

Prepared in cooperation with the Oklahoma Water Resources Board

Hydrogeologic Framework and Conceptual Groundwater-Flow Model of the Panhandle and Northwest Parts of the High Plains (Ogallala) Aquifer in Oklahoma, 1998–2022



Scientific Investigations Report 2026–5009

Cover.

Top left, Mesas overlooking northwest Oklahoma, September 22, 2022.

Top middle, A horned lizard found in the sand, August 23, 2023.

Top right, Nuclear magnetic resonance testing in the panhandle of Oklahoma, November 13, 2023.

Bottom left, Fields overlying the Ogallala aquifer, August 24, 2023.

Bottom right, A wellhead assembly by a fallow field in Oklahoma, October 10, 2022.

Top right photograph by Isaac Dale, formerly with U.S. Geological Survey (USGS).

Remaining photographs by Colin Baciocco, formerly with USGS.

Hydrogeologic Framework and Conceptual Groundwater-Flow Model of the Panhandle and Northwest Parts of the High Plains (Ogallala) Aquifer in Oklahoma, 1998–2022

By Amy S. Morris, Colin A. Baciocco, Isaac A. Dale, Chloe Codner, Ethan A. Kirby, Grant M. Graves, Derrick L. Wagner, Eric G. Fiorentino, Alan LePera, Jon E. Sanford, and Lara Joy

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Contents

Acknowledgments	iii
Abstract	1
Introduction.....	1
Purpose and Scope	2
Description of the Ogallala Aquifer Focus Area	8
Land Cover	8
Climate	8
Groundwater Use.....	13
Groundwater Levels in the Ogallala Aquifer Focus Area.....	17
Streamflow and Base-Flow Characteristics	17
Hydrogeology of the Ogallala Aquifer Focus Area.....	22
Structural Features.....	22
Cenozoic Geologic and Hydrogeologic Units.....	22
Mesozoic Geologic and Hydrogeologic Units.....	22
Paleozoic Geologic and Hydrogeologic Units.....	25
Groundwater Quality	25
Hydrogeologic Framework of the Ogallala Aquifer Focus Area	29
Ogallala Aquifer Focus Area Extent and Base.....	29
Potentiometric Surface and Saturated Thickness	29
Textural and Hydraulic Properties	33
Hydraulic Properties Estimated From Nuclear Magnetic Resonance.....	33
Hydraulic Properties Estimated From Slug Tests	34
Horizontal Hydraulic Conductivity Estimated From Lithologic Logs	35
Groundwater Storage	35
Conceptual Groundwater-Flow Model.....	36
Hydrologic Boundaries	36
Recharge	36
Groundwater-Use Regression	39
Soil-Water-Balance Code.....	39
Irrigation Return Flows	44
Well Withdrawals	44
Saturated-Zone Evapotranspiration	44
Streambed Seepage.....	46
Change in Groundwater Storage	46
Lateral Groundwater Flows.....	51
Vertical Leakage	51
Conceptual-Model Water Budget.....	51
Summary.....	52
References Cited.....	53

Figures

1. Map of the High Plains (Ogallala) aquifer study area showing selected data-collection stations and the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area	3
2. Map showing land- and cropland-cover types over the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area, 2022.....	9
3. Graphs showing distribution of land- and cropland-cover types in the Ogallala aquifer focus area and the panhandle and northwest parts of the Ogallala aquifer, Oklahoma, 2022	10
4. Graphs showing annual mean precipitation and annual mean air temperature, panhandle part of the Ogallala aquifer, Oklahoma, 1915–2022	11
5. Graphs showing annual mean precipitation and annual mean air temperature, northwest part of the Ogallala aquifer, Oklahoma, 1915–2022	12
6. Map showing dedicated land areas and wells with permitted groundwater use in the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area, 2024	14
7. Graphs showing mean annual reported groundwater use and annual reported groundwater use by category, panhandle part of the Ogallala aquifer, Oklahoma, 1967–2022	15
8. Graphs showing mean annual reported groundwater use and annual reported groundwater use by category, northwest part of the Ogallala aquifer, Oklahoma, 1967–2022	16
9. Graph showing groundwater-level data from U.S. Geological Survey (USGS) continuous groundwater-level recorder well USGS 363033101440701 01N-12E-35 BDD 1 Texhoma GW Well, Oklahoma	18
10. Graph showing groundwater-level data from U.S. Geological Survey (USGS) continuous groundwater-level recorder well USGS 361739099323301 21N-22W-15 CAD Woodward 15, Oklahoma.....	18
11. Graphs showing annual streamflow, annual base flow, and annual base-flow index for U.S. Geological Survey (USGS) streamgage 07234000 Beaver River at Beaver, Oklahoma, and USGS streamgage 07156900 Cimarron River near Forgan, Oklahoma	20
12. Graphs showing annual streamflow, annual base flow, and annual base-flow index for U.S. Geological Survey (USGS) streamgage 07236000 Wolf Creek near Fargo, Oklahoma, and USGS streamgage 07235600 Wolf Creek near Gage, Oklahoma	21
13. Map showing surficial extent of geologic units in the High Plains (Ogallala) aquifer study area, southeastern Colorado, southwestern Kansas, northeastern New Mexico, northwestern Oklahoma, and northwestern Texas.....	23
14. Stratigraphic chart showing surficial geologic and hydrogeologic units in the Ogallala aquifer study area, southeastern Colorado, southwestern Kansas, northeastern New Mexico, northwestern Oklahoma, and northwestern Texas	24
15. Trilinear diagram showing major cation and anion concentrations in water produced from the panhandle part of the Ogallala aquifer, Oklahoma, 1958–2021	27
16. Trilinear diagram showing major cation and anion concentrations in water produced from the northwest part of the Ogallala aquifer, Oklahoma, 1951–2019.....	28
17. Map showing the altitude of the base of the Ogallala aquifer in the Ogallala aquifer focus area, Oklahoma	30

18.	Map showing potentiometric surface contours and general direction of groundwater flow within the Ogallala aquifer focus area, Oklahoma, March 2021	31
19.	Map showing estimated saturated thickness of the Ogallala aquifer in the Ogallala aquifer focus area, Oklahoma, March 2021	32
20.	Graph showing distribution of estimated horizontal hydraulic conductivity values calculated from lithologic logs in the Ogallala aquifer focus area, Oklahoma....	36
21.	Graph showing estimated mean annual inflows and outflows by hydrologic boundary for the conceptual groundwater-flow model of the panhandle and northwest parts of the Ogallala aquifer, Oklahoma, 1998–2022	38
22.	Graph showing relation between annual groundwater use and average annual groundwater-level change in the Ogallala aquifer focus area, Oklahoma, 1988–2019	42
23.	Graphs showing annual precipitation and annual recharge estimated by using the Soil-Water-Balance code in the panhandle part of the Ogallala aquifer, the northwest part of the Ogallala aquifer, and the Ogallala aquifer focus area, Oklahoma, 1998–2022	43
24.	Map showing spatially distributed mean annual recharge for the 1998–2022 study period estimated by using the Soil-Water-Balance code for the High Plains (Ogallala) aquifer study area, southeastern Colorado, southwestern Kansas, northeastern New Mexico, northwestern Oklahoma, and northwestern Texas.....	45
25.	Map showing seepage-run measurements for selected streams that overlie the Ogallala aquifer focus area, Oklahoma, January 17–26, 2023.....	47
26.	Graph showing observed number of no-flow days for selected continuous-record streamgages in the Ogallala aquifer focus area, Oklahoma, 1998–2022.....	48
27.	Map showing groundwater-level changes in the Ogallala aquifer focus area, Oklahoma, predevelopment–2019.....	49
28.	Map showing groundwater-level changes in the Ogallala aquifer focus area, Oklahoma, 1998–2019.....	50

Tables

1.	Selected data-collection stations in the High Plains (Ogallala) aquifer study area, southeastern Colorado, southwestern Kansas, northeastern New Mexico, northwestern Oklahoma, and northwestern Texas	4
2.	Summary statistics of reported annual groundwater use in the panhandle part of the Ogallala aquifer, Oklahoma, 1967–2022.....	17
3.	Summary statistics of reported annual groundwater use in the northwest part of the Ogallala aquifer, Oklahoma, 1967–2022.....	17
4.	Mean annual streamflow, base flow, and base-flow index values for selected U.S. Geological Survey streamgages during the streamgage periods of record and the study period (1998–2022) in the High Plains (Ogallala) aquifer study area, Oklahoma	19
5.	Summary of saturated thickness and total groundwater storage for the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area, March 2021	33
6.	Hydraulic properties for the saturated zone of the Ogallala aquifer derived from nuclear magnetic resonance measurements from selected wells in the Ogallala aquifer focus area, Oklahoma, November 2023.....	34

7.	Hydraulic properties for the Ogallala aquifer derived from slug-test measurements from selected wells in the Ogallala aquifer focus area, Oklahoma, 2023	35
8.	Conceptual groundwater-flow model water budget of estimated mean annual inflows and outflows for the hydrologic boundaries for the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area, 1998–2022.....	37
9.	Summary of recharge rates for the High Plains (Ogallala) aquifer study area from previously published reports, modified from Stanton and others (2011).....	40
10.	Summary of mean annual recharge estimated by using the Soil-Water-Balance code for the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area, 1998–2022.....	44
11.	Summary of change in groundwater storage for the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area, predevelopment–2019 and 1998–2019	51

Conversion Factors

U.S. customary units to International System of Units

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

Temperature in degrees Celsius ($^{\circ}\text{C}$) may be converted to degrees Fahrenheit ($^{\circ}\text{F}$) as follows:
 $^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$.

Temperature in degrees Fahrenheit ($^{\circ}\text{F}$) may be converted to degrees Celsius ($^{\circ}\text{C}$) as follows:
 $^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$.

Datums

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

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

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

Supplemental Information

Specific conductance is in microsiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$ at 25°C).

Concentrations of chemical constituents in water are in milligrams per liter (mg/L).

Abbreviations

BFI	base-flow index
DEM	digital elevation model
EPS	equal-proportionate-share
MAY	maximum annual yield
NMR	nuclear magnetic resonance
OWRB	Oklahoma Water Resources Board
SWB	Soil-Water-Balance (code)
TDS	total dissolved solids
USGS	U.S. Geological Survey

Hydrogeologic Framework and Conceptual Groundwater-Flow Model of the Panhandle and Northwest Parts of the High Plains (Ogallala) Aquifer in Oklahoma, 1998–2022

By Amy S. Morris,¹ Colin A. Baciocco,¹ Isaac A. Dale,¹ Chloe Codner,¹ Ethan A. Kirby,¹ Grant M. Graves,¹ Derrick L. Wagner,² Eric G. Fiorentino,² Alan LePera,² Jon E. Sanford,² and Lara Joy²

Abstract

This study was conducted by the U.S. Geological Survey, in cooperation with the Oklahoma Water Resources Board, to update the hydrogeologic framework and conceptual flow model for the panhandle and northwest parts of the High Plains (Ogallala) aquifer in Oklahoma, which together compose the Ogallala aquifer focus area. The study included the construction of a potentiometric surface, and available geologic and hydrologic data were used to evaluate saturated thickness of the aquifer. The water budget for the updated conceptual groundwater-flow model was based on estimated inflows and outflows for the 1998–2022 study period.

Saturated thickness of the Ogallala aquifer averaged 127 and 116 feet for the panhandle and northwest parts, respectively. Groundwater withdrawals from the Ogallala aquifer for 1998–2022 averaged 422,054 and 39,645 acre-feet per year (acre-ft/yr) for the panhandle and northwest parts, respectively. Recharge, the primary inflow, was estimated at 0.63 inch per year for the 1998–2022 study period, with the panhandle part of the Ogallala aquifer receiving 175,068 acre-ft/yr and the northwest part of the Ogallala aquifer receiving 49,376 acre-ft/yr. Additional inflows included irrigation return flows, estimated at 8,111 and 642 acre-ft/yr for the panhandle and northwest parts, respectively, of the Ogallala aquifer. Net lateral groundwater flows, considered to be aquifer outflows, were estimated to account for 31,908 acre-ft/yr for the Ogallala aquifer focus area. Streambed seepage, which was an outflow of 5,535 acre-ft/yr, was only present in the northwest part of the Ogallala aquifer. Vertical leakage and saturated-zone evapotranspiration were considered negligible outflows. These findings provide a revised conceptual groundwater-flow model water budget for the Ogallala aquifer focus area in Oklahoma.

Introduction

The 1973 Oklahoma Groundwater Law (Oklahoma Statute § 82-1020.5 [Oklahoma State Legislature, 2021a]) requires the Oklahoma Water Resources Board (OWRB) to conduct hydrologic investigations of the State's aquifers (referred to as “groundwater basins” in the statutes) to support a determination of the maximum annual yield (MAY) for each aquifer. The MAY is defined as the amount of fresh groundwater that can be withdrawn annually while ensuring a minimum 20-year life of the aquifer (OWRB, 2012, 2024a). For bedrock aquifers, the groundwater-basin-life requirement is satisfied if, after 20 years of MAY withdrawals, 50 percent of the groundwater basin (hereinafter referred to as an “aquifer”) retains a saturated thickness of at least 15 feet (ft). Although 20 years is the minimum period required by law, the OWRB may consider multiple management scenarios. The MAY is divided by the total land area overlying the aquifer to determine the annual volume of groundwater allocated per acre of land, or the equal-proportionate-share (EPS) pumping rate. The annual volume of water allocated to a given groundwater permit applicant is therefore proportional to the land area overlying the aquifer that is owned or leased by a permit applicant.

The High Plains aquifer is a generally unconfined shallow bedrock aquifer in the central United States that underlies parts of eight states: Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (fig. 1). Most of the High Plains aquifer in Oklahoma is part of a lobe of the aquifer that extends from the Arkansas River to the Canadian River and includes parts of southeastern Colorado, southwestern Kansas, northeastern New Mexico, northwestern Oklahoma, and northern panhandle of Texas (fig. 1). The OWRB (as well as water-regulating agencies in neighboring States) refers to most of the High Plains aquifer as the “Ogallala aquifer” (OWRB, 2024b; Kansas Geological Survey, 2026; Texas Water Development Board, 2026). Consequently, this report uses “Ogallala aquifer” when referring to the High Plains aquifer in Oklahoma. For purposes of permitting, the OWRB has divided the Ogallala

¹U.S. Geological Survey.

²Oklahoma Water Resources Board.

2 Hydrogeologic Framework and Conceptual Groundwater-Flow Model, High Plains (Ogallala) Aquifer, Oklahoma, 1998–2022

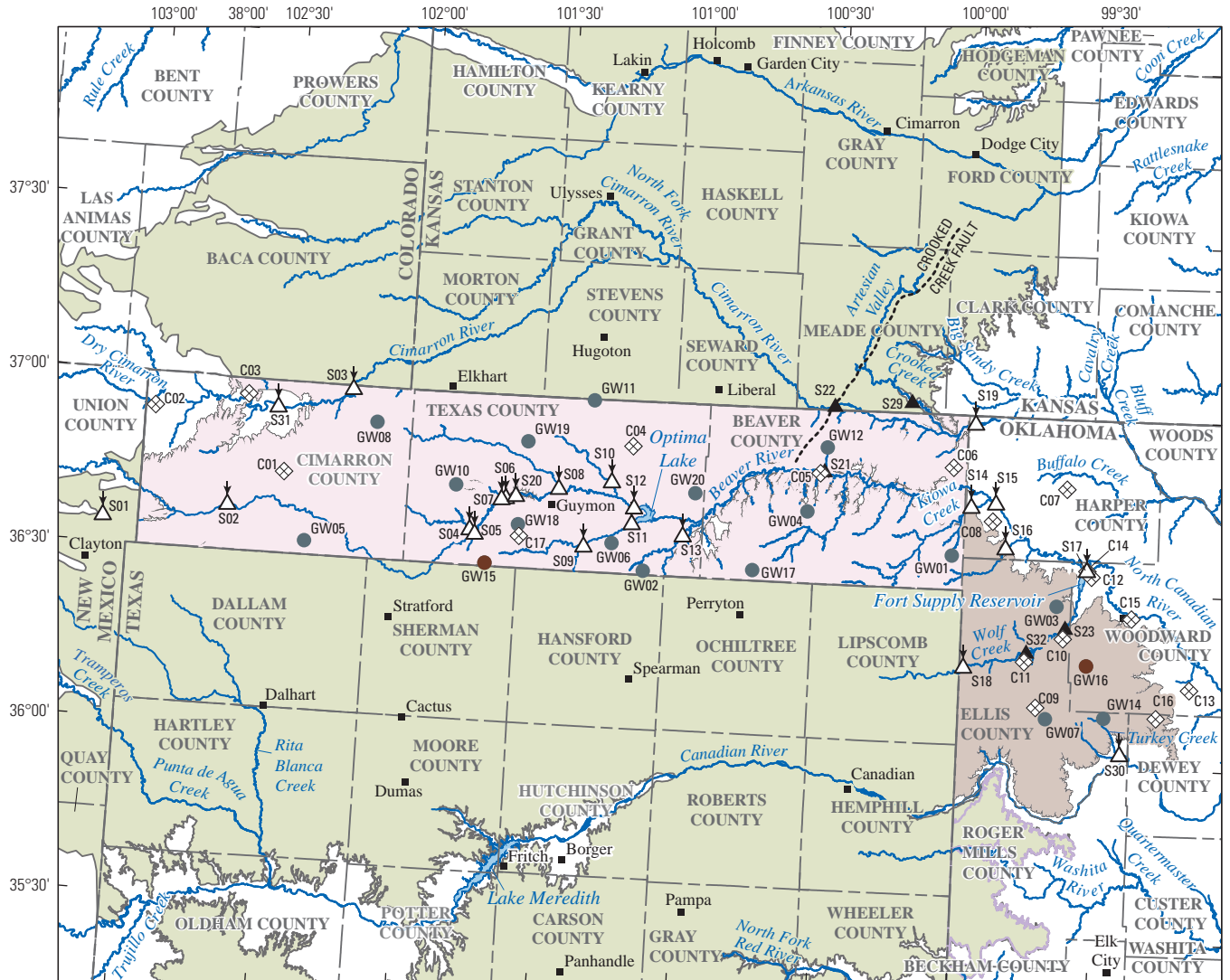
aquifer into three parts: panhandle, northwest, and Roger Mills (OWRB, 2012). The panhandle part encompasses the Ogallala aquifer in Beaver, Cimarron, and Texas Counties, Okla. The northwest part encompasses the Ogallala aquifer in Dewey, Ellis, Harper, and Woodward Counties, Okla. The Roger Mills part encompasses only the Ogallala aquifer in Roger Mills County, Okla.

The OWRB issued final orders on March 12, 2002, that established MAYs and EPS pumping rates for the panhandle part and the northwest part of the Ogallala aquifer. For the panhandle part of the Ogallala aquifer, the MAY was established at 6,773,760 acre-feet per year (acre-ft/yr), and the EPS pumping rate was determined to be 2.0 acre-feet per acre per year (acre-ft/acre/yr) (Grady Grandstaff, Oklahoma Water Resources Board, written commun., 2002). For the northwest part of the Ogallala aquifer, the MAY was established at 1,189,500 acre-ft/yr, and the EPS pumping rate was determined to be 1.4 acre-ft/acre/yr (Grady Grandstaff, Oklahoma Water Resources Board, written commun., 2002). These MAY and EPS values were based on a hydrologic investigation completed by Luckey and Becker (1999) who used a numerical groundwater-flow model to evaluate the effects of potential groundwater withdrawals on groundwater availability in the Ogallala aquifer. The OWRB completed a hydrologic investigation (Belden and Osborn, 2002) of the Roger Mills part of the Ogallala aquifer but has not yet established MAY and EPS values for that part of the Ogallala aquifer (Sanford, 2023). The OWRB is statutorily required to periodically update the hydrologic investigations on which the MAY determinations were based (OWRB, 2024a). Because more than 20 years have elapsed since the March 12, 2002, final orders, the U.S. Geological Survey (USGS), in cooperation with the OWRB, carried out a hydrologic investigation to update the hydrogeologic framework and

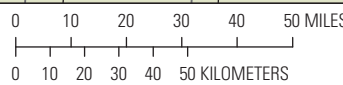
conceptual flow model for the panhandle and northwest parts of the Ogallala aquifer. Data associated with this report are available in the associated data release (Codner and others, 2026).

Purpose and Scope

The purposes of this report are to (1) provide an updated summary of the hydrogeology and hydrogeologic framework of the panhandle and northwest parts of the Ogallala aquifer and (2) describe the development of a conceptual groundwater-flow model and water budget representing the study period 1998–2022. This report uses the terms “High Plains (Ogallala) aquifer study area” (hereinafter referred to as “study area”) and “Ogallala aquifer focus area” for specific purposes. The study area (fig. 1) includes most of the High Plains aquifer extent between the Arkansas and Canadian Rivers and contains some data-collection stations (table 1) that may be outside of the aquifer extent. The Ogallala aquifer focus area (fig. 1) is equivalent to the combined extents of the panhandle and northwest parts of the Ogallala aquifer and includes all or parts of Beaver, Cimarron, Dewey, Ellis, Harper, Texas, and Woodward Counties in Oklahoma. Although the analysis described in this report is primarily centered on the Ogallala aquifer focus area, data and influences from the wider High Plains aquifer in the study area were also included in the analysis. Likewise, although the analysis described in this report is primarily centered on the 1998–2022 study period, data collected outside of the study period also were used to inform the conceptual groundwater-flow model and water budget.



