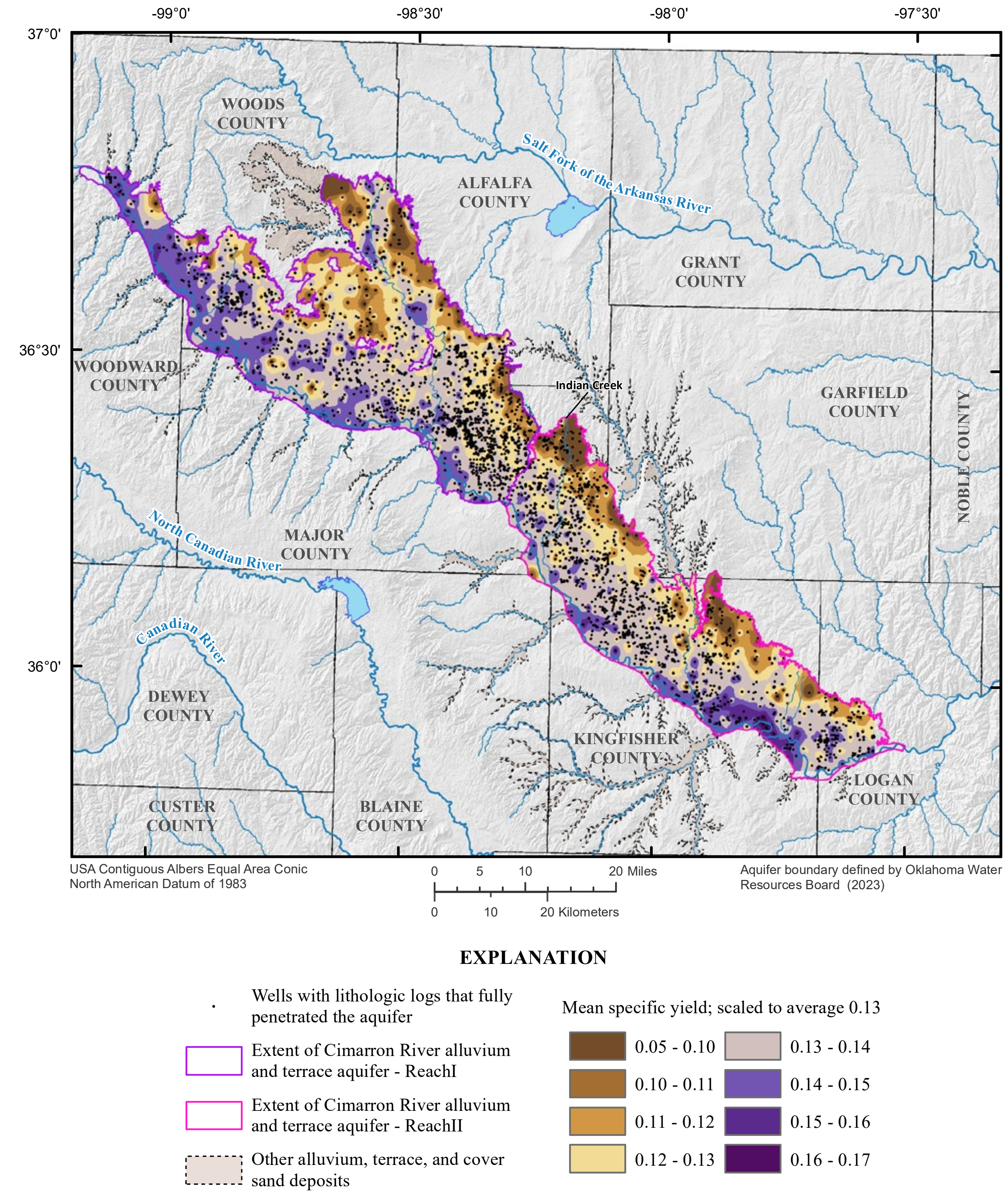

Figure AF6. Spatially interpolated mean specific yield for the Cimarron River alluvium and terrace aquifer, northwestern Oklahoma, from the lithologic log standardization method of Mashburn and others per year for the full Reach I area. The mean annual recharge to the contributing area of Reach II was estimated to be about 95,402 acre-feet per year or about 3.81 inches per year (11.3 percent of mean annual precipitation [33.6 inches per year]) for the period 1974–2023; mean annual recharge is about 110,701 acre-feet per year for the full Reach II area. A diagram of the water budget method is show in **Figure AF7**.