Base from U.S. Geological Survey (USGS) 1:2,200,000-scale digital data, 2015
 Albers Equal-Area Conic,
 USGS contiguous United States projection
 North American Datum of 1983



Ogallala aquifer boundary modified from Qi (2010) and Oklahoma Water Resources Board (OWRB; 2024b)
 Hydrography from Horizon Systems Corporation (2015)

EXPLANATION

- High Plains aquifer
- Ogallala aquifer focus area**
- Panhandle part of the Ogallala aquifer
- Northwest part of the Ogallala aquifer
- Boundary of Roger Mills part of the Ogallala aquifer in Oklahoma
- Climate station (Oklahoma Climatological Survey, 2023; National Centers for Environmental Information, 2023) and map identifier (table 1)
- S22 **USGS continuous-record streamgauge (USGS, 2024a) with map identifier (table 1)**
- S01 **USGS discrete streamflow measurement site (USGS, 2024a) with map identifier (table 1)**
- GW05 **Continuous-recorder well (OWRB, 2024c) with map identifier (table 1)**
- GW15 **Continuous-recorder well (USGS, 2024a) with map identifier (table 1)**

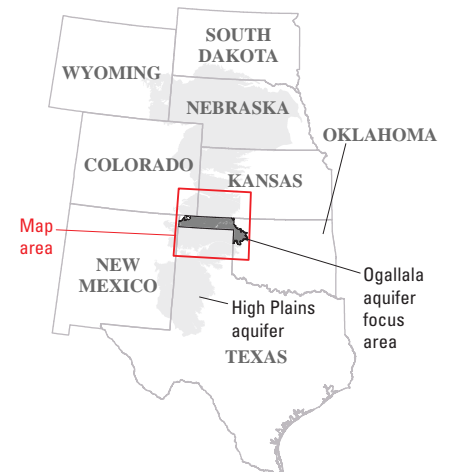


Figure 1. Map of the High Plains (Ogallala) aquifer study area showing selected data-collection stations and the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area.

Table 1. Selected data-collection stations in the High Plains (Ogallala) aquifer study area, southeastern Colorado, southwestern Kansas, northeastern New Mexico, northwestern Oklahoma, and northwestern Texas.

[U.S. Geological Survey (USGS) data can be accessed by using the 8- or 15-digit station number or other identifier. Dates are in month/day/year format. NAVD 88, North American Vertical Datum of 1988; --, unknown or not applicable; OWRB, Oklahoma Water Resources Board]

Station name	Map identifier (fig. 1)	Station number	Latitude (decimal degrees NAD 83)	Longitude (decimal degrees NAD 83)	County	Period of record (may contain gaps) or single measurement date		Land-surface altitude (feet above NAVD 88)	Well or hole depth (feet below land surface)
						Begin	End		
Discrete streamflow measurement sites (USGS, 2024a)									
Seneca Creek at State Rd 18, near Clayton, N. Mex.	S01	363426103074610	36.5739	-103.1299	Union	01/17/2023	--	--	--
Beaver River near Felt, Okla.	S02	07232250	36.6297	-102.6815	Cimarron	01/17/2023	--	--	--
Cimarron River near Keyes, Okla.	S03	07155570	36.9835	-102.2505	Cimarron	01/18/2023	--	--	--
Beaver (Sand) Creek near Texhoma, Okla.	S04	07232400	36.6022	-101.7976	Texas	01/18/2023	--	--	--
Beaver River near Texhoma, Okla.	S05	07232405	36.5905	-101.7786	Texas	01/18/2023	--	--	--
Beaver River near Eva, Okla.	S06	07232460	36.6978	-101.6729	Texas	01/18/2023	--	--	--
Tepee Creek near Goodwell, Okla.	S07	07232455	36.6942	-101.6884	Texas	01/18/2023	--	--	--
Goff Creek N. of Guymon, Okla.	S08	07232585	36.7334	-101.4824	Texas	01/18/2023	--	--	--
Coldwater Creek near Guymon, Okla.	S09	07232900	36.572	-101.3815	Texas	01/18/2023	--	--	--
Poney Creek near Optima, Okla.	S10	07232620	36.7609	-101.2909	Texas	01/18/2023	--	--	--
Coldwater Creek near Hardesty, Okla.	S11	07233000	36.6439	-101.2109	Texas	01/18/2023	--	--	--
Beaver River near Hooker, Okla.	S12	07232630	36.6895	-101.2057	Texas	01/18/2023	--	--	--
Palo Duro Creek near Range, Okla.	S13	07233700	36.6167	-101.0237	Texas	01/18/2023	--	--	--
Kiowa Creek near Laverne, Okla.	S14	07234255	36.7378	-99.9797	Harper	01/18/2023	--	--	--

Table 1. Selected data-collection stations in the High Plains (Ogallala) aquifer study area, southeastern Colorado, southwestern Kansas, northeastern New Mexico, northwestern Oklahoma, and northwestern Texas.—Continued

[U.S. Geological Survey (USGS) data can be accessed by using the 8- or 15-digit station number or other identifier. Dates are in month/day/year format. NAVD 88, North American Vertical Datum of 1988; --, unknown or not applicable; OWRB, Oklahoma Water Resources Board]

Station name	Map identifier (fig. 1)	Station number	Latitude (decimal degrees NAD 83)	Longitude (decimal degrees NAD 83)	County	Period of record (may contain gaps) or single measurement date		Land-surface altitude (feet above NAVD 88)	Well or hole depth (feet below land surface)
						Begin	End		
Discrete streamflow measurement sites (USGS, 2024a)—Continued									
Beaver River near Laverne, Okla.	S15	07234260	36.7503	-99.8912	Harper	01/18/2023	--	--	--
Clear Creek near May, Okla.	S16	07234300	36.6228	-99.8504	Harper	01/18/2023	--	--	--
Wolf Creek near Fort Supply, Okla.	S17	07237000	36.5667	-99.5518	Woodward	01/18/2023	--	--	--
Wolf Creek near State Line near Shattuck, Okla.	S18	07235490	36.278	-99.9862	Ellis	01/18/2023	--	--	--
Cimarron River near Englewood, Kans.	S19	07157580	36.9773	-99.9759	Harper	01/26/2023	--	--	--
Beaver River near Goodwell, Okla.	S20	07232470	36.7059	-101.6368	Texas	01/23/2023	--	--	--
Turkey Creek near Camargo, Okla.	S30	07228220	36.0417	-99.4087	Ellis	01/26/2023	--	--	--
Cimarron River near Boise City, Okla.	S31	07155500	36.9189	-102.5196	Cimarron	01/17/2023	--	--	--
Continuous-record streamgages (USGS, 2024a)									
Beaver River at Beaver, Okla.	S21	07234000	36.8222	-100.5193	Beaver	10/14/1937	2024	--	--
Cimarron River near Forgan, Okla.	S22	07156900	37.0111	-100.4918	Meade	10/01/1965	2024	--	--
Wolf Creek near Fargo, Okla.	S23	07236000	36.3992	-99.6232	Ellis	10/15/1942	05/26/1976	--	--
Crooked Creek near Englewood, Kans.	S29	07157500	37.0325	-100.2112	Meade	10/01/1942	2024	--	--
Wolf Creek near Gage, Okla.	S32	07235600	36.3266	-99.7611	Ellis	11/06/2009	2024	--	--

Table 1. Selected data-collection stations in the High Plains (Ogallala) aquifer study area, southeastern Colorado, southwestern Kansas, northeastern New Mexico, northwestern Oklahoma, and northwestern Texas.—Continued

[U.S. Geological Survey (USGS) data can be accessed by using the 8- or 15-digit station number or other identifier. Dates are in month/day/year format. NAVD 88, North American Vertical Datum of 1988; --, unknown or not applicable; OWRB, Oklahoma Water Resources Board]

Station name	Map identifier (fig. 1)	Station number	Latitude (decimal degrees NAD 83)	Longitude (decimal degrees NAD 83)	County	Period of record (may contain gaps) or single measurement date		Land- surface altitude (feet above NAVD 88)	Well or hole depth (feet below land surface)
						Begin	End		
Continuous groundwater-level recorder wells (OWRB, 2024c; USGS, 2024a)									
OWRB-349	GW01	349	36.5976	−100.0443	Beaver	11/30/2022	2024	2,457.6	260
OWRB-927	GW02	927	36.5111	−101.1616	Texas	11/29/2022	2024	1,938.7	240
OWRB-3270	GW03	3270	36.4627	−99.6569	Ellis	11/29/2022	2024	2,188.1	260
OWRB-9051	GW04	9051	36.7056	−100.5755	Beaver	11/29/2022	2024	2,757.2	180
OWRB-24401	GW05	24401	36.5398	−102.3947	Cimarron	09/13/2022	2024	3,997.3	140
OWRB-33768	GW06	33768	36.5856	−101.2803	Texas	09/12/2022	2024	2,928.3	280
OWRB-42791	GW07	42791	36.1386	−99.6833	Ellis	09/13/2022	2024	2,465.8	280
OWRB-129152	GW08	129152	36.8932	−102.1565	Cimarron	09/13/2022	2024	3,871.9	314
OWRB-24408	GW10	24408	36.72798	−101.8561	Texas	08/30/2022	2024	3,481.4	140
OWRB-1886	GW11	1886	36.9925	−101.3697	Texas	09/27/2022	2024	3,153.9	300
OWRB-58046	GW12	58046	36.8933	−100.5129	Beaver	08/30/2022	2024	2,508.7	160
OWRB-140808	GW14	140808	36.14596	−99.4732	Ellis	11/21/2013	2024	2,353.9	200
01N-12E-35 BDD 1 Texhoma GW Well	GW15	363033101440701	36.5092	−101.7357	Texas	07/26/1956	2024	3,430.6	386
21N-22W-15 CAD Woodward 15	GW16	361739099323301	36.2943	−99.5426	Woodward	07/27/2012	2024	2,310.1	300
OWRB-137270	GW17	13270	36.5295	−100.7653	Beaver	11/29/2022	2024	2,920.5	420
OWRB-23628	GW18	23628	36.6243	−101.6233	Texas	08/22/2023	2024	3,293.9	370
OWRB-110093	GW19	110093	36.8640	−101.6031	Texas	08/30/2022	2024	3,313.9	380
OWRB-24822	GW20	24822	36.7419	−100.9859	Texas	09/14/2022	2024	3,153.9	300
Climate stations (Oklahoma Climatological Survey, 2023)									
Boise City 2 E	C01	908	36.7340	−102.4840	Cimarron	01/1908	02/2020	--	--
Kenton	C02	4766	36.9001	−102.9670	Cimarron	11/1900	04/2006	--	--
Regnier	C03	7534	36.9500	−102.6300	Cimarron	04/1890	03/2006	--	--
Hooker	C04	4298	36.8670	−101.2200	Texas	06/1906	01/2024	--	--
Beaver	C05	593	36.8170	−100.5340	Beaver	02/1896	08/2017	--	--

Table 1. Selected data-collection stations in the High Plains (Ogallala) aquifer study area, southeastern Colorado, southwestern Kansas, northeastern New Mexico, northwestern Oklahoma, and northwestern Texas.—Continued

[U.S. Geological Survey (USGS) data can be accessed by using the 8- or 15-digit station number or other identifier. Dates are in month/day/year format. NAVD 88, North American Vertical Datum of 1988; --, unknown or not applicable; OWRB, Oklahoma Water Resources Board]

Station name	Map identifier (fig. 1)	Station number	Latitude (decimal degrees NAD 83)	Longitude (decimal degrees NAD 83)	County	Period of record (may contain gaps) or single measurement date		Land-surface altitude (feet above NAVD 88)	Well or hole depth (feet below land surface)
						Begin	End		
Climate stations (Oklahoma Climatological Survey, 2023)—Continued									
Gate	C06	3489	36.8500	-100.0500	Beaver	07/1959	01/2024	--	--
Buffalo 2 SSW	C07	1243	36.8000	-99.63400	Harper	02/1907	01/2013	--	--
Laverne	C08	5045	36.7000	-99.9000	Harper	02/1939	09/2010	--	--
Arnett 3NE	C09	332	36.1700	-99.7200	Ellis	03/1911	2024	--	--
Fargo	C10	3070	36.3700	-99.6300	Ellis	06/1942	2024	--	--
Gage Airport	C11	3407	36.3000	-99.7670	Ellis	05/1904	2024	--	--
Fort Supply Dam	C12	3304	36.5500	-99.5340	Woodward	07/1940	01/2013	--	--
Mutual	C13	6139	36.2340	-99.1670	Woodward	01/1915	11/2023	--	--
Supply 1 E	C14	8627	36.5670	-99.5500	Woodward	02/1893	11/1975	--	--
Woodward	C15	9760	36.4340	-99.3840	Woodward	10/1895	2024	--	--
Vici	C16	9172	36.1500	-99.2840	Dewey	05/1995	03/2024	--	--
Climate stations (National Centers for Environmental Information, 2023)									
Goodwell Research Station	C17	3628	36.5913	-101.618	Texas	02/15/1910	02/04/2024	--	--

Description of the Ogallala Aquifer Focus Area

The Ogallala aquifer focus area encompasses 4,275,122 acres in Oklahoma (OWRB, 2024b). The panhandle part of the Ogallala aquifer encompasses 3,334,636 acres (78.0 percent), and the northwest part of the Ogallala aquifer encompasses 940,486 acres (22.0 percent).

Groundwater levels in the Ogallala aquifer focus area (and the High Plains aquifer) have been declining since about 1950 when the development of the groundwater for irrigation began (Wahl and Tortorelli, 1997; McGuire and Strauch, 2024b); therefore, “predevelopment” in this report refers to the period prior to 1950. The recharge ages for groundwater in the Ogallala aquifer focus area range from decades to nearly 9,000 years (Andrews and others, 2000). Luckey and Becker (1998) estimated the predevelopment (pre-1950s) groundwater discharge from the High Plains aquifer to the streams of the study area by analyzing winter low flows at streamgages. Estimates of predevelopment groundwater discharges to major streams overlying the Ogallala aquifer focus area were 42 cubic feet per second (ft³/s) for the Cimarron River near Forgan, Okla. (07156900), 4.5 ft³/s for the Beaver River at Beaver, Okla. (07234000), and 28 ft³/s for the Wolf Creek near Fargo, Okla. (07236000) streamgages (Luckey and Becker, 1998; [fig. 1](#); [table 1](#)). Since the predevelopment–1998 study period of Luckey and Becker (1998), most of these rivers are no longer perennial across the study area (Gutentag and others, 1980; Luckey and Becker, 1998). Optima Lake is on the Beaver River in the panhandle part of the Ogallala aquifer ([fig. 1](#)). According to Smith and others (2015, p. 2),

Optima Lake on the Beaver River ([fig. 1](#)) is a good illustration of the degree to which the surface-water hydrology has changed in the Oklahoma Panhandle. *** Optima Dam was designed and authorized using streamflow data from the predevelopment period and was constructed from 1966 to 1978. Because of decreased streamflows in the irrigated period from 1978 to present (2015), Optima Lake never filled to more than 6 percent of the conservation pool storage and never met expectations for municipal water supply and recreation in the Oklahoma Panhandle.

Land Cover

Land cover over the Ogallala aquifer focus area ([fig. 2](#)) was mostly grass/pasture and cropland (undifferentiated), which accounted for 48.4 and 29.8 percent of land cover, respectively, in 2022 (National Agricultural Statistics Service, 2023; [fig. 3A](#)). The most prominent cropland-cover types in the Ogallala aquifer focus area in 2022 were winter wheat (34.9 percent), fallow/idle cropland (23.4 percent), sorghum (22.7 percent), and corn (10.1 percent). These types together accounted for 91.1 percent of cropland cover in the Ogallala

aquifer focus area in 2022. However, cropland-cover types and proportions may change annually with seasonal, economic, and hydrologic factors. The Ogallala aquifer focus area is almost entirely rural; only 3.6 percent of the land cover is developed. About 0.3 percent of the land cover is combined water, wetland, or barren areas.

Land cover over the panhandle part of the Ogallala aquifer was mostly grass/pasture and cropland (undifferentiated), which accounted for 43.3 and 34.8 percent of land cover, respectively, in 2022 ([fig. 3B](#)). Winter wheat (31.9 percent) was the most common cropland-cover type in the panhandle part of the Ogallala aquifer. The northwest part of the Ogallala aquifer had a greater proportion of grass/pasture (66.6 percent) and lesser proportion of cropland cover (12.3 percent) than the entire Ogallala aquifer focus area in 2022 ([fig. 3C](#)). Winter wheat (65.2 percent) was the most common cropland-cover type in the northwest part of the Ogallala aquifer.

Climate

The climate of the Ogallala aquifer focus area is classified as humid subtropical and cold semi-arid according to the Köppen-Geiger climate classification (Kottek and others, 2006). Historical daily precipitation data from 17 climate stations ([fig. 1](#); [table 1](#); National Centers for Environmental Information, 2023; Oklahoma Climatological Survey, 2023) in the Ogallala aquifer study area were summarized annually for the period 1915–2022. Precipitation data from climate stations in Cimarron, Texas, and Beaver Counties, Okla., were used to represent the panhandle part of the Ogallala aquifer ([fig. 4A](#)), and precipitation data from climate stations in Dewey, Ellis, Harper, and Woodward Counties, Okla., were used to represent the northwest part of the Ogallala aquifer ([fig. 5A](#)). Daily precipitation data from years with fewer than 10 months of recorded data and from months with fewer than 25 days of recorded data were omitted from the analysis. Stations with less than 54 years of precipitation and air temperature data also were excluded, resulting in 17 climate stations ([fig. 1](#); [table 1](#)). Historical annual air temperature data from 1915 to 2022 (Vose and others, 2023) for Cimarron, Texas, and Beaver Counties, Okla., were averaged and used to represent the panhandle part of the Ogallala aquifer ([fig. 4B](#)); historical annual air temperature data from 1915 to 2022 (Vose and others, 2023) for Ellis County, Okla., were used to represent the northwest part of the Ogallala aquifer ([fig. 5B](#)). A locally weighted scatterplot smoothing (LOWESS) curve (Cleveland, 1979) was applied to the annual data to determine periods of above-mean or below-mean precipitation and air temperature. Drought periods were selected based on methods from Shivers and Andrews (2013) and Tian and Quiring (2019) ([figs. 4–5](#)).

The mean annual precipitation and air temperature for the 1915–2022 period of record, were 21.11 inches (in.) and 58.86 degrees Fahrenheit (°F), respectively, in the Ogallala aquifer focus area (National Weather Service, 2023; Oklahoma

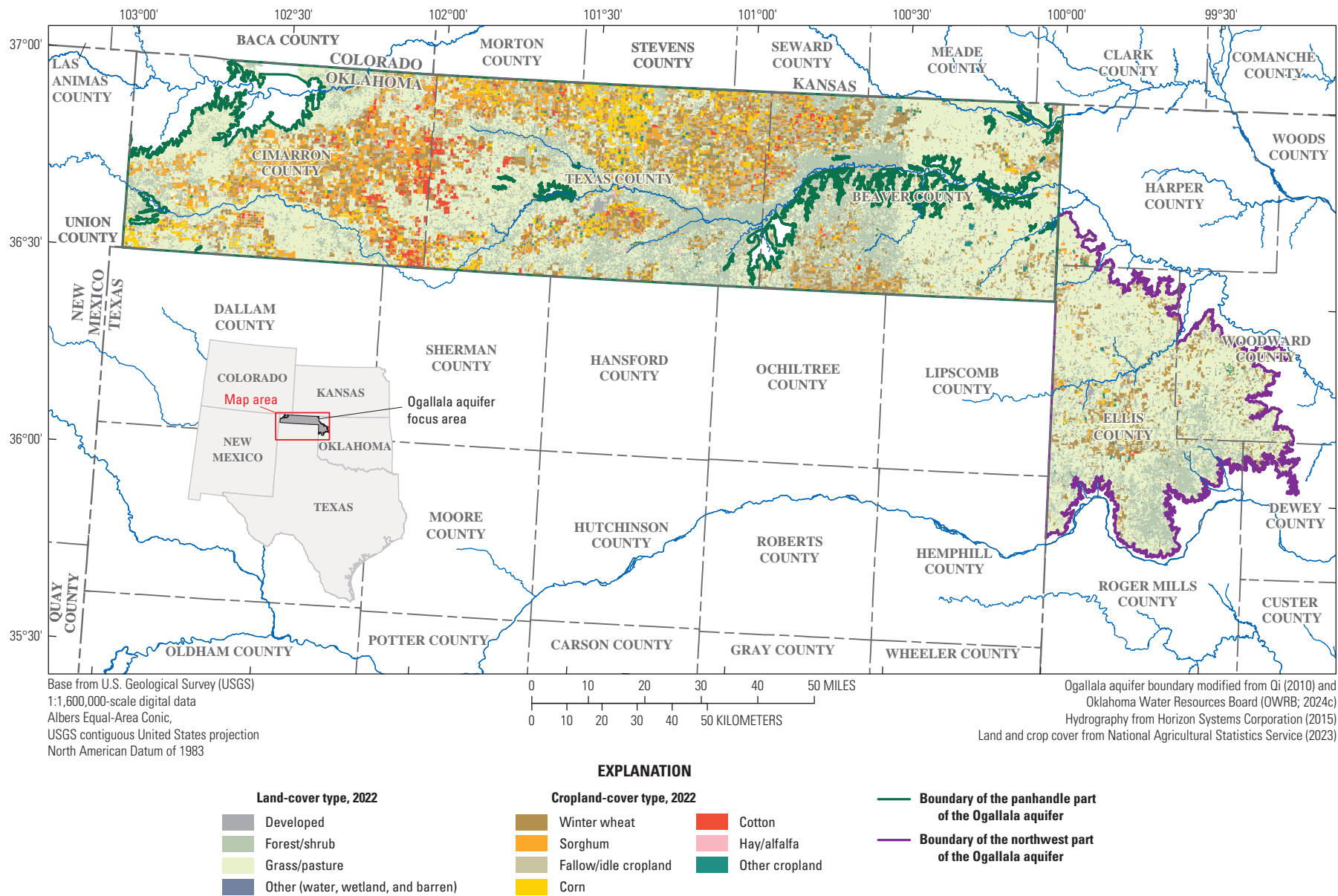
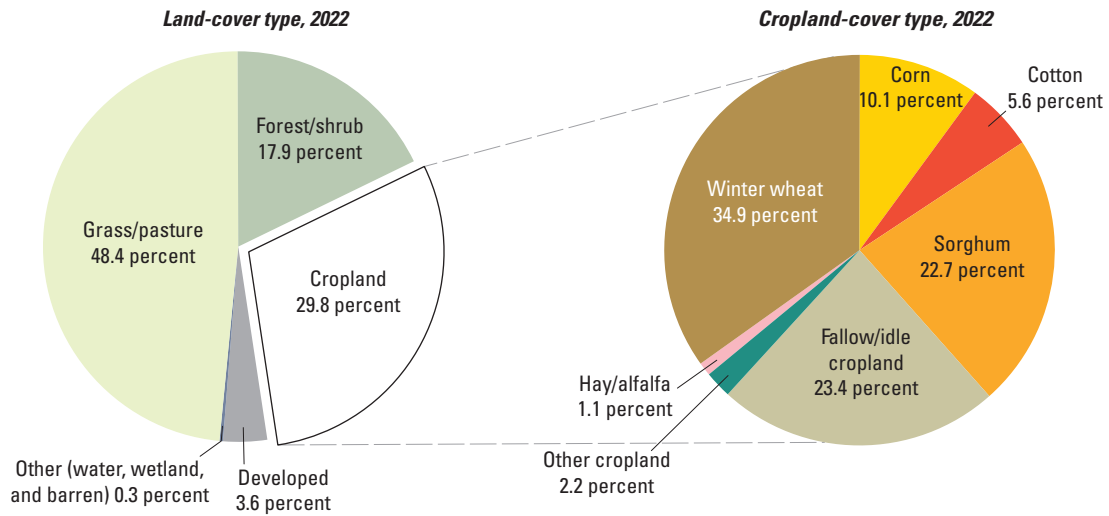
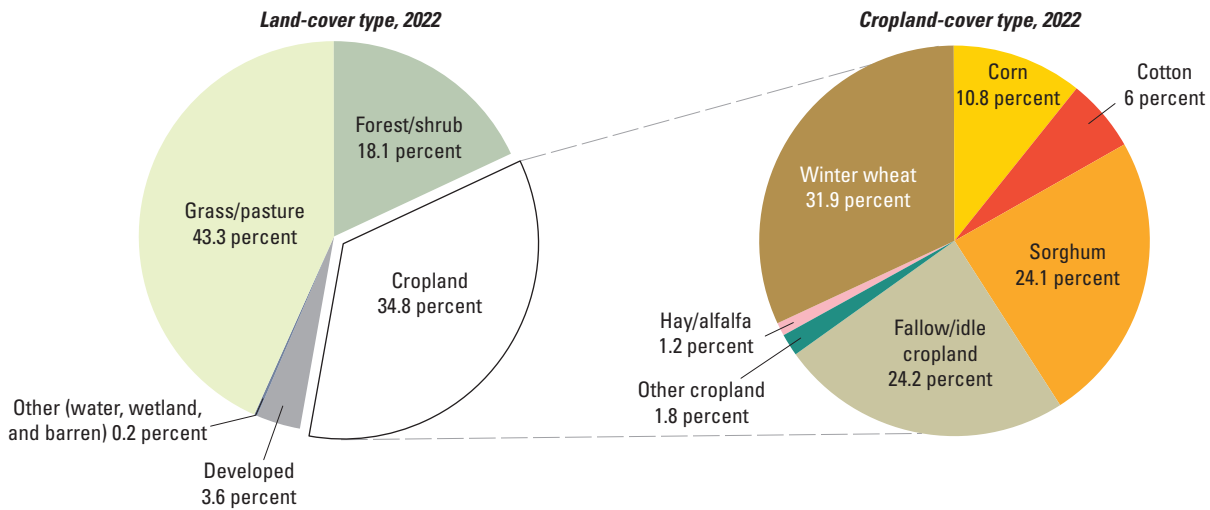


Figure 2. Land- and cropland-cover types over the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area, 2022.

A. Land use for the Ogallala aquifer focus area



B. Land use for the panhandle part of the Ogallala aquifer



C. Land use for the northwest part of the Ogallala aquifer

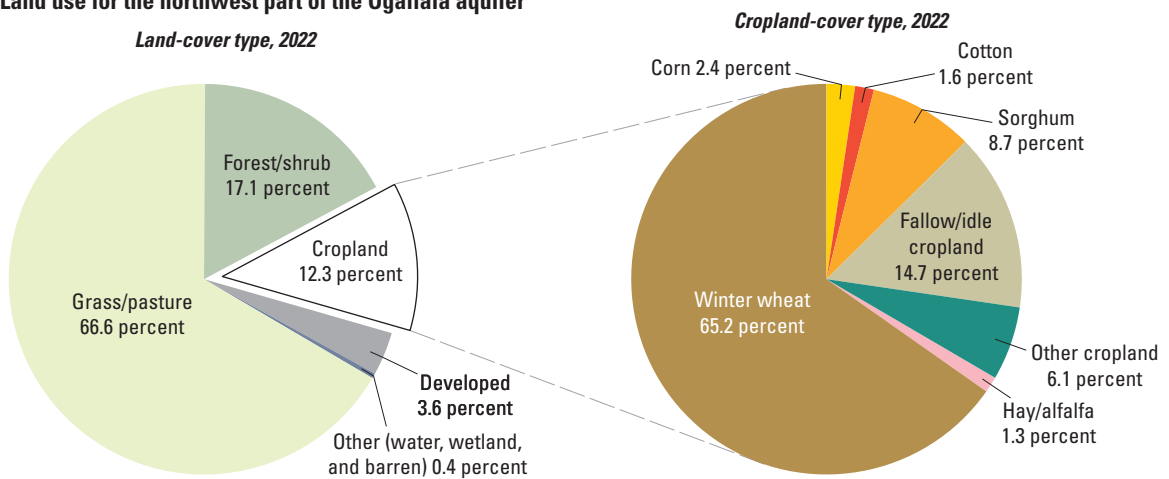
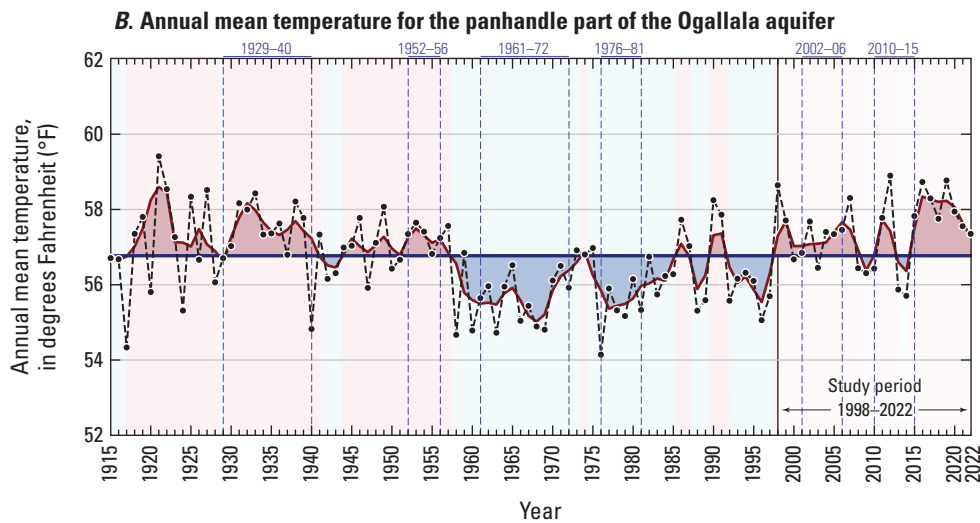
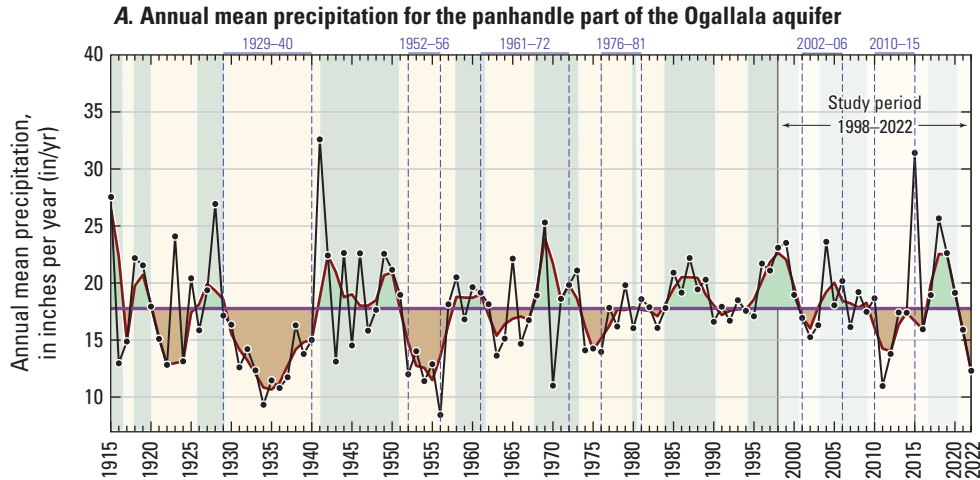


Figure 3. Distribution of land- and cropland-cover types in A, the Ogallala aquifer focus area and the B, panhandle and C, northwest parts of the Ogallala aquifer, Oklahoma, 2022 (National Agricultural Statistics Service, 2023).

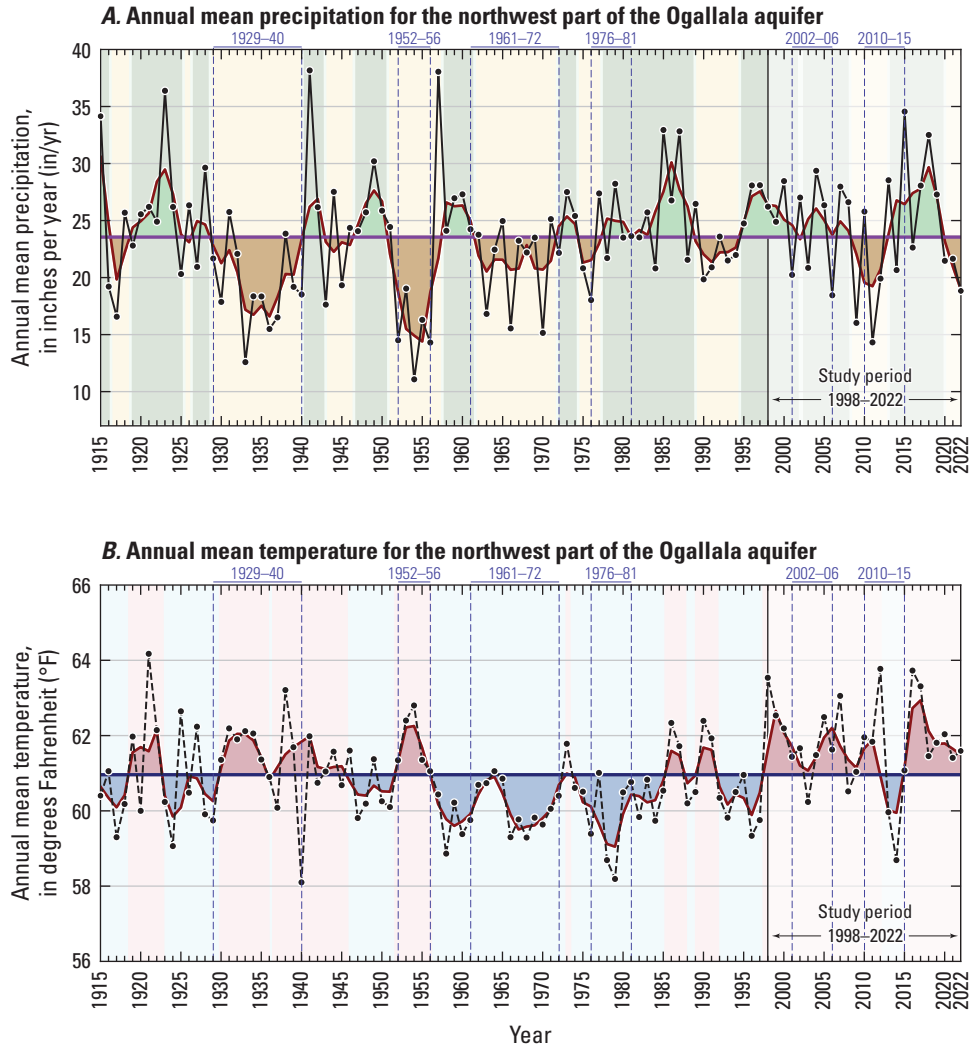


EXPLANATION

- Period above or below 1915–2022 mean annual precipitation**—Lighter shade shown for study period 1998–2022
 - Wet period
 - Dry period
- Period above or below 1915–2022 mean annual temperature**—Lighter shade shown for study period 1998–2022
 - Cool period
 - Warm period
- Northwestern Oklahoma drought period** (modified from Shivers and Andrews, 2013; Tian and Quiring, 2019)
- Periods when 5 percent LOWESS curve (percent of the overall mean) was above or below 1915–2022 mean annual precipitation or temperature**
 - Period when precipitation was above the mean annual precipitation
 - Period when precipitation was below the mean annual precipitation
 - Period when temperature was above the mean annual temperature
 - Period when temperature was below the mean annual temperature
- LOWESS smooth (Cleveland, 1979)**
- Annual mean precipitation¹**
- Mean annual precipitation (17.76 in/yr) for the period of record 1915–2022**
- Annual mean temperature (Vose and others, 2023)**
- Mean annual temperature (56.77 °F) for the period of record 1915–2022**

¹Summarized from daily precipitation data from 17 climate stations (table 1; fig. 1; Oklahoma Climatological Survey, 2023; National Centers for Environmental Information, 2023) in the Ogallala aquifer focus area.

Figure 4. A, Annual mean precipitation (Oklahoma Climatological Survey, 2023) and B, annual mean air temperature (National Weather Service, 2023), panhandle part of the Ogallala aquifer, Oklahoma, 1915–2022.



EXPLANATION

- Period above or below 1915–2022 mean annual precipitation**—Lighter shade shown for study period 1998–2022
 - Wet period
 - Dry period
- Period above or below 1915–2022 mean annual temperature**—Lighter shade shown for study period 1998–2022
 - Cool period
 - Warm period
- Northwestern Oklahoma drought period (modified from Shivers and Andrews, 2013; Tian and Quiring, 2019)**
- Periods when 5 percent LOWESS curve (percent of the overall mean) was above or below 1915–2022 mean annual precipitation or temperature**
 - Period when precipitation was above the mean annual precipitation
 - Period when precipitation was below the mean annual precipitation
 - Period when temperature was above the mean annual temperature
 - Period when temperature was below the mean annual temperature
- LOWESS smooth (Cleveland, 1979)**
- Annual mean precipitation¹**
- Mean annual precipitation (23.54 in/yr) for the period of record 1915–2022**
- Annual mean temperature (Vose and others, 2023)**
- Mean annual temperature (60.95 °F) for the period of record 1915–2022**

¹Summarized from daily precipitation data from 17 climate stations (table 1; fig. 1; Oklahoma Climatological Survey, 2023; National Centers for Environmental Information, 2023) in the Ogallala aquifer focus area.

Figure 5. A, Annual mean precipitation (Oklahoma Climatological Survey, 2023) and B, annual mean air temperature (National Weather Service, 2023), northwest part of the Ogallala aquifer, Oklahoma, 1915–2022.

Climatological Survey, 2023). The mean annual precipitation and air temperature for the 1915–2022 period of record were 17.76 in. and 56.77 °F, respectively, in the panhandle part of the Ogallala aquifer and 23.54 in. and 60.95 °F, respectively, in the northwest part of the Ogallala aquifer (figs. 4–5).

The mean annual precipitation and air temperature for the 1998–2022 study period were 22.09 in. and 59.61 °F, respectively, in the Ogallala aquifer focus area. The mean annual precipitation and air temperature for the 1998–2022 study period were 18.75 in. and 57.47 °F, respectively, in the panhandle part of the Ogallala aquifer and 24.34 in. and 61.78 °F, respectively, in the northwest part of the Ogallala aquifer. The panhandle and northwest parts of the Ogallala aquifer had warmer air temperatures over the 1998–2022 study period than over the 1915–2022 period of record.

Groundwater Use

The OWRB permits and regulates all nondomestic groundwater use and some domestic groundwater use (Oklahoma Statute § 82-1020.1[2] [Oklahoma State Legislature, 2021b]); domestic groundwater use of 5 acre-ft/yr or less is exempt from permitting (Oklahoma Statute § 82-1020.3 [Oklahoma State Legislature, 2021c]). OWRB (2025, p. 1) explains domestic use as follows:

Domestic use includes the use of water for household purposes, farm and domestic animals up to the normal grazing capacity of the land, and the irrigation of land not exceeding a total of three acres in area for the growing of gardens, orchards, and lawns. Domestic use also includes water used for agricultural purposes by natural individuals, use for fire protection, and use by non-household entities for drinking water, restrooms, and watering of lawns, provided such uses do not exceed five acre-feet per year.

Groundwater permits issued by the OWRB are divided into nine categories: irrigation; public supply; industrial; power; mining; commercial; recreation, fish, and wildlife; agriculture; and other (OWRB, 2024d). For the purposes of this report, the categories of industrial; power; mining; commercial; recreation, fish, and wildlife; and other were combined and are hereinafter referred to as “other.” Most of the groundwater permits in the Ogallala aquifer focus area were for irrigation in the panhandle part of the Ogallala aquifer (fig. 6); of the more than 4,100 irrigation permits in the Ogallala aquifer focus area, more than 3,800 are in the panhandle part of the Ogallala aquifer (OWRB, 2024d).

Permitted groundwater users have been required to submit annual groundwater-use reports to the OWRB since 1967 (Oklahoma Statute § 82-1020.12 [Oklahoma State Legislature, 2021d]). Reported annual groundwater-use data from the panhandle and northwest parts of the Ogallala aquifer

were summarized for the period of record (1967–2022), the study period (1998–2022), and a recent drought period (2010–15; figs. 4–5 and 7–8; tables 2–3).

Most of the reported groundwater use in the panhandle part of the Ogallala aquifer was for irrigation, which accounted for 346,988 acre-ft/yr or 96.9 percent of mean annual groundwater use during the 1967–2022 period of record (fig. 7A). During the same period, 4,967 acre-ft/yr or 1.4 percent of groundwater use was for public supply (fig. 7A), primarily for the towns of Beaver, Boise City, Goodwell, Guymon, and Hooker, Okla. (fig. 6). The remaining groundwater use was for agriculture (1.3 percent), and other (0.4 percent) uses (fig. 7A). Annual groundwater use during the 1967–2022 period of record in the panhandle part of the Ogallala aquifer ranged from a minimum of 251,781 acre-ft/yr in 1981 to a maximum of 568,066 acre-ft/yr in 2014 (table 2; fig. 7B). From 2010 to 2015, most of Oklahoma was in a period of drought (figs. 4A–5A), which coincided with an increase in annual groundwater use (National Integrated Drought Information System, 2024). Mean annual groundwater use in the panhandle part of the Ogallala aquifer for the 2010–15 drought period was 522,143 acre-ft/yr, or 163,978 acre-ft/yr greater than mean annual groundwater use in the panhandle part of the Ogallala aquifer during the 1967–2022 period of record (table 2). Precipitation events which occurred in the summer of 2015 ended the 2010–15 drought period, but groundwater use continued to be elevated compared to pre-2010 levels through 2022 (fig. 7B). During the 1998–2022 study period, mean annual groundwater use in the panhandle part of the Ogallala aquifer was 422,054 acre-ft/yr, which was 63,889 acre-ft/yr greater than mean annual groundwater use during the 1967–2022 period of record but less than the mean annual groundwater use during the 2010–2015 drought period (table 2; Codner and others, 2026).