As discussed in the Soil-Water Balance Method section of the main report, the SWB code estimates spatial and temporal variations in recharge at the regional scale using tabular daily climate data (precipitation and minimum/maximum temperature), gridded landscape data (soil type, available soil-water capacity, and land use), and a properties matrix based on different combinations of soil type and land use (Westenbroek and others, 2010). The SWB code was used to estimate annual recharge for the period 1980–2023. Mean annual recharge rate for the period of analysis was about 3.13 inches per year (**Figure 18**). The SWB code was not run for each reach individually. Instead, annual recharge was determined for each reach by clipping the SWB recharge rasters to the areas of each reach. Mean annual recharge in Reach I varied from 0.20 inches in 2006 to 6.52 inches in 1993, with a mean of 2.73 inches per year (9.4 percent of mean annual precipitation [29.1 in/yr]) for the period 1980–2023 (**Figure AF8**). Mean annual recharge in Reach II varied from 0.25 inches in 2006 to 7.26 inches in 2019, with a mean of 3.66 inches per year (10.8 percent of mean annual precipitation [34.0 inches per year]) for the period 1980–2023 (**Figure AF8**). define such intervals.

Groundwater Storage

The amount of groundwater in storage in Reach I of the Cimarron River alluvium and terrace aquifer was estimated to be about 1.40 million acre-feet, based on the aquifer area of 734 square miles, the mean saturated thickness of 23 feet, and the specific yield value of 0.13. Varying the specific yield by ± 0.03 resulted in groundwater storage estimates of 1.08 and 1.73 million acre-feet, respectively. The amount of groundwater in storage in Reach II of the Cimarron River alluvium and terrace aquifer was estimated to be about 1.31 million acre-feet, based on the contributing area of 545 square miles, the mean saturated thickness of 29 feet, and the specific yield value of 0.13. Varying the specific yield by ± 0.03 resulted in groundwater storage estimates of 1.01 and 1.62 million acre-feet, respectively. These estimations were considered rough approximations of groundwater in storage because they were based on mean saturated thickness.

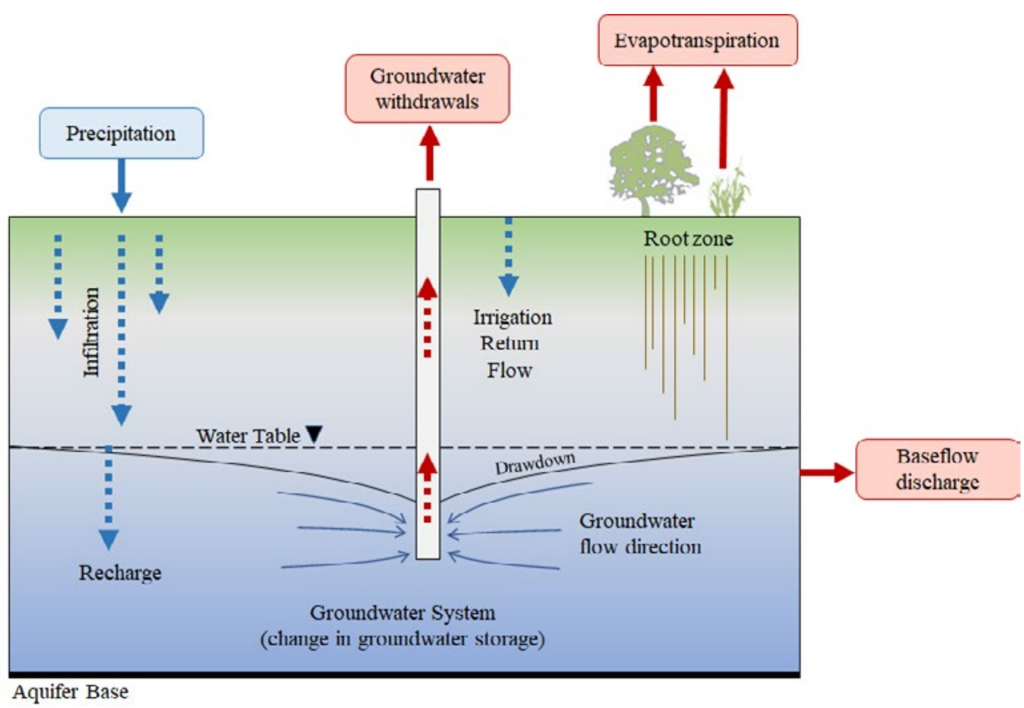

Figure AF7. Conceptual water budget model as used in this hydrologic investigation of the Cimarron River alluvium and terrace aquifer, northwestern Oklahoma.