Like in the panhandle part of the Ogallala aquifer, most of the reported groundwater use in the northwest part of the Ogallala aquifer was for irrigation, which accounted for 28,805 acre-ft/yr or 83.3 percent of mean annual groundwater use during the 1967–2022 period of record (fig. 8A). During the same period, 5,376 acre-ft/yr or 15.6 percent of groundwater use was for public supply (fig. 8A), primarily for the towns of Shattuck and Woodward, Okla. (fig. 6). The remaining groundwater use was classified as other (0.7 percent) and agriculture (0.4 percent). During the 1967–2022 period of record, annual groundwater use ranged from a minimum of 2,680 acre-ft/yr in 1967 to a maximum of 65,386 acre-ft/yr in 2001 in the northwest part of the Ogallala aquifer (table 3; fig. 8B); mean annual groundwater use was 34,579 acre-ft/yr. The pattern of increased groundwater use in the panhandle part of the Ogallala aquifer beginning in 2010 was repeated in the northwest part of the Ogallala aquifer where years with the highest groundwater use were all prior to 2010. The 2010–15 drought period was more severe in terms of the persistence of below average precipitation and

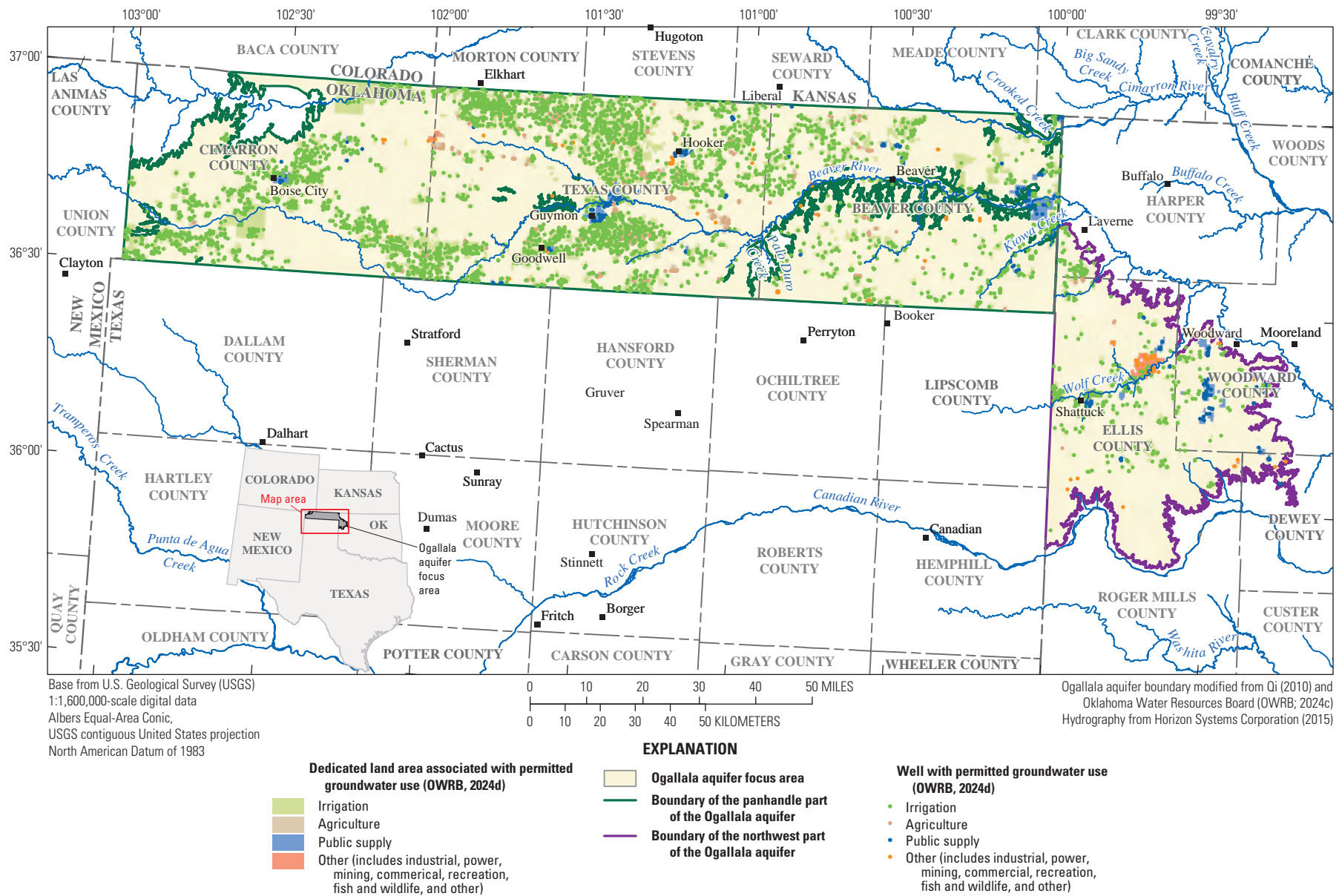
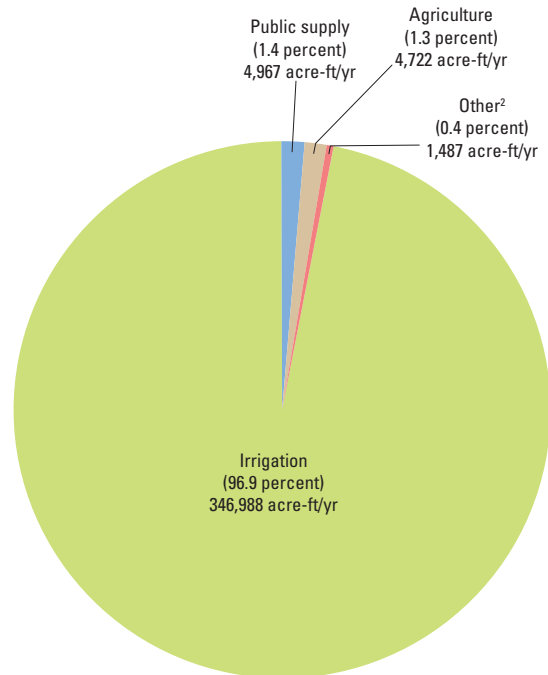
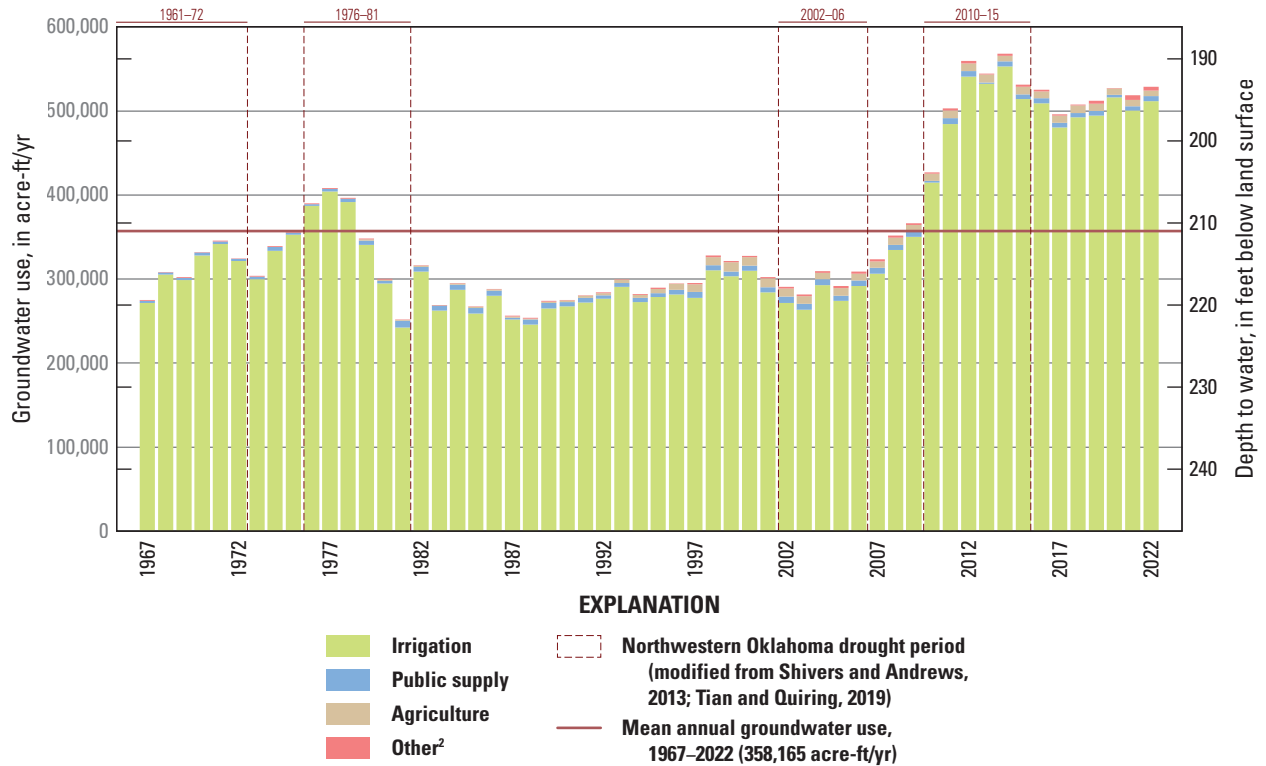


Figure 6. Dedicated land areas and wells with permitted groundwater use in the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area, 2024.

A. Mean annual reported groundwater use,¹ in percent and acre-feet per year (acre-ft/yr), panhandle part of the Ogallala aquifer, 1967–2022



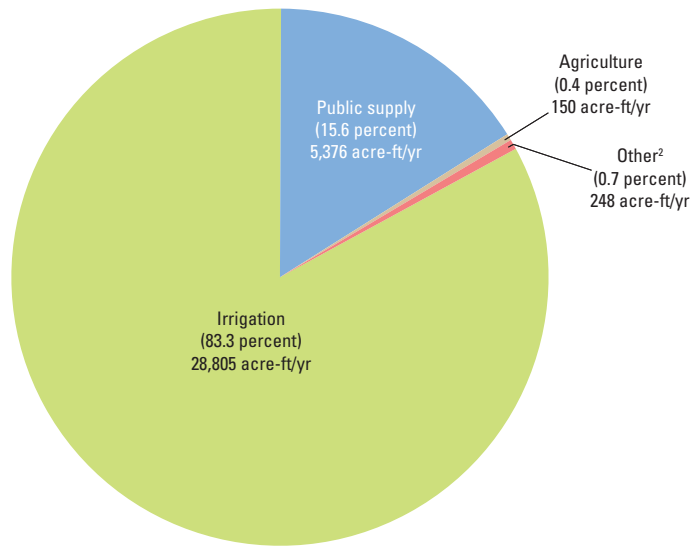
B. Annual reported groundwater use,¹ panhandle part of the Ogallala aquifer, 1967–2022



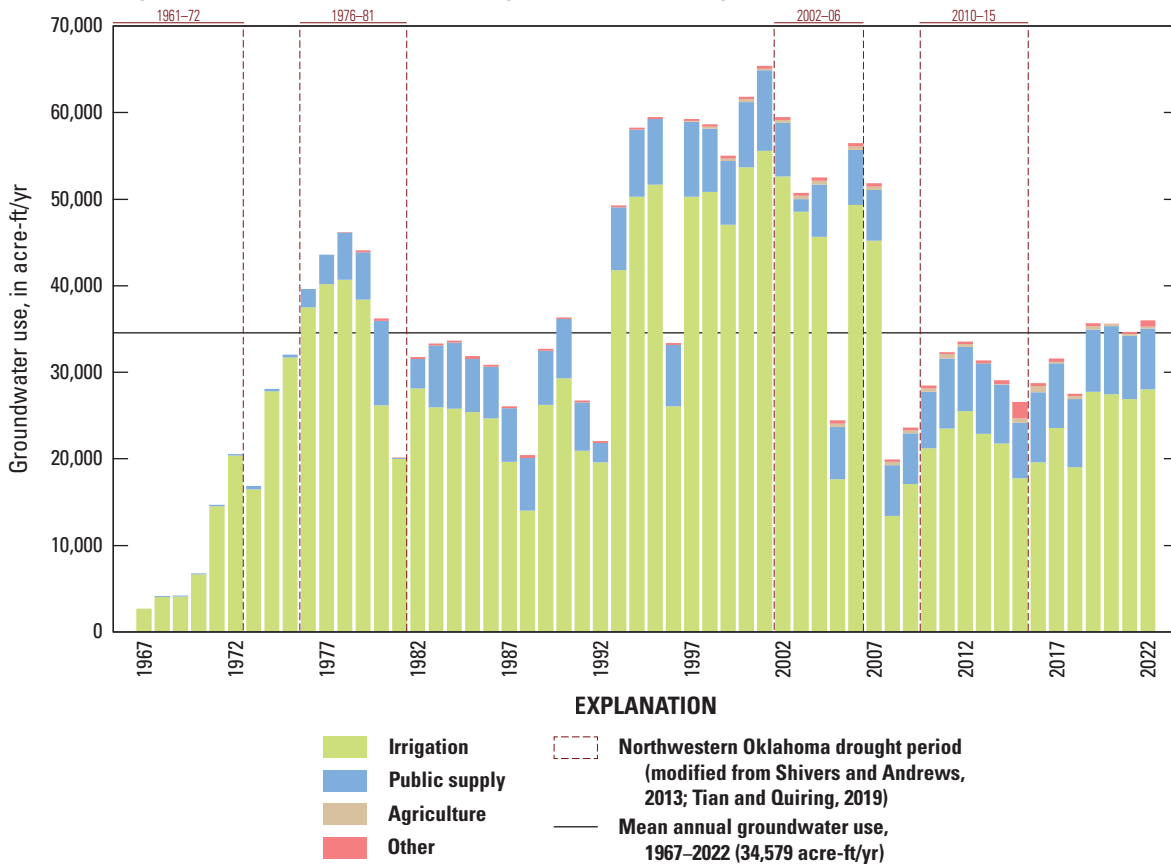
¹Groundwater-use data provided by the Oklahoma Water Resources Board (OWRB) and available in Codner and others (2026).
²Other includes OWRB permit categories industrial, power, mining, commercial, recreation, fish and wildlife, and other.

Figure 7. A, Mean annual reported groundwater use and B, annual reported groundwater use by category, panhandle part of the Ogallala aquifer, Oklahoma, 1967–2022.

A. Mean annual reported groundwater use,¹ in percent and acre-feet per year (acre-ft/yr), northwest part of the Ogallala aquifer, 1967–2022



B. Annual reported groundwater use,¹ northwest part of the Ogallala aquifer, 1967–2022



¹Groundwater-use data provided by the Oklahoma Water Resources Board (OWRB) and available in Codner and others (2026).

²Other includes OWRB permit categories industrial, power, mining, commercial, recreation, fish and wildlife, and other.

Figure 8. A, Mean annual reported groundwater use and B, annual reported groundwater use by category, northwest part of the Ogallala aquifer, Oklahoma, 1967–2022.

Table 2. Summary statistics of reported annual groundwater use in the panhandle part of the Ogallala aquifer, Oklahoma, 1967–2022.

[Groundwater-use data were provided by the Oklahoma Water Resources Board and are available in Codner and others (2026). Table excludes groundwater use of less than 5 acre-feet per year for domestic and agricultural purposes and groundwater use for irrigation of fewer than 3 acres of land for growing of gardens, orchards, or lawns (Oklahoma Statute § 82-1020.3; Oklahoma State Legislature, 2021c)]

Period	Timespan	Reported annual groundwater use (acre-feet per year)			
		Minimum (year)	Median	Mean	Maximum (year)
Period of record	1967–2022	251,781 (1981)	319,146	358,165	568,066 (2014)
Study period	1998–2022	281,452 (2003)	426,831	422,054	568,066 (2014)
Drought period	2010–15	426,831 (2010)	537,797	522,143	568,066 (2014)

Table 3. Summary statistics of reported annual groundwater use in the northwest part of the Ogallala aquifer, Oklahoma, 1967–2022.

[Groundwater-use data were provided by the Oklahoma Water Resources Board and are available in Codner and others (2026). Table excludes groundwater use of less than 5 acre-feet per year for domestic and agricultural purposes and groundwater use for irrigation of fewer than 3 acres of land for growing of gardens, orchards, or lawns (Oklahoma Statute § 82-1020.3; Oklahoma State Legislature, 2021c)]

Period	Timespan	Reported annual groundwater use (acre-feet per year)			
		Minimum (year)	Median	Mean	Maximum (year)
Period of record	1967–2022	2,680 (1967)	32,544	34,579	65,386 (2001)
Study period	1998–2022	19,960 (2008)	34,694	39,645	65,386 (2001)
Drought period	2010–15	26,594 (2015)	30,232	30,231	33,526 (2012)

above average temperature in the panhandle part than in the northwest part of the Ogallala aquifer, which could explain why groundwater use was not as elevated in this part of the aquifer when compared to the panhandle part of the Ogallala aquifer (figs. 4–5). Mean annual groundwater use in the northwest part of the Ogallala aquifer during the 2010–15 drought period was 30,231 acre-ft/yr, or 4,348 acre-ft/yr less than mean annual groundwater use for the 1967–2022 period of record (table 3). During the 1998–2022 study period, mean annual groundwater use in the northwest part of the Ogallala aquifer was 39,645 acre-ft/yr, or 5,066 acre-ft/yr greater than the mean annual groundwater use during the 1967–2022 period of record (table 3).

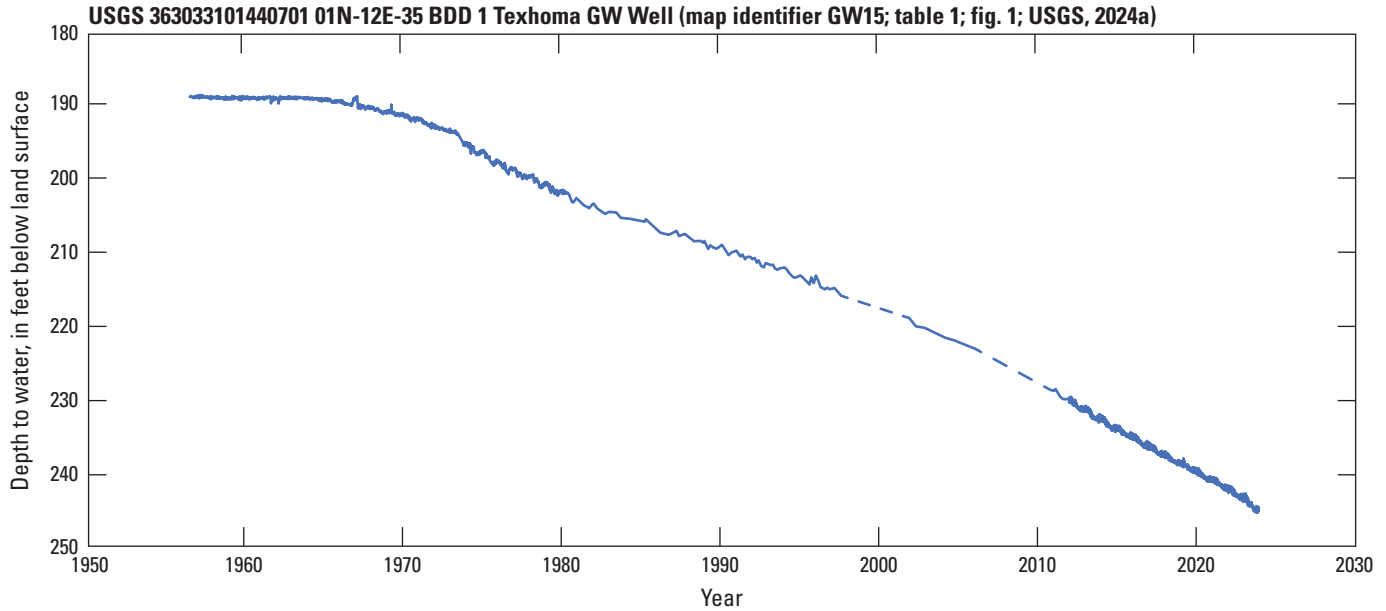
Groundwater use for irrigation was used to estimate irrigation return flows, further explained in the “Recharge” section of this report. Mean annual groundwater use for irrigation during the 1998–2022 study period in the panhandle part of the Ogallala aquifer was 405,541 acre-ft/yr (Codner and others, 2026). Mean annual groundwater use for irrigation during the 1998–2022 study period in the northwest part of the Ogallala aquifer was 32,075 acre-ft/yr (Codner and others, 2026).

Groundwater Levels in the Ogallala Aquifer Focus Area

The USGS installed two continuous groundwater-level recorders in wells in the Ogallala aquifer focus area: GW15 installed in 1956 and GW16 installed in 2012 (fig. 1; table 1; USGS, 2024a). The OWRB installed 18 continuous groundwater-level recorders in wells in the Ogallala aquifer focus area as part of their Groundwater Monitoring and Assessment Program starting in 2022 (fig. 1; table 1; OWRB, 2024c). Tomlinson and others (2024) provide a map showing groundwater-level changes in the panhandle during 1982–2022 which could be used as a reference for future tracking of groundwater levels in the aquifer. Groundwater-level data from the USGS continuous-recorder wells (GW15 and GW16) indicate seasonal patterns, with declines starting around June through September and increases in October through May (figs. 9, 10). Groundwater levels at GW15 have a decreasing pattern, and those at GW16 are relatively steady through time. These patterns are consistent with the groundwater-level change data presented in McGuire and Strauch (2024b).

Streamflow and Base-Flow Characteristics

Daily streamflows measured at USGS streamgages consist of two primary components: base flow and runoff. Base flow is the component of streamflow discharged by surrounding groundwater systems. Runoff is the component



Dashed where estimations for water-level readings were used during August 1997–January 2011.

Figure 9. Groundwater-level data from U.S. Geological Survey (USGS) continuous groundwater-level recorder well USGS 363033101440701 01N-12E-35 BDD 1 Texhoma GW Well, Oklahoma.

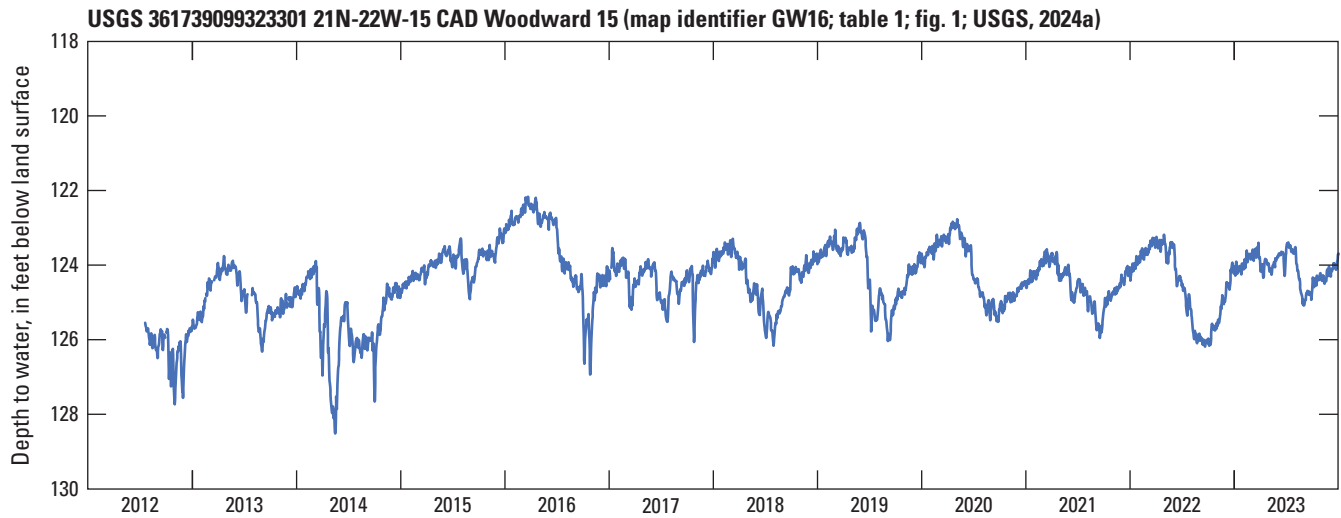


Figure 10. Groundwater-level data from U.S. Geological Survey (USGS) continuous groundwater-level recorder well USGS 361739099323301 21N-22W-15 CAD Woodward 15, Oklahoma.

of streamflow supplied by overland flow and stormflow (interflow) of precipitation into a stream channel (Barlow and Leake, 2012). The Base-Flow Index code (Wahl and Wahl, 1995) in the USGS Groundwater Toolbox (Barlow and others, 2015) was used to separate daily streamflow data from the USGS National Water Information System (USGS, 2024a) into base-flow and runoff components. The Base-Flow Index code divided daily streamflow data into n -day-long windows (where n is the user-defined number of days) and identified the minimum streamflow within each window. Turning points

were then identified by comparing the minimums of each window below a certain fraction (the user-defined f -statistic, in this case 0.9 or 90 percent) to immediately adjacent minimums. If 90 percent of a given minimum was less than the preceding and succeeding minimums, that minimum was considered a turning point. These turning points were then used to construct a base-flow hydrograph with semilogarithmic interpolation. By using the turning points, the base-flow index (BFI), or the ratio of base flow to total streamflow, was calculated. Multiple n -day windows were tested by plotting

mean BFI against different n -day values (from 2 to 15 days), and a slope change was evident around 3 days in most daily streamflow data analyzed. For consistency, a 3-day window and an f -statistic of 0.9 were used for base-flow analysis in this study.

The Beaver River and Cimarron River are the two main drainage features in the panhandle part of the Ogallala aquifer (fig. 1; Luckey and Becker, 1999). USGS streamgage 07234000 Beaver River at Beaver, Okla. (map identifier S21, fig. 1), and USGS streamgage 07156900 Cimarron River near Forgan, Okla. (map identifier S22, fig. 1), were selected for base-flow analysis (table 4). Although S22 is outside of the Ogallala aquifer, it is 5 miles upstream of the aquifer and was therefore considered an important part of the historical streamflow analysis. S21 and S22 had a large gap in data during 2022, so a base-flow analysis could not be completed for that year. Therefore, the period 1998–2021 was used for the base-flow analysis.

For S21, the mean annual BFI for the period of record (1938–2021) was 34.26 percent, which was 21.51 percent less than the mean annual BFI for the study period (1998–2021) of 55.77 percent (table 4). For S22, the mean annual BFI for the period of record (1966–2021) was 84.80 percent, which was 5.90 percent less than the mean annual BFI for the study period (1998–2021) of 90.70 percent. S21 and S22 display a pattern of decreasing annual total streamflows and base flows throughout their respective periods of record (fig. 11). The annual BFI 5-year moving average displays an increasing pattern for most of the period of record for sites S21 and S22; however, the annual BFI shows less variation for S22 than for S21. The annual BFI 5-year moving average for S21

also shows a decreasing pattern starting in 2001 that is not present in the annual BFI 5-year moving average for S22. The decreasing pattern in annual streamflows and base flows and the increasing pattern in annual BFI for S21 and S22 coincide with the 1998–2022 climatic period during which the mean annual precipitation (18.75 in/yr) for the panhandle part of the Ogallala aquifer was greater than the historical (1915–2022) mean annual precipitation (17.76 in/yr) for the panhandle part of the Ogallala aquifer (fig. 4).

Wolf Creek is the main drainage feature in the northwest part of the Ogallala aquifer (fig. 1). USGS 07235600 Wolf Creek near Gage, Okla. (map identifier S32), and USGS 07236000 Wolf Creek near Fargo, Okla. (map identifier S23), have data that together cover most of the period between predevelopment and the study period (table 4; fig. 12). S23 covers the period 1943–75 and has a mean annual BFI of 53.53 percent (fig. 12A). Available data from S32 only partially cover the 1998–2022 study period (fig. 12B) but still were used to represent the study period (table 4). S32 had a mean annual BFI of 82.69 percent (fig. 12B). If data from S23 and S32 are viewed as one record representing Wolf Creek, the record shows an increasing pattern in annual BFI that is similar to those for annual BFI at S21 and S22.

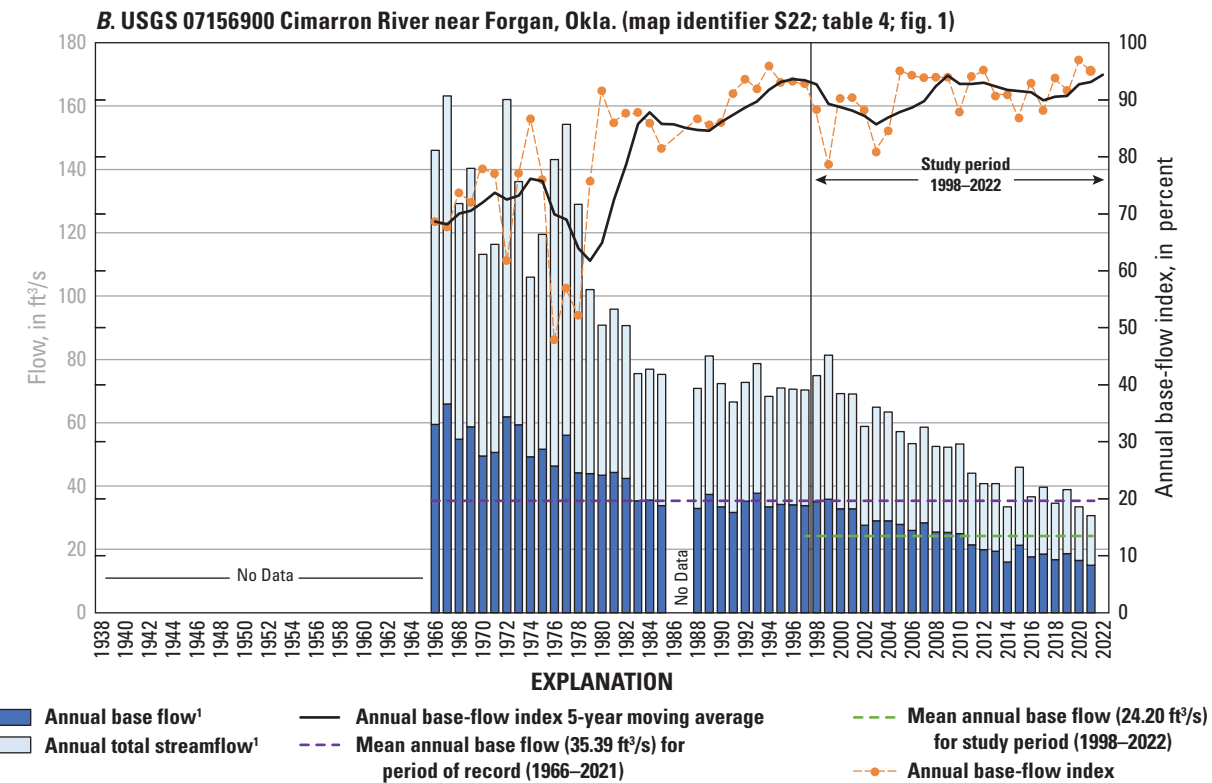
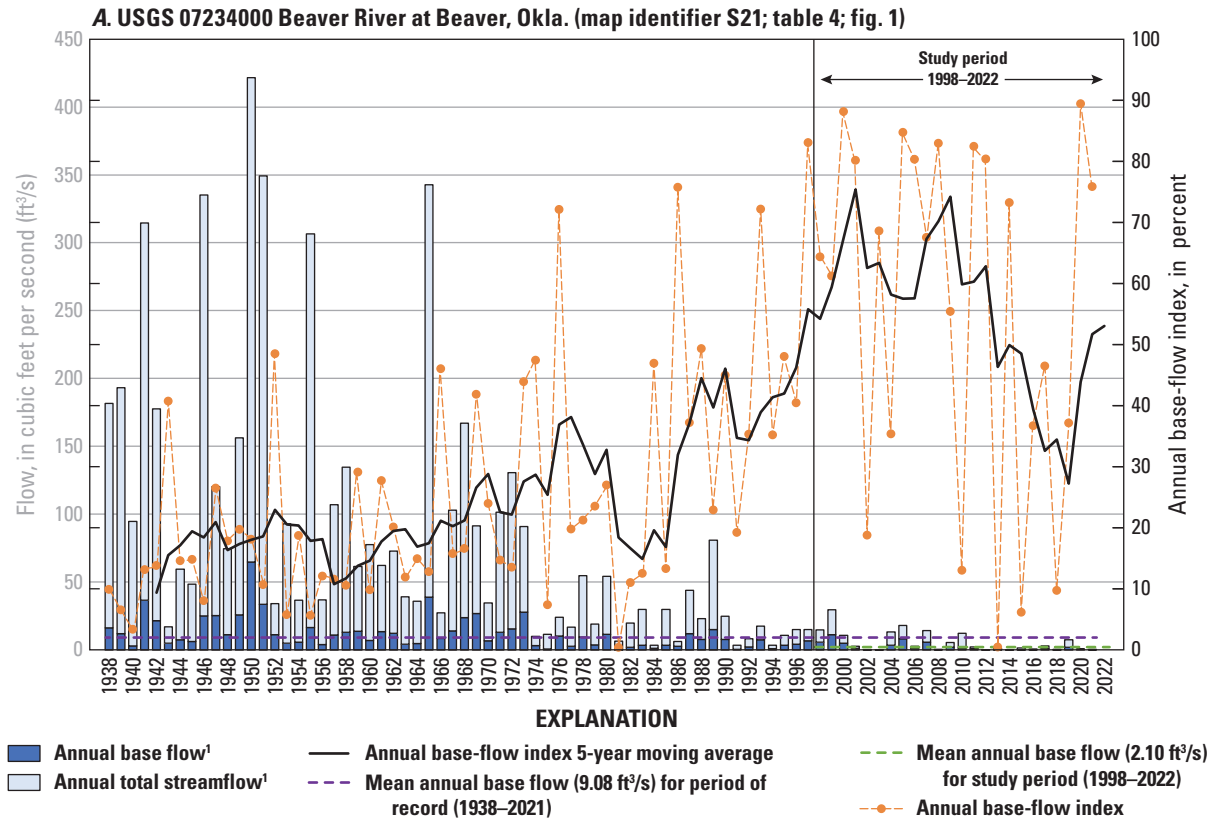
The increases in the annual BFI for Beaver River and Wolf Creek over the streamgage periods of record indicate that the proportion of annual total streamflow that comes from annual base flow is increasing relative to annual runoff. Annual base flows and runoff have both decreased, but annual runoff has decreased by a greater percentage than annual base flows (Wahl and Tortorelli, 1997; Esralew and Lewis, 2010).

Table 4. Mean annual streamflow, base flow, and base-flow index values for selected U.S. Geological Survey streamgages during the streamgage periods of record and the study period (1998–2022) in the High Plains (Ogallala) aquifer study area, Oklahoma.

[Data from U.S. Geological Survey (USGS), 2024a; POR, period of record; ft³/s, cubic foot per second; BFI, base-flow index; --, no data]

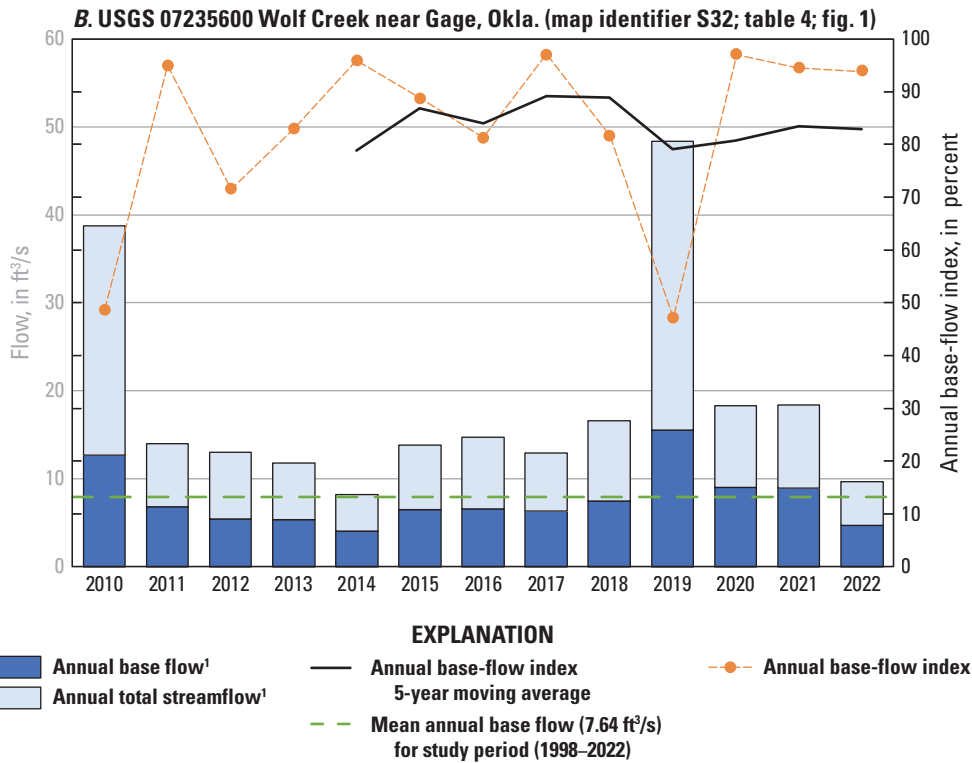
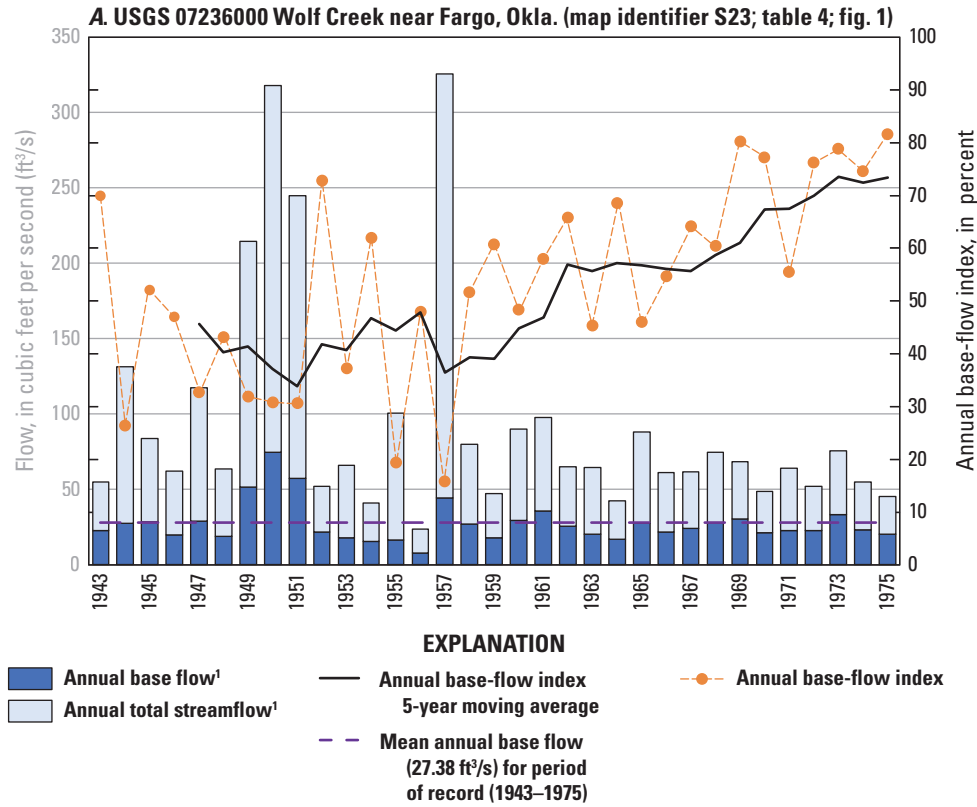
Station name	USGS streamgage (table 1; USGS, 2024a)	Map identifier (fig. 1)	POR for base flow analysis	Mean annual streamflow (ft ³ /s)		Mean annual base flow (ft ³ /s)		Mean annual BFI (percent)	
				Study period	POR	Study period	POR	Study period	POR
Beaver River at Beaver, Okla.	07234000	S21	1938–2021	3.81	55.26	2.10	9.08	55.77	34.26
Cimarron River near Forgan, Okla.	07156900	S22	1966–2021	26.95	44.52	24.20	35.39	90.70	84.80
Wolf Creek near Fargo, Okla.	07236000	S23	1943–75	--	65.96	--	27.38	--	53.53
Wolf Creek near Gage, Okla. ¹	07235600	S32	2010–22	10.71	10.71	7.64	7.64	82.69	82.69

¹Data for this site do not cover the entire study period.



¹Codner and others (2026).

Figure 11. Annual streamflow, annual base flow, and annual base-flow index for A, U.S. Geological Survey (USGS) streamgauge 07234000 Beaver River at Beaver, Oklahoma, and B, USGS streamgauge 07156900 Cimarron River near Forgan, Oklahoma.



¹Codner and others (2026).

Figure 12. Annual streamflow, annual base flow, and annual base-flow index for *A*, U.S. Geological Survey (USGS) streamgauge 07236000 Wolf Creek near Fargo, Oklahoma, and *B*, USGS streamgauge 07235600 Wolf Creek near Gage, Oklahoma.

Hydrogeology of the Ogallala Aquifer Focus Area

The Ogallala aquifer is contained in the Miocene to Pliocene Ogallala Formation, although overlying Quaternary alluvium, dune sand, and terrace deposits, for the purposes of this report, are also considered as part of the Ogallala aquifer where they directly overlie the Ogallala Formation. The Permian bedrock units are considered the base of the Ogallala aquifer throughout most of the focus area, although Triassic, Jurassic, and Cretaceous hydrogeologic units act as bases to the Ogallala aquifer in the western portion of the study area (figs. 13–14; Gutentag and others, 1984).

Structural Features

In the eastern part of the study area in Kansas and Oklahoma, the Crooked Creek Fault displaced Permian through Tertiary sediments (fig. 13; Luckey and Becker, 1999). The Crooked Creek Fault creates an offset in the base of the Ogallala aquifer and causes abrupt changes in saturated thickness in northern Beaver County, Okla. The Cimarron Arch is a local feature mapped in Cimarron and Texas Counties, Okla. (Northcutt and Campbell, 1995). The northwest part of the Ogallala aquifer is predominantly in the Anadarko Basin, which is the primary basin of the Ogallala aquifer focus area where sediments were deposited (Luckey and Becker, 1999). Surficial geologic units in the Ogallala aquifer focus area dip to the southeast at an average rate of 1 degree or less (Hart and others, 1976). Additional structural features that affect the Ogallala aquifer focus area are described in Hart and others (1976) and Luckey and Becker (1999).

Cenozoic Geologic and Hydrogeologic Units

Quaternary alluvium, dune sand, and terrace deposits overlie the Ogallala Formation in some parts of the Ogallala aquifer focus area. Alluvium and terrace deposits overlie the Ogallala Formation along streams (figs. 13, 14) and consist of unconsolidated sand, gravel, clay, and silt (Hart and others, 1976). Dune sands are present on the northern side of the Beaver River and were deposited by prevailing southerly winds (fig. 13; Gutentag and others, 1984). The terrace deposits were formed when sediments from streambed erosion were carried downstream and eventually deposited onto terraces (Gutentag and others, 1984). Some of the high terrace deposits were derived from the erosion of the Ogallala Formation; however, most of the terrace deposits were formed later, during the Quaternary Period. Alluvium and terrace deposits east of Beaver County (but within the study area) contain the Beaver-North Canadian River alluvial aquifer in areas where these deposits do not directly overlie the Ogallala Formation (Ryter and Correll, 2016). Alluvium deposits and

dune sands that overlie the Ogallala Formation are considered part of the Ogallala aquifer because they have similar appearance and hydraulic properties to the Ogallala Formation (Hart and others, 1976).