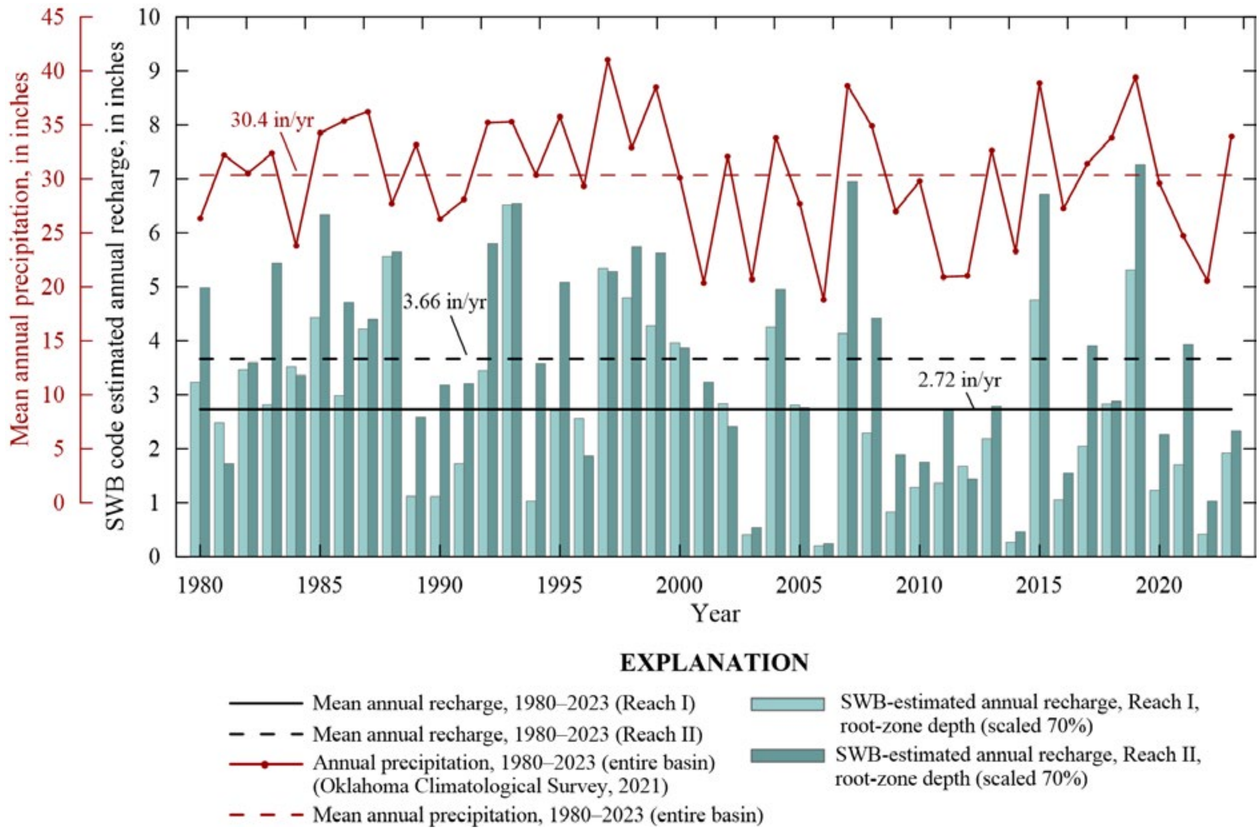

Figure AF8 Mean annual precipitation and recharge estimated using the Soil-Water-Balance code (SWB; Westenbroek and others, 2010) for reaches I and II the Cimarron River alluvium and terrace aquifer, 1980–2023.

Kind local farmer pulling two OWRB field trucks stuck in the sand back onto the road, October 27, 2017. Photograph taken by Derrick Wagner, Oklahoma Water Resources Baord.

Sand dunes in Little Sahara State Park, November 22, 2022. Photograph taken by Alan LePera, Oklahoma Water Resources Board.

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