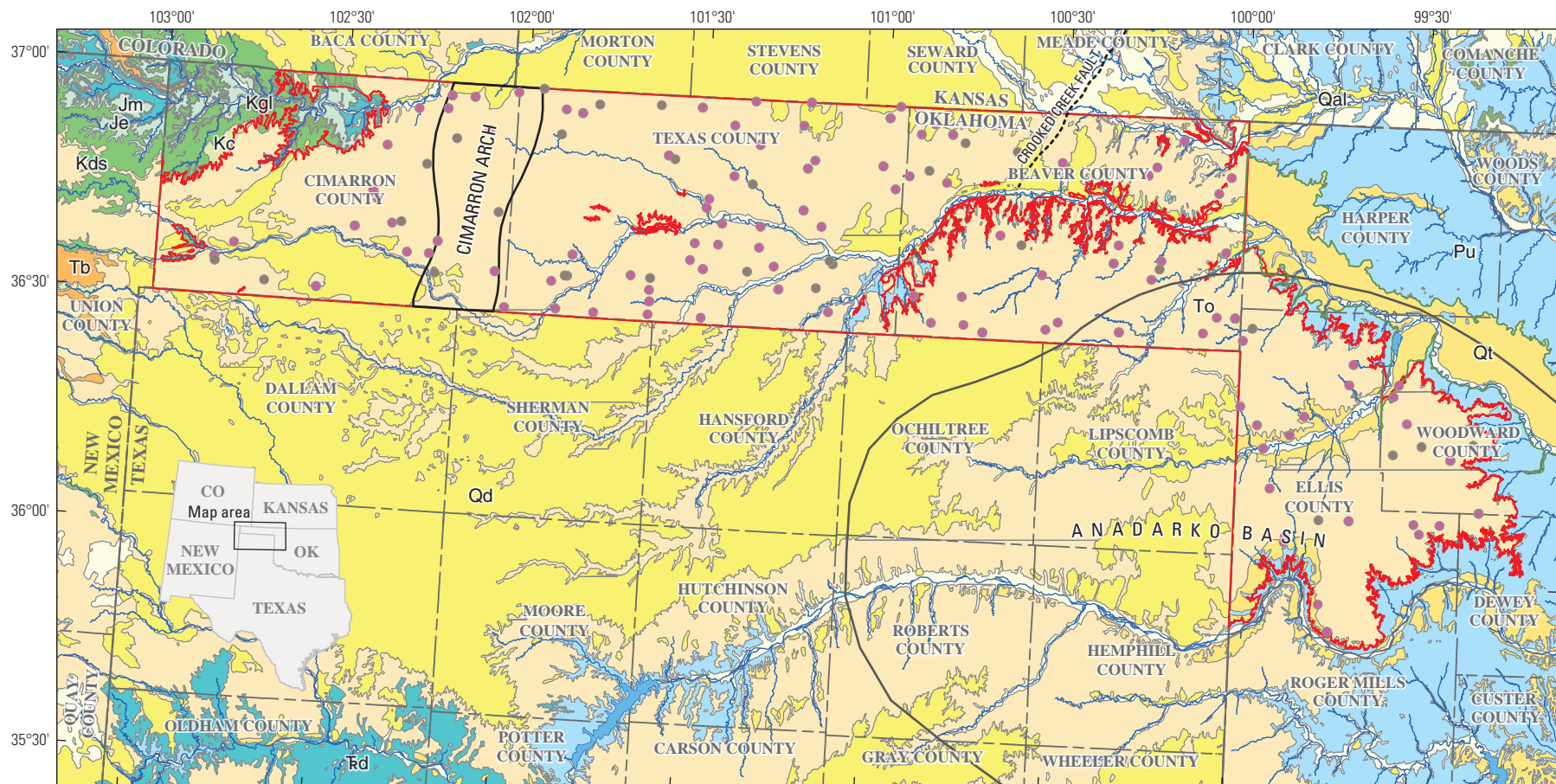
The Black Mesa Basalt in the northwest corner of Cimarron County, Okla., is an outcrop of Pliocene igneous rock that is composed of a dense, olivine basalt (figs. 13–14; Hart and others, 1976; chart D of Fay, 1997). Isolated areas of volcanic ash are present in the study area (Hart and others, 1976). The volcanic ash deposits are not distinguished from other geologic units in the Ogallala aquifer focus area (fig. 13), nor are they expected to have a substantial hydraulic contribution to the hydrogeology of the Ogallala aquifer focus area.

The surficial geology in the Ogallala aquifer focus area is dominated by the Miocene to Pliocene Ogallala Formation (fig. 13; Luza and Fay, 2003; Stoesser and others, 2005). The Ogallala Formation is a heterogeneous mixture of gravel, sand, silt, clay, and caliche, which can be difficult to differentiate from overlying unconsolidated materials (Hart and others, 1976). The Ogallala Formation consists of several hundred feet of coarse sand and fine gravel in certain areas and hundreds of feet of clay with lenses of very fine sand in others (Hart and others, 1976). Well yields from the Ogallala aquifer, except where it is very thin, are at least 500 gallons per minute and can be as much as 2,000 gallons per minute (Luckey and Becker, 1999).

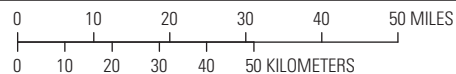
Mesozoic Geologic and Hydrogeologic Units

In the western half of Cimarron County, Cretaceous bedrock units underlie the Ogallala Formation (Hart and others, 1976). In parts of Cimarron and Texas Counties, Triassic to Jurassic geologic units underlie the Ogallala Formation (Hart and others, 1976). Well yields from the hydrogeologic units contained in the Mesozoic geologic units that underlie the Ogallala aquifer are generally less than well yields from the Ogallala aquifer; well yields can be used to identify the base of the Ogallala aquifer (Hart and others, 1976).

The Cretaceous geologic units contain three different hydrogeologic units that are hydraulically connected to the Ogallala aquifer (fig. 14). The Upper Cretaceous Greenhorn Limestone of the Colorado Group contains an aquifer in areas outside the study area (fig. 14; Barkmann and others, 2021). The Greenhorn Limestone is a mix of gray limestone and calcareous shale with some bentonite (fig. 14; Hart and others, 1976). The Greenhorn Limestone is underlain by the Upper Cretaceous Graneros Shale of the Colorado Group, which is a confining unit and is a gray to black shale (fig. 14; Barkmann and others, 2021). The Dakota aquifer underlies the Graneros Shale and is contained in the Upper Cretaceous Dakota Sandstone and the Lower Cretaceous Glencairn Formation and Lytle Sandstone (Macfarlane, 1995). The Dakota Sandstone is mostly fine- to medium-grained sand, and is buff to



Base from U.S. Geological Survey (USGS)
 1:1,650,000-scale digital data
 Albers Equal-Area Conic,
 USGS contiguous United States projection
 North American Datum of 1983



Hydrography from Horizon Systems Corporation (2015)
 Data for mapping surficial geologic units from
 Luza and Fay (2003) and Stoesser and others (2005)
 Structural boundaries from Northcutt and Campbell (1995)

EXPLANATION

Surficial geologic unit (refer to fig. 14)			
Qal	Alluvium (Quaternary)	Tb	Black Mesa Basalt (Tertiary)
Qd	Dune sand (Quaternary)	To	Ogallala Formation (Tertiary)
Qt	Terrace deposits (Quaternary)	Kc	Colorado Group (Cretaceous)
		Kds	Dakota Sandstone (Cretaceous)
		Kgl	Glencairn Formation and Lytle Sandstone, undifferentiated (Cretaceous)
		Jm	Morrison Formation (Jurassic)
		Je	Exeter Sandstone (Jurassic)
		Rd	Dockum Formation (Triassic)
		Pu	Permian rocks, undifferentiated
			Boundary of the Ogallala aquifer in Oklahoma
			Boundary of the North Canadian River alluvial aquifer
			Well with groundwater-quality samples
			● 2013–2021 (Oklahoma Water Resources Board, 2018)
			● 1958–2015 (USGS, 2024a)

Figure 13. Surficial extent of geologic units in the High Plains (Ogallala) aquifer study area, southeastern Colorado, southwestern Kansas, northeastern New Mexico, northwestern Oklahoma, and northwestern Texas.

24 Hydrogeologic Framework and Conceptual Groundwater-Flow Model, High Plains (Ogallala) Aquifer, Oklahoma, 1998–2022

[*, no further subdivision; --, not specified; modified from Gutentag and others (1984)]

Erathem	System	Series	Geologic unit	Physical characteristics	Hydrogeologic unit	Geologic map unit symbol and color	
Cenozoic	Quaternary	Holocene	Alluvium	Unconsolidated sand, silt, clay, and gravel in stream channels.	Alluvial aquifer (alluvium and terrace deposits typically combined for aquifer; example is Beaver-North Canadian River aquifer ²)	Qal	
			Dune sand	Light brown, fine- to medium-grained sand with lesser amounts of clay, silt, and coarse sand. Formed into hills and ridges by wind.		Qd	
			Terrace deposits ¹	Light brown to gray silt, clay, sand, and gravel laid down at levels along former courses of streams.		Qt	
	Tertiary	Pliocene	Black Mesa Basalt ³	Dark, dense, vesicular rock forming cap rock of Black Mesa.	--	Tb	
		Miocene	Ogallala Formation (includes Dune Sand undivided on top of Ogallala Formation in Oklahoma)	Brown to light tan with red, pink, and yellow silt, clay, sand, and gravel. Caliche is common near surface. Mostly unconsolidated material, but some consolidated by lime cement.	Ogallala aquifer ⁴	To	
Mesozoic	Cretaceous	Upper	Colorado Group	Greenhorn Limestone	Gray limestone and calcareous shale, with some bentonite.	--	Kc
				Graneros Shale	Gray to black shale.	Confining unit	
		Lower	Dakota Sandstone	Buff to light brown, fine- to medium-grained sand with interbedded shale.	Dakota aquifer ⁵	Kds	
			Glencairn Formation	Gray to black fossiliferous shale with some fine-grained sandstone in the upper part.		Kgl	
	Jurassic	Upper	Morrison Formation	Varicolored shale, fine- to very coarse-grained sandstone, limestone, dolomite, and conglomerate.	Confining unit		Jm
		Middle	Exeter Sandstone ³	Massive, white to buff, fine- to medium-grained sandstone.	--	Je	
	Triassic	Upper	Dockum Formation	Varicolored claystone, siltstone, fine-grained sandstone, limestone, and conglomerate.	Dockum aquifer ⁶	Td	
	Paleozoic	Permian	Upper	*	Predominantly red or orange shale, mudstone, silt, and anhydrite; locally limestones and halite.	Confining unit	Pu

¹Referred to as Dune Sand in Texas (Fay, 1997).

²Ryter and Correll (2016).

³Fay (1997).

⁴OWRB (2012).

⁵Macfarlane (1995).

⁶Dutton and Simpkins (1986).

Figure 14. Surficial geologic and hydrogeologic units in the Ogallala aquifer study area, southeastern Colorado, southwestern Kansas, northeastern New Mexico, northwestern Oklahoma, and northwestern Texas.

light-brown (Hart and others, 1976). The Dakota Sandstone is present in the western part of Cimarron County but has been eroded away in the remainder of the Ogallala aquifer focus area (fig. 13; plate 1 of Hart and others, 1976). The Glencairn Formation and Lytle Sandstone directly underlie the Ogallala Formation in western Cimarron County where the Dakota Sandstone has been eroded away (plate 1 of Hart and others, 1976). The Glencairn Formation and Lytle Sandstone were previously grouped and called the Purgatoire Formation, but for this report they are mapped separately (Luza and Fay, 2003). The Glencairn Formation is a fossiliferous shale with interbedded sandstones (Luckey and Becker, 1999). The Lytle Sandstone is a fine- to medium-grained, white to buff sandstone (Luckey and Becker, 1999).

Two hydrogeologic units are contained in Jurassic geologic units in the study area. The Upper Jurassic Morrison Formation contains a confining unit identified outside of the study area, which is a varicolored shale, fine- to very coarse-grained sandstone, limestone, dolomite, and conglomerate, but variations in lithology are common (Luckey and Becker, 1999). The Morrison Formation is considered a lower confining unit for the Ogallala aquifer in Colorado and western Cimarron County, Okla. (Hart and others, 1976; Barkmann and others, 2021). The color is highly variable, with greenish gray being the dominant color (Hart and others, 1976). The Middle Jurassic Exeter Sandstone contains an aquifer located outside the study area (Robson and Banta, 1995). The Exeter Sandstone is disconformable with the overlying Morrison Formation (fig. 14; Hart and others, 1976) and is sometimes called the Entrada Sandstone (Fay, 1997). The Exeter Sandstone is a fine- to medium-grained sandstone, with some gravels found locally (Luckey and Becker, 1999).

The Dockum aquifer, which is recognized as a minor aquifer in Texas but not Oklahoma, is contained in the Upper Triassic Dockum Formation (Dutton and Simpkins, 1986), which underlies the Exeter Sandstone. The Dockum Formation is a sandstone that grades upward to a shaly sandstone (Luckey and Becker, 1999). The Dockum aquifer directly underlies the Ogallala aquifer in eastern Cimarron County and western Texas County, Okla., (Hart and others, 1976) but yields less groundwater than the Ogallala aquifer (Hart and others, 1976). The difference in geochemistry of the groundwater in the Ogallala and Dockum aquifers has been used to determine the base of the Ogallala aquifer (Dutton and Simpkins, 1986).

Paleozoic Geologic and Hydrogeologic Units

For most of the Ogallala aquifer focus area, undifferentiated Permian geologic units, which are commonly referred to as red beds, unconformably underlie the Ogallala Formation (fig. 14; Gutentag and others, 1984). The Permian geologic units consist of predominantly red or orange shale, silty mudstone, and anhydrite; limestone and halite are locally present (Luckey and Becker, 1999). These undifferentiated Permian geologic units generally function as a lower confining

unit to the Ogallala aquifer (Luckey and Becker, 1999). The Permian units unconformably underlie Mesozoic units in the western part of the Ogallala aquifer.

Groundwater Quality

The types and concentrations of dissolved chemical constituents in groundwater vary based on the lithologic and hydrologic properties of the geologic material through which the water flows. Other factors that affect groundwater quality include recharge rates, residence times within the aquifer, variations in temperature and pressure, land use (particularly agriculture), and pumping which can induce upward migration of saline waters from deeper parts of the aquifer or underlying geologic units. The range of the age of the groundwater in the Ogallala aquifer focus area is from less than 1,000 years to 9,000 years (Andrews and others, 2000).

Groundwater-quality data of the Ogallala aquifer focus area presented in this report were measured by the USGS and the OWRB as part of their Groundwater Monitoring and Assessment Program (OWRB, 2018). The USGS sampled groundwater from 25 wells in the panhandle part of the Ogallala aquifer during the period of November 20, 1958, to April 20, 2021, and 5 groundwater wells in the northwest part of the Ogallala aquifer during the period of November 19, 1951, to May 11, 2015 (USGS, 2024a). The OWRB sampled groundwater from 93 wells in the panhandle part of the Ogallala aquifer in July–October 2016 and June 2021 and 24 wells in the northwest part of the Ogallala aquifer in August–September 2013 and July–August 2019 (OWRB, 2024e).

Descriptions of groundwater quality in this report focus on total dissolved solids (TDS) concentrations and specific conductance values as well as concentrations of major cations and anions. TDS and specific conductance values were similar between the panhandle and the northwest parts of the Ogallala aquifer. TDS concentrations in the panhandle part of the Ogallala aquifer ranged from 223.0 to 1,559.0 milligrams per liter (mg/L), with a mean of 454.5 mg/L (OWRB, 2024e). TDS concentrations in the northwest part of the Ogallala aquifer ranged from 265.0 to 724.0 mg/L, with a mean of 393.1 mg/L. The U.S. Environmental Protection Agency (2022) has established a secondary drinking water standard of 500 mg/L for TDS; however, the State of Oklahoma specifies a beneficial use designation for groundwater, with TDS concentrations less than 3,000 mg/L for all purposes, and a limited beneficial use designation for treated groundwater, with TDS concentrations between 3,000 and 5,000 mg/L (Legal Information Institute, 2022). Groundwater samples from 37 wells in the panhandle part of the Ogallala aquifer and from 1 well in the northwest part of the Ogallala aquifer exceeded the secondary drinking water standard for TDS (OWRB, 2024e; USGS, 2024a). However, no groundwater samples from the Ogallala aquifer focus area had TDS concentrations greater than 3,000 mg/L in Oklahoma. Specific conductance values for groundwater samples from the

panhandle part of the Ogallala aquifer ranged from 334.5 to 2,078.0 microsiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$ at 25 °C), with a mean of 648.9 $\mu\text{S}/\text{cm}$ at 25 °C (OWRB, 2024e; USGS, 2024a). Specific conductance values for groundwater samples from the northwest part of the Ogallala aquifer ranged from 355.0 to 1,050.0 $\mu\text{S}/\text{cm}$ at 25 °C, with a mean of 552.6 $\mu\text{S}/\text{cm}$ at 25 °C.

Major cation and anion concentrations in groundwater samples were examined by using the Piper (1944) method (figs. 15, 16). For the use of the Piper (1944) method, samples were required to include calcium, magnesium, sodium, potassium, bicarbonate, carbonate, chloride, sulfate, and fluoride concentrations. Concentrations in milligrams per liter were converted to units of milliequivalents per liter, and samples were excluded from analysis if the difference in the cation-anion balance for the sample was greater than

10 percent. In total, 174 out of the 181 groundwater-quality samples met the aforementioned criteria; 141 samples were from the panhandle part of the Ogallala aquifer, and 33 samples were from the northwest part (OWRB, 2024e; USGS, 2024a). Most groundwater samples in both parts of the aquifer were bicarbonate type, with calcium having the highest relative cation concentration and then magnesium in most samples (figs. 15, 16). Groundwater samples collected from the northwest part of the Ogallala aquifer were less mixed than groundwater samples from the panhandle part and had a larger milliequivalent concentration of calcium bicarbonate. The calcium bicarbonate likely indicates high amounts of caliche, a calcium carbonate hardpan, that interacts with rainwater during recharge (Sanford, 2023).

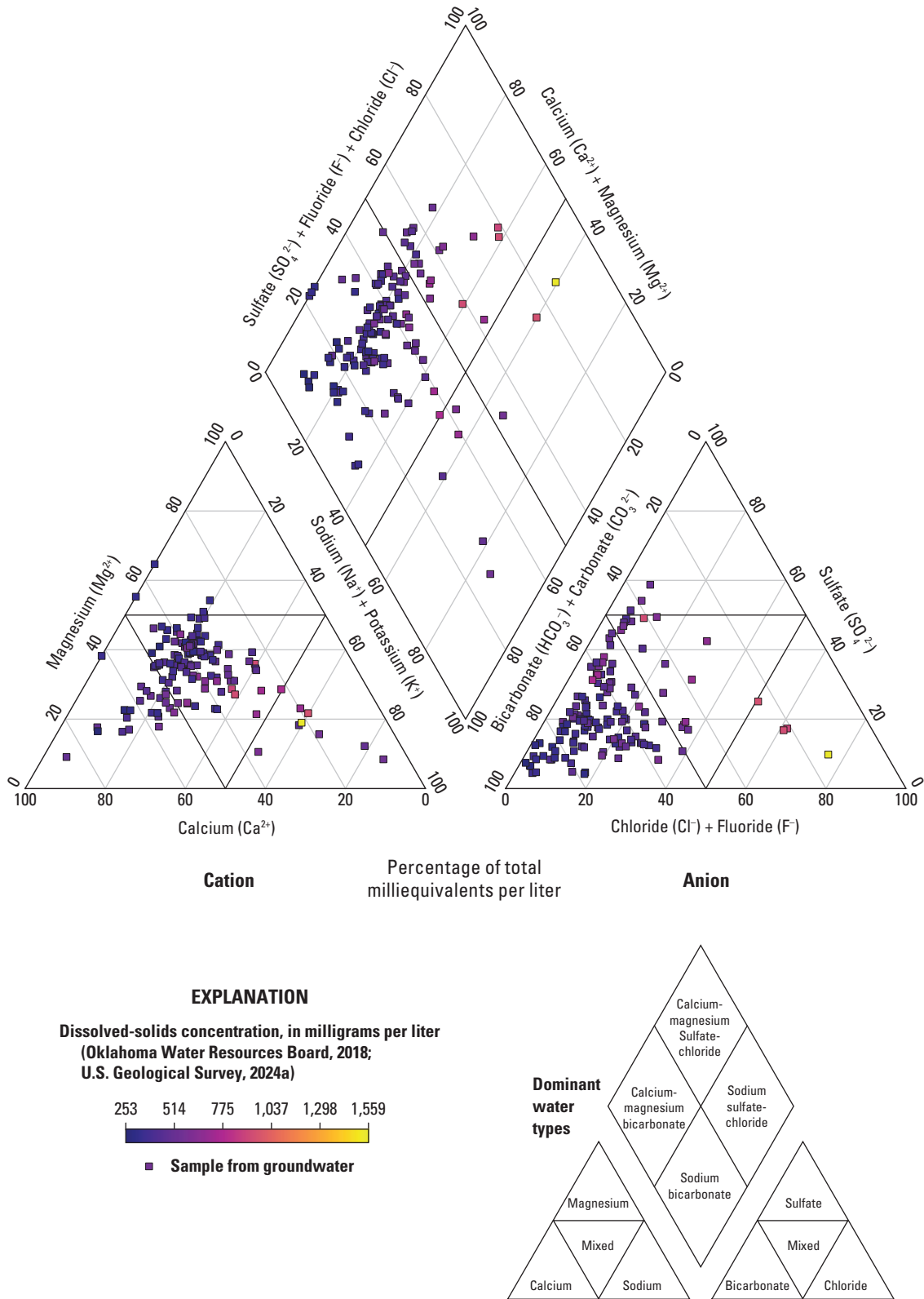


Figure 15. Major cation and anion concentrations in water produced from the panhandle part of the Ogallala aquifer, Oklahoma, 1958–2021.

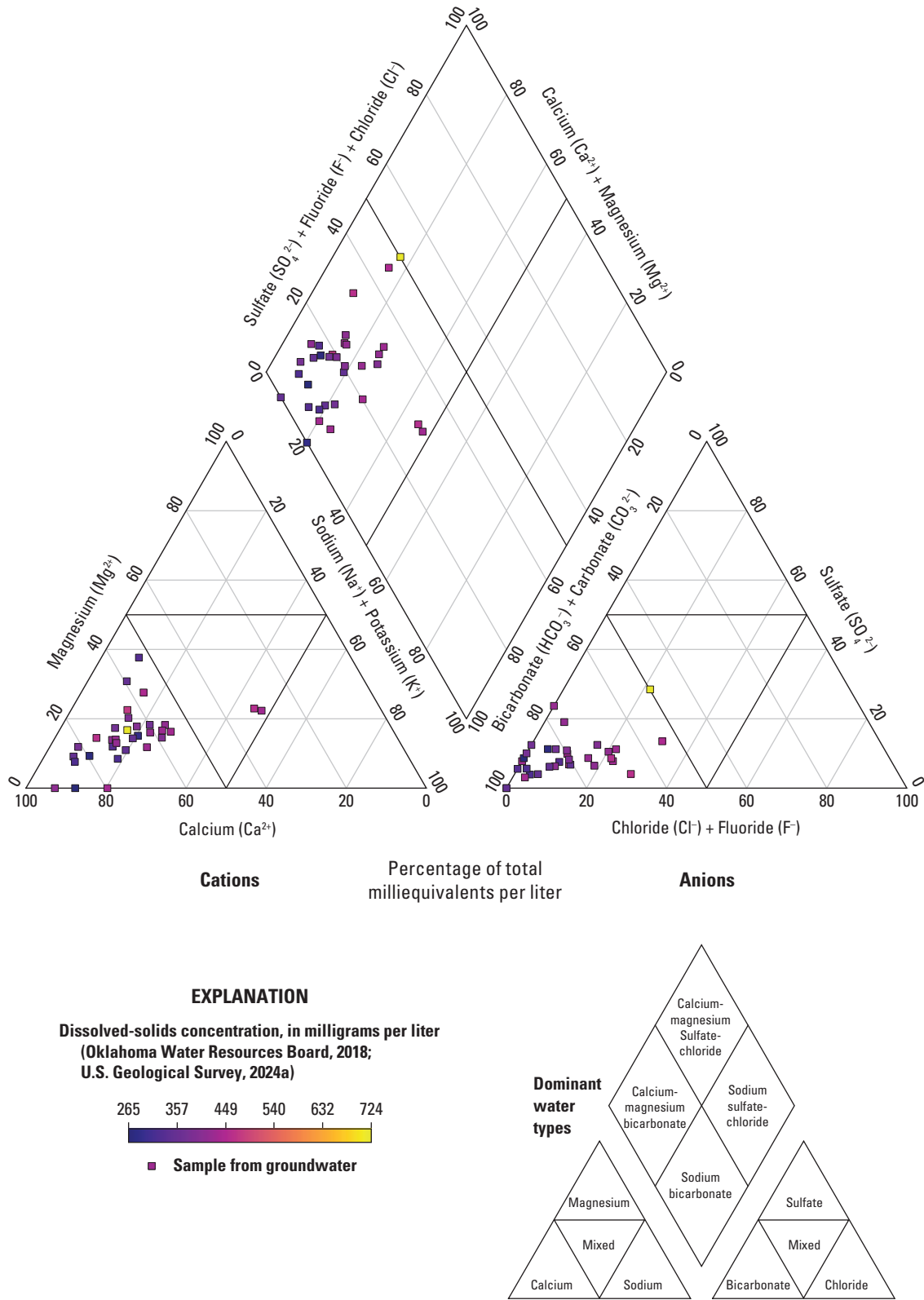


Figure 16. Major cation and anion concentrations in water produced from the northwest part of the Ogallala aquifer, Oklahoma, 1951–2019.

Hydrogeologic Framework of the Ogallala Aquifer Focus Area

A hydrogeologic framework is a three-dimensional representation of an aquifer that explains how it interfaces with surrounding geologic units at a scale that captures the regional controls on groundwater flow (Smith and others, 2021). An updated hydrogeologic framework was developed for the Ogallala aquifer focus area, including an updated definition of the potentiometric surface and a description of the textural and hydraulic properties of the aquifer materials. The hydrogeologic framework was used to inform the construction of the conceptual groundwater-flow model of the Ogallala aquifer focus area described in this report.

Ogallala Aquifer Focus Area Extent and Base

The geographic extent of the Ogallala aquifer focus area (fig. 1) was established by the OWRB (2024b). Because the Ogallala aquifer is an unconfined bedrock aquifer, the aquifer extent was generally defined by the surficial exposure of the Ogallala Formation as shown on 1:250,000-scale geologic maps from Stoesser and others (2005). The top of the Ogallala aquifer in the focus area was defined as the land-surface altitude obtained from a 10-meter (horizontal resolution) digital elevation model (DEM) (USGS, 2015). The altitude of the base of the Ogallala aquifer in the focus area (fig. 17) was generally considered to be the top of the underlying Permian or Cretaceous rocks. The altitude of the base of the aquifer was calculated by subtracting the depth to the top of these underlying bedrock units from the altitude of the top of the Ogallala aquifer.

Well completion reports containing drillers' lithologic logs obtained from the OWRB (2024b) were used to modify the base of the Ogallala aquifer from Luckey and Becker (1999). Approximately 330 wells were considered fully penetrating; therefore, the depths of those wells were assumed to be depths to the base of the aquifer (top of the underlying Permian and Cretaceous units). The drillers' lithologic logs were searched for terms representing the Permian and Cretaceous bedrock units (for example, redbed, blue clay, and yellow clay). The depth of the first occurrence of these terms was subtracted from the altitude of the top of the aquifer to calculate the altitude of the aquifer base. The altitudes of the aquifer base were then used to modify the aquifer-base contours from Luckey and Becker (1999), primarily in Texas, Beaver, and Ellis Counties, Okla., to incorporate data from the newer well logs.

Potentiometric Surface and Saturated Thickness

A potentiometric-surface map is a contour map of the altitudes of the water surface in tightly cased wells at a specified time (Fetter, 2001). The potentiometric surface is contoured from synoptic water-table altitude measurements in many groundwater wells across an aquifer extent. Potentiometric-surface maps can be used to show the general directions of groundwater flow in the aquifer. Groundwater flows perpendicularly to the contours towards decreasing contour altitudes.

In March 2021, the OWRB made synoptic water-table altitude measurements (Codner and others, 2026) at groundwater wells (fig. 18) throughout the Ogallala aquifer focus area. The depth to water below the land surface was measured at 311 wells (Codner and others, 2026) to determine the altitude of the water table referenced to the North American Vertical Datum of 1988. Five measurements were not used because there was evidence of pumping during or immediately before the levels were measured. For the purposes of the potentiometric-surface measurements, the OWRB combined the Dakota and Dockum aquifers and used them as a part of the Ogallala aquifer for this analysis (Codner and others, 2026). Because the Ogallala aquifer is an unconfined aquifer, the groundwater-level altitude measurements were calculated by subtracting the depth-to-water measurements from the land-surface altitude obtained from a 10-meter (m; horizontal resolution) DEM (USGS, 2015). The groundwater-level altitude measurements were gridded to make a potentiometric surface for the Ogallala aquifer focus area by using the inverse-distance-weighted interpolation method in the ArcGIS Topo to Raster tool (Esri, 2024d) and contoured by using the ArcGIS Contour tool (Esri, 2024a). The potentiometric-surface contours from Luckey and Becker (1999) were used as control points for areas with little to no groundwater-level altitude data. Additional control points were created along streamlines in the Ogallala aquifer focus area and were assigned groundwater-level altitudes from the 10-m DEM minus 15 ft to ensure that the potentiometric contours were below the land surface near streams. Based on the potentiometric surface, groundwater within the Ogallala aquifer focus area generally flows from west to east and begins flowing toward streams in eastern Texas County (fig. 18).

The saturated thickness of the Ogallala aquifer within the Ogallala aquifer focus area (fig. 19) was determined by subtracting the gridded altitude of the aquifer base from the gridded potentiometric-surface altitude (figs. 17, 18). The saturated thickness ranged from less than 20 ft in some areas in western Cimarron County to 517 ft in the downthrown parts of Crooked Creek Fault in Beaver County (fig. 19). The mean saturated thickness of the Ogallala aquifer within the focus area was 125 ft in March 2021 (table 5).

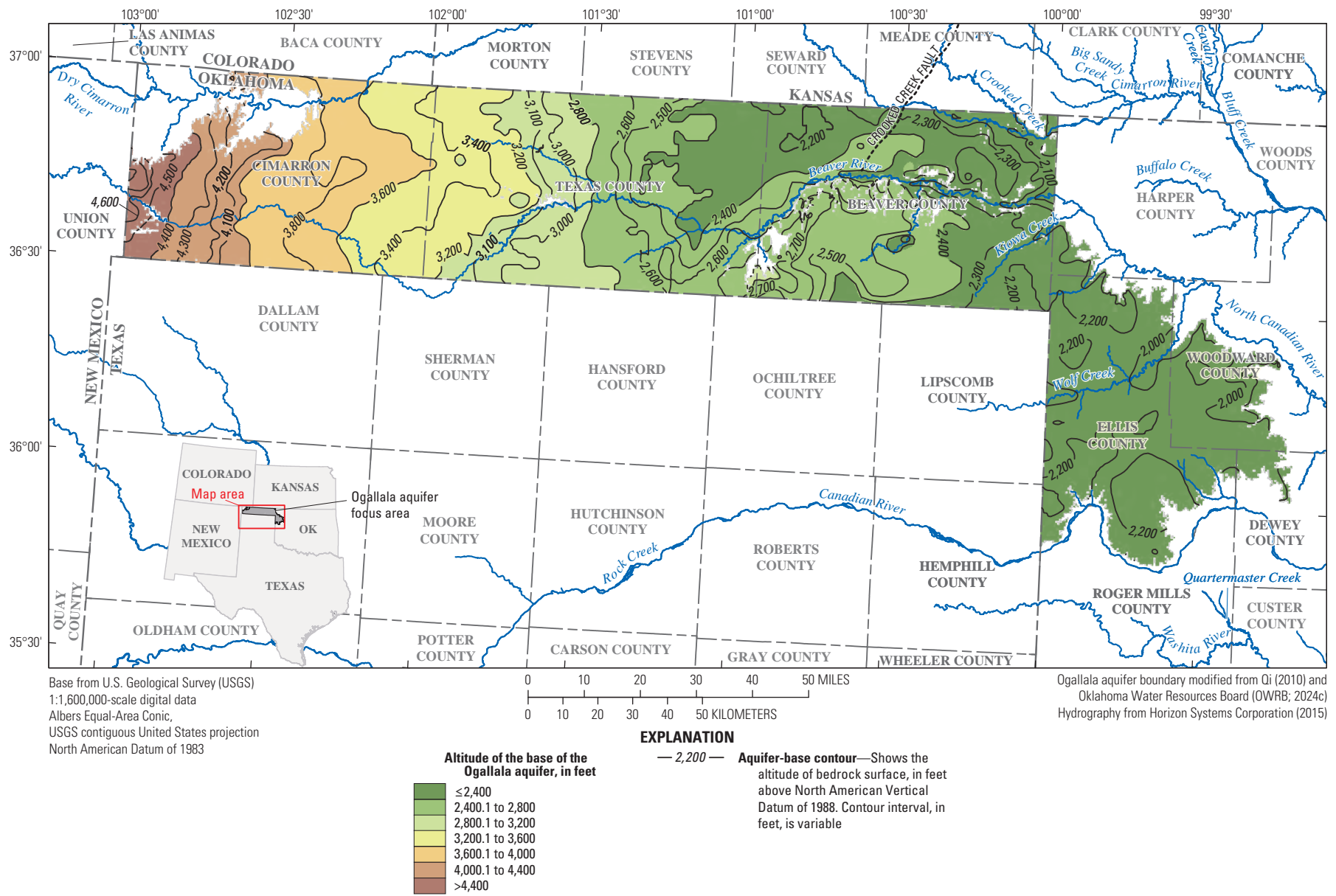


Figure 17. The altitude of the base of the Ogallala aquifer in the Ogallala aquifer focus area, Oklahoma.

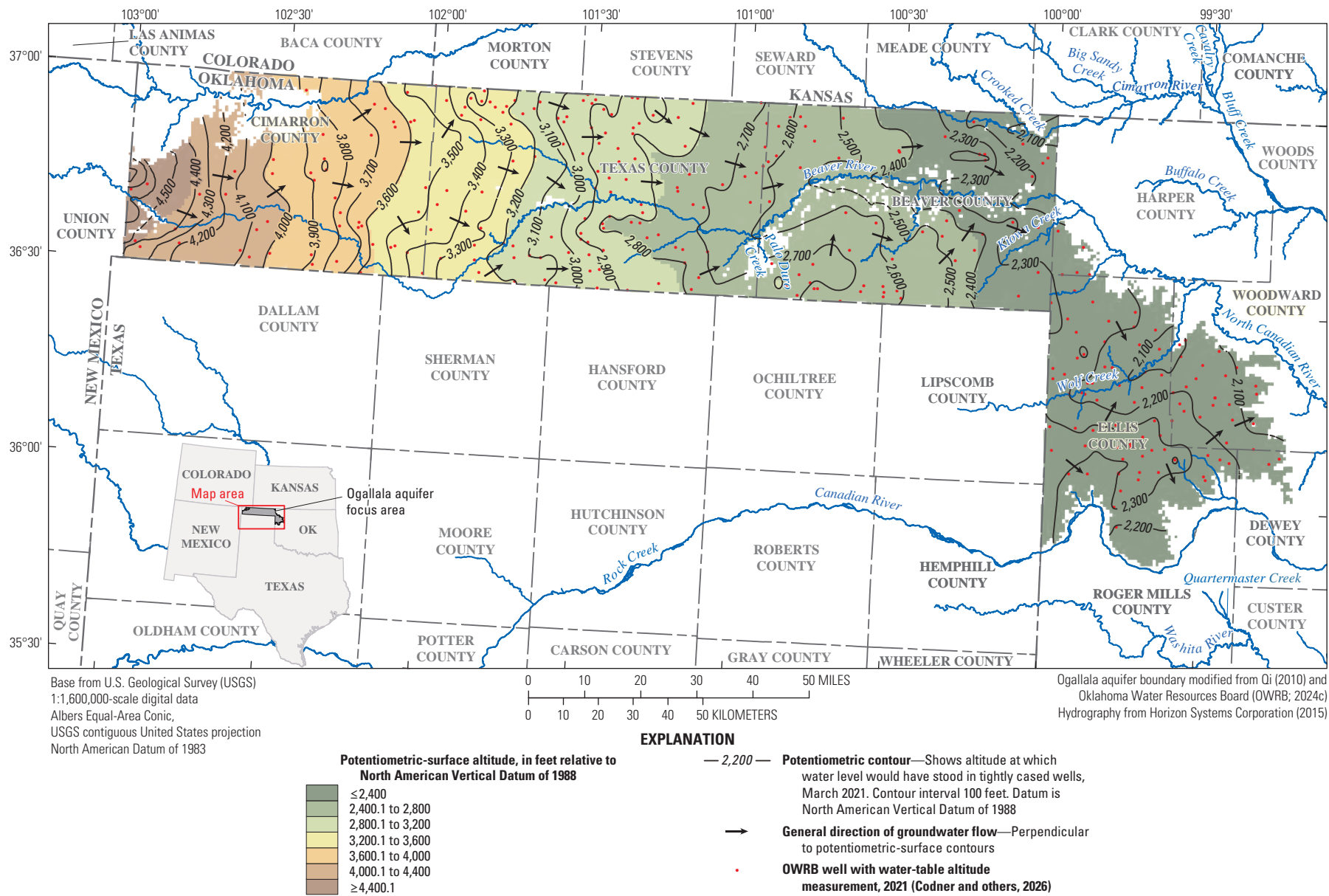


Figure 18. Potentiometric surface contours and general direction of groundwater flow within the Ogallala aquifer focus area, Oklahoma, March 2021.

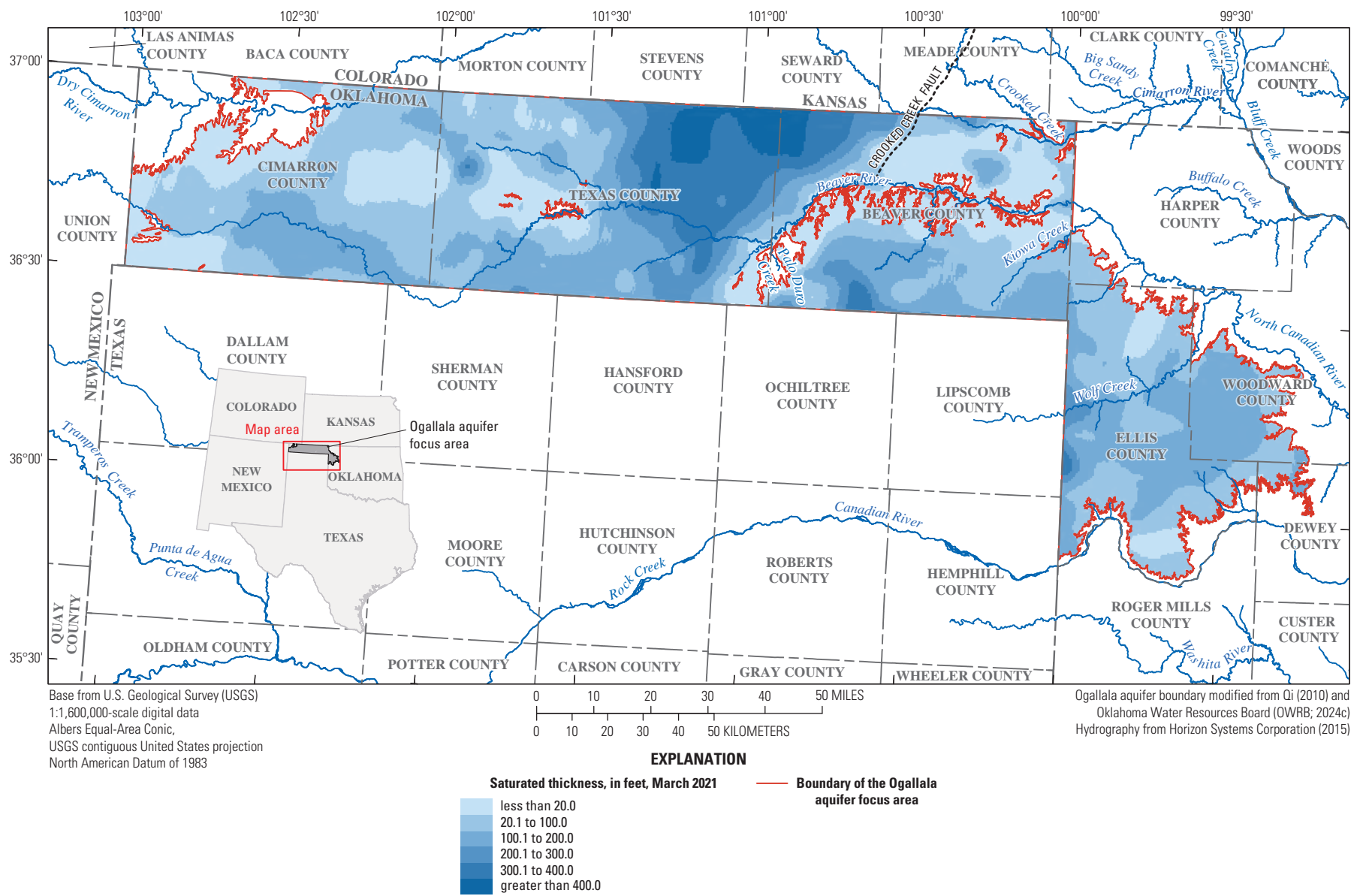


Figure 19. Estimated saturated thickness of the Ogallala aquifer in the Ogallala aquifer focus area, Oklahoma, March 2021.

Table 5. Summary of saturated thickness and total groundwater storage for the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area, March 2021.

Region	Area (acres)	Mean saturated thickness (feet; fig. 19)	Mean estimated specific yield (table 6)	Total groundwater storage (acre-feet)
Panhandle part of the Ogallala aquifer	3,334,636	127	0.09	38,114,889
Northwest part of the Ogallala aquifer	940,486	116	0.09	9,818,674
Ogallala aquifer focus area	4,275,122	125	0.09	147,933,563

¹This value was calculated as the sum of the aquifer parts and was not calculated from mean saturated thickness of the Ogallala aquifer in the focus area.

Textural and Hydraulic Properties

The distribution and variability of textural and hydraulic properties of aquifer materials, especially the horizontal hydraulic conductivity, are the primary controls on groundwater flow in the Ogallala aquifer focus area. Hydraulic properties were previously studied throughout the Ogallala aquifer focus area, but this investigation focused on studies that were completed in Oklahoma and Texas. Hart and others (1976) performed 10 multiwell pumping tests in the panhandle part of the Ogallala aquifer to determine transmissivity, storage coefficient (which is roughly equivalent to specific yield in unconfined aquifers), and hydraulic conductivity values. The transmissivity values ranged from 500 to 11,800 feet squared per day (ft²/d), with a mean of 5,438 ft²/d; the storage coefficient values ranged from 0.002 to 0.11, with a mean of 0.05; and the hydraulic conductivity values ranged from 2.1 to 55 feet per day (ft/d), with a mean of 25.7 ft/d. Teeple and others (2021) estimated hydraulic conductivity and specific yield values in the Ogallala aquifer in Texas by using single-well aquifer tests, borehole electromagnetic flowmeter measurements, and borehole nuclear magnetic resonance (NMR) measurements. Those hydraulic conductivity values ranged from 0.55 to 350 ft/d, with a median of 5.7 ft/d, and specific yield values ranged from 0.03 to 0.13, with a median of 0.09.

Multiple methods were used in this study to estimate the range and central tendency of hydraulic conductivity values in the Ogallala aquifer focus area. These methods included borehole NMR measurements, slug tests, and analysis of lithologic descriptions from wells completed in the Ogallala aquifer. Even though these methods were consistently used across the Ogallala aquifer focus area, hydraulic properties between the panhandle and northwest parts of the Ogallala aquifer could not be differentiated because of limitations on the amount of testing that could be completed. Therefore, hydraulic properties are presented for the Ogallala aquifer focus area as a whole.

Hydraulic Properties Estimated From Nuclear Magnetic Resonance

NMR is a borehole geophysical technique that measures the aquifer water content directly in the subsurface by detecting how water molecules react to magnetic fields generated by the geophysical tool. The NMR method involves disturbing the magnetic moments of hydrogen atoms in water molecules and measuring the time it takes for those magnetic moments to recover to a previously established stable moment (Dunn and others, 2002). The amount of time it takes for the hydrogen atoms' magnetic moment to relax from this stimulation is known as the transverse relaxation time T_2 , which conveys information about the pore space volume in the subsurface (Dlubac and others, 2013). A relatively longer T_2 indicates a relatively larger pore space.

A wireline Javelin JPX-350 (Vista Clara Inc., 2024) was used to collect NMR data for this investigation (USGS, 2024b). The tool has a diameter of 3.5 inches and a length of approximately 15 ft. The diameter of sensitivity ranges from 10 to 15 inches through the center of the tool (Teeple and others, 2021). Groundwater-well construction was considered to ensure that hydraulic properties of the aquifer were measured rather than the well pack or screen properties. Therefore, only wells with an internal diameter of 4–9 inches were chosen for investigation to reduce the influence of the well pack or screen and thus maximize the influence of the aquifer materials on NMR measurements. To avoid magnetic interference, NMR measurements were restricted to wells that were free of metal in the well, casing, or well pack. The NMR data were processed by using Javelin Pro Plus software version 3.7 (Vista Clara Inc., 2024). Frequency measurements, produced after processing the NMR measurements, with greater than 15 percent residual noise were removed. The T_2 decay data, which were determined from frequency measurements with less than 15 percent residual noise, were filtered by using an impulse noise filter and adjusted by removing the ambient noise; ambient noise data were collected with an external reference coil at the land surface. Depth-averaging across three measurements was applied to smooth the data and dampen the effects of any unfiltered noise. The

four frequency measurements for each log were “noise-stacked,” meaning that they were combined in proportion to their relative noise (Teeple and others, 2021).

Total porosity is divided into mobile, capillary, and bound water percentages, and these porosity components were determined from T_2 relaxation times (Morris and others, 1997). Software defaults for capillary and bound water are 33 and 4 milliseconds, respectively, and are generally accepted as cutoff values (Timur, 1969; Walsh and others, 2013; Behroozmand and others, 2015; Teeple and others, 2021). The average mobile-water fraction of the total porosity for the saturated part of the aquifer, regardless of well opening or screened interval, was used to represent the specific yield of the aquifer at the well location (Teeple and others, 2021). Bound water for this study will be described separately as clay- and capillary-bound water. Hydraulic conductivity estimates were calculated with the Schlumberger-Doll equation (Kenyon and others, 1988).

Six groundwater wells (table 6) were used to conduct NMR tests in November 2023. For each well, naturally occurring gamma rays, conductivity, and resistivity were measured in addition to the NMR measurements. These data were used to estimate hydraulic conductivity and specific yield in the aquifer saturated zone intersected by the wells. The saturated zone is the portion of the aquifer in which mobile water content, capillary bound fluid content, and clay bound fluid content exceed 0 percent (USGS, 2024b). Mean estimated productive zone horizontal hydraulic conductivities from each well ranged from 5.9 to 144.8 ft/d (table 6). The estimated specific yield values from NMR measurements ranged from about 0.053 to 0.134 with a mean of about 0.09 (table 6).

Geophysical data collection followed the borehole geophysical standard procedures set by ASTM International (2017, 2018, 2019). Tabular data were archived as Log American Standard Code for Information Interchange

Standard (LAS) files (Canadian Well Logging Society, 2024) and presented as chart logs in Portable Document Format (PDF) files. The LAS, PDF, original binary, and image files of the NMR data are available in the USGS GeoLog Locator database (USGS, 2024b).

Hydraulic Properties Estimated From Slug Tests

Slug tests were performed at nine groundwater wells (table 7) across the Ogallala aquifer focus area. Multiple slug tests were performed at each well to ensure repeatability and well integrity. The decision to use either mechanical or poured slugs depended on the depth to water in each well; a mechanical slug is a sand-filled polyvinyl chloride pipe that is lowered into and pulled out of the water column, whereas a poured slug is water poured down the well quickly to induce a nearly instantaneous change in the altitude of the water column in the well. A submersible pressure transducer was used to monitor groundwater-level changes every quarter-second for the duration of the slug tests. The slug test responses were analyzed by using the AQTESOLV 4.50 software package (HydroSOLVE, Inc., 2011) and were matched to an analytical solution dependent on the well construction and the observed response of each test using the methods explained in Butler (1998). The analytical solutions used for the slug tests included the Kansas Geological Survey solution (Hyder and others, 1994) for unconfined aquifers and the Bouwer and Rice (1976) solution for unconfined aquifers. More details on the analyses of the slug tests are included in the accompanying data release (Codner and others, 2026).

The horizontal hydraulic conductivity values determined from the analytical solutions ranged from 0.9 to 13.2 ft/d (table 7). Transmissivity values, which are the products of hydraulic conductivity and saturated thickness, ranged from 177.0 to 1,705.5 ft²/d (table 7).

Table 6. Hydraulic properties for the saturated zone of the Ogallala aquifer derived from nuclear magnetic resonance (NMR) measurements from selected wells in the Ogallala aquifer focus area, Oklahoma, November 2023.

[NMR data are available in the U.S. Geological Survey (USGS) GeoLog Locator database (USGS, 2024b); OWRB, Oklahoma Water Resources Board; ft/d, foot per day; --, not applicable]

Map identifier (fig. 1; table 1)	USGS station number (USGS, 2024a, b)	OWRB station number	NMR-estimated depth to water (feet below land surface)	Estimated specific yield	Interpreted saturated zone (feet)	Range of NMR-estimated horizontal hydraulic conductivity (ft/d)	Mean NMR-estimated horizontal hydraulic conductivity (ft/d)
GW01	363536100024701	349	121.3	0.134	150.0–240.4	0.34–110.13	20.5
GW02	363045101094201	927	148.6	0.063	190.0–205.0	0.18–55.12	17.7
GW03	362750099392701	3270	69.6	0.105	152.0–243.3	0.02–36.94	11.8
GW04	364228100341701	9051	83.1	0.071	100.0–120.0	2.4–15.25	7.5
GW07	360819099406001	42791	124.9	0.053	170.0–182.6	2.07–9.12	5.9
GW11	365933101221001	1886	111.3	0.127	111.3–130.3	0.03–275.93	144.8
Mean			109.8	0.092	--	--	34.7

Table 7. Hydraulic properties for the Ogallala aquifer derived from slug-test measurements from selected wells in the Ogallala aquifer focus area, Oklahoma, 2023.

[Data available in Codner and others (2026); USGS, U.S. Geological Survey; OWRB, Oklahoma Water Resources Board]

Map identifier (fig. 1; table 1)	USGS station number (USGS, 2024a)	OWRB station number	Depth to water (feet below land surface)	Horizontal hydraulic conductivity (feet per day)	Transmissivity values (feet squared per day)
GW01	363536100024701	349	116.0	12.5	1,312.2
GW02	363045101094201	927	155.5	2.8–3.8	507.6–614.2
GW03	362750099392701	3270	58.9	6.7–8.6	805.9–1,025.4
GW04	364228100341701	9051	91.9	2.1–2.4	564.7–629.2
GW05	363223102234101	24401	76.6	8.9–11.4	684.8–1,656.8
GW06	363511101164201	33768	130.1	0.9–1.0	177.0–203.6
GW07	360819099406001	42791	151.0	13.0–13.2	1,682.1–1,705.5
GW08	365335102092301	129152	216.4	3.9–4.6	411.2–481.6
GW17	Not applicable	137270	230.8	7.1–7.4	1,341.2–1,401.8

Horizontal Hydraulic Conductivity Estimated From Lithologic Logs

The horizontal hydraulic conductivity distribution for the Ogallala aquifer focus area was estimated by using more than 8,000 lithologic logs associated with well-completion reports (OWRB, 2024b). The lithologies provided in the lithologic logs were standardized, categorized, and converted to percentage-coarse-material values by using the methods of Mashburn and others (2014).

The lithologic logs included terms such as “gravel,” “sand,” “silt,” and “clay” to describe drill cuttings from the geologic units of the Ogallala aquifer focus area; however, the terms varied among the drillers. The lithologic logs were simplified and standardized into five lithologic categories (clay/silt, fine sand, medium sand, coarse sand, and gravel) with corresponding percentage-coarse-material quantile ranges (0–19, 20–39, 40–59, 60–79, and 80–100 percent). The midpoint for each percentage-coarse-material quantile range (10, 30, 50, 70, and 90 percent) was assigned to each lithologic log depth interval. The percentage-coarse-material value for each lithologic depth interval was computed as the thickness-weighted mean percentage-coarse-material value assigned to the lithologic categories in each log. The gravel material was the maximum material size and was assigned a percentage-coarse-material value of 90 percent. The clay material was the minimum material size and was assigned a percentage-coarse-material value of 10 percent.

The horizontal hydraulic conductivity values estimated from lithologic logs ranged from 2.09 to 55 ft/d, using the previously published maximum and minimum estimated horizontal hydraulic conductivity values from the multiwell aquifer test (Hart and others, 1976). By using this range and methods from Ellis and others (2017), the following equation was developed by correlating the minimum and maximum

horizontal hydraulic conductivity values to 10- and 90-percent coarse material, respectively, and performing a linear regression to characterize the relation between horizontal hydraulic conductivity and the percentage-coarse material for the Ogallala aquifer focus area:

$$K_h = (0.66 \times P_s) - 4.52, \tag{1}$$

where

- K_h is the horizontal hydraulic conductivity, in feet per day; and
- P_s is the percentage-coarse-material value.

Equation 1 was used in this study to estimate horizontal hydraulic conductivity values from lithologic logs in the Ogallala aquifer focus area. The lithologic-log-estimated hydraulic conductivity values ranged from 2.09 to 55.00 ft/d, with a mean of about 16.11 ft/d (fig. 20). The mean lithologic-log-estimated hydraulic conductivity of 16.11 ft/d is within the range of values determined from NMR measurements.

Groundwater Storage

Groundwater storage, in acre-feet (table 5), was calculated for the Ogallala aquifer focus area for the year 2021 by using the following formula, which was modified from Fetter (2001) for an unconfined aquifer:

$$Groundwater\ storage = S_y \times b_a \times A, \tag{2}$$

where

- S_y is the specific yield, dimensionless;
- b_a is the mean saturated thickness of the aquifer, in feet; and
- A is the aquifer area, in acres.

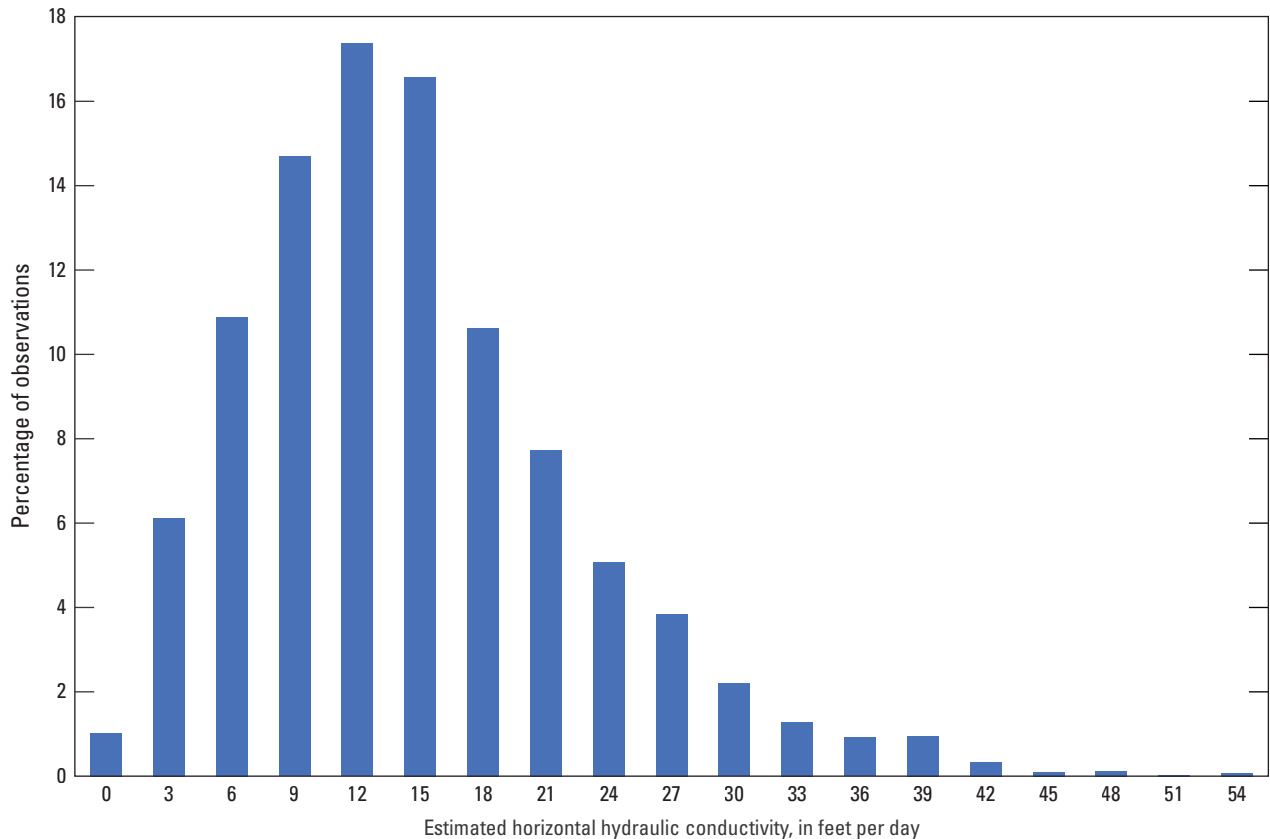


Figure 20. Distribution of estimated horizontal hydraulic conductivity values calculated from lithologic logs in the Ogallala aquifer focus area, Oklahoma.

A specific yield value of 0.09 was assigned to the Ogallala aquifer focus area based on the NMR measurements described in the “Hydraulic Properties Estimated from Nuclear Magnetic Resonance” section. This value is comparable to the specific yield of 0.10 determined from the aquifer tests of Hart and others (1976). Total groundwater storage for the panhandle and northwest parts of the Ogallala aquifer were calculated by multiplying the mean estimated specific yield of 0.09 by the aquifer area and the mean saturated thickness (fig. 19; table 5)

Conceptual Groundwater-Flow Model

A conceptual groundwater-flow model (hereinafter referred to as the “conceptual model”) is a simplified representation of the groundwater-flow system which accounts for the major inflow and outflow sources across hydrologic boundaries for a specified period. The conceptual model for the Ogallala aquifer focus area (table 8; fig. 21) was based on the hydrogeologic framework and climatic conditions to approximate the conceptual-model water budget for the 1998–2022 study period.

Hydrologic Boundaries

Hydrologic boundaries in the conceptual model represent real-world sources (inflows) and sinks (outflows) of water to and from the aquifer. Boundaries that act as both inflows and outflows may be referred to as “net inflows” or “net outflows” depending on which flow component dominates. Hydrologic boundary flows considered in this report include recharge, irrigation return flows, well withdrawals, saturated zone evapotranspiration, streambed seepage, change in groundwater storage, lateral groundwater flows, and vertical leakage (fig. 21; table 8).

Recharge

Recharge, as defined in this report, is groundwater from infiltrating precipitation and snowmelt that has reached the water table of an unconfined aquifer. Recharge rates to the High Plains aquifer in the study area are highly variable; published recharge rates range from 0 to 7 in/yr, with a mean value of 0.915 in/yr in the study area (table 9; Stanton and others, 2011; OWRB, 2012; Wyatt and others, 2018). The mean value was calculated from the mean recharge values for specific locations which are listed in table 9. Recharge probably occurs more rapidly and in greater amounts in areas

Table 8. Conceptual groundwater-flow model water budget of estimated mean annual inflows and outflows for the hydrologic boundaries for the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area, 1998–2022.

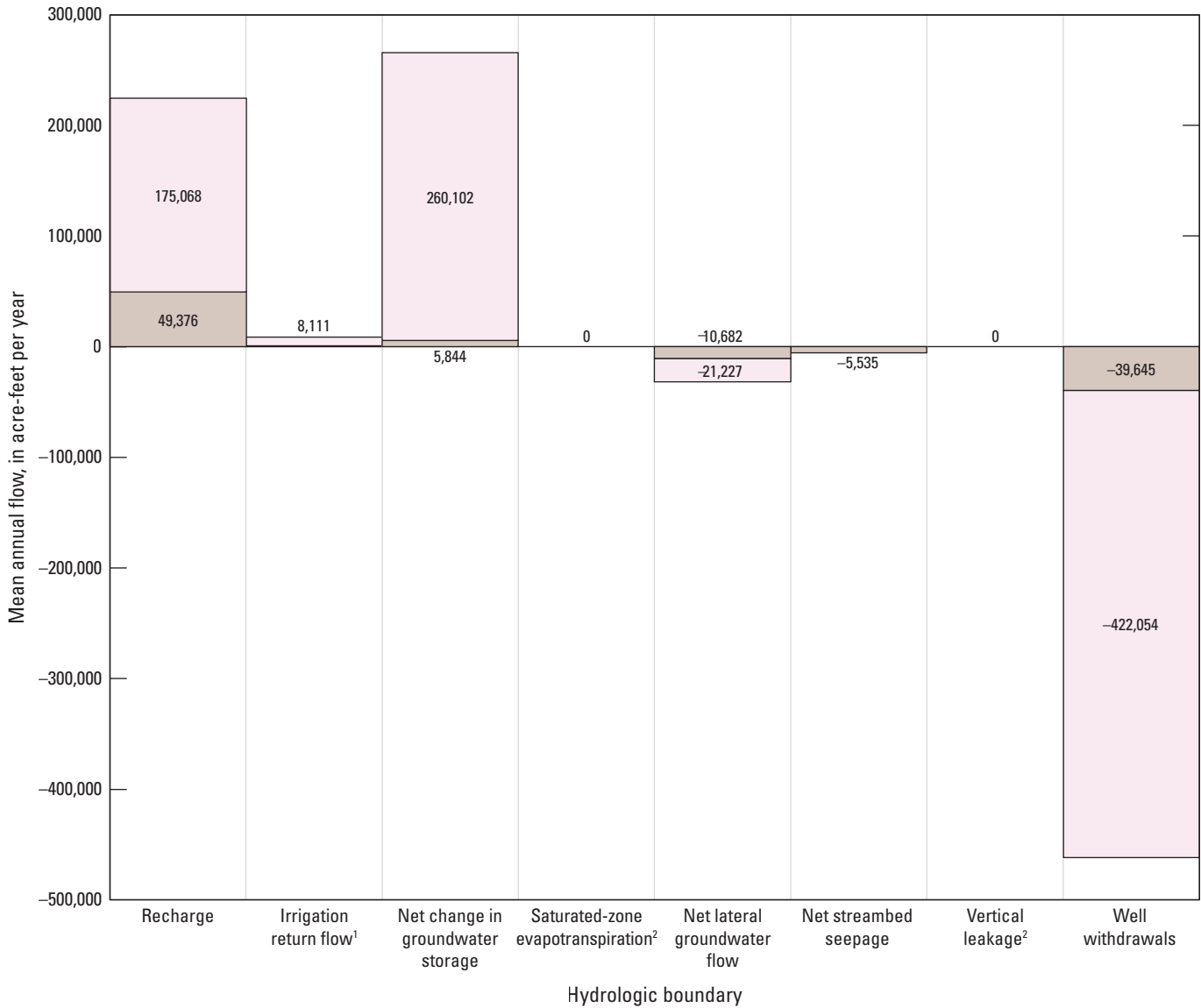
[acre-ft/yr, acre-foot per year; in/yr, inch per year; --, not quantified; ft, foot; ft³/s, cubic foot per second; USGS, U.S. Geological Survey; OWRB, Oklahoma Water Resources Board; NWI, National Wetlands Inventory]

Hydrologic boundary	Panhandle part of the Ogallala aquifer ¹ (acre-ft/yr)	Northwest part of the Ogallala aquifer ² (acre-ft/yr)	Total (Ogallala aquifer focus area) ³ (acre-ft/yr)	Percentage of water budget	Notes
Inflows					
Recharge	175,068	49,376	224,444	44.97	Estimated 0.63 in/yr using Whittemore and others (2015) method (fig. 22).
Irrigation return flow	8,111	642	8,753	1.75	Estimated from Luckey and Becker (1999) assumption that irrigation return flows were 2 percent of well withdrawals of 405,541 acre-ft/yr for panhandle and 32,075 acre-ft/yr for northwest part of the Ogallala aquifer (Codner and others, 2026).
Net change in groundwater storage	260,102	5,844	265,946	53.28	14.5-ft decrease in groundwater level across the whole aquifer.
Total inflow	443,281	55,862	499,143	100.00	
Outflows					
Saturated-zone evapotranspiration	--	--	--	--	Assumed to be a negligible part of water budget.
Net lateral groundwater flow	21,227	10,682	31,908	6.39	Unknown; calculated as balance of water budget.
Net streambed seepage	--	5,535	5,535	1.11	Estimated from mean annual base flow (2010–22) of 7.64 ft ³ /s at USGS 07235600 Wolf Creek near Gage, Okla. (table 4; fig. 12B).
Vertical leakage	--	--	--	--	Assumed to be a negligible part of water budget.
Well withdrawals	422,054	39,645	461,700	92.50	From OWRB-reported water-use data (tables 2, 3).
Total outflow	443,281	55,862	499,143	100.00	

¹Area of the panhandle part of the Ogallala aquifer is 3,334,636 acres.

²Area of the northwest part of the Ogallala aquifer is 940,486 acres.

³Area of the Ogallala aquifer focus area is 4,275,122 acres.



EXPLANATION

Conceptual groundwater-flow model water budget with mean annual flow (1998–2022)

175,068	Panhandle part of the Ogallala aquifer
49,376	Northwest part of the Ogallala aquifer

¹The irrigation return flow for the northwest part of the Ogallala aquifer is 642 acre-feet per year, which is not large enough to be represented on the graph.

²Assumed to be a negligible part of water budget.

Figure 21. Estimated mean annual inflows and outflows by hydrologic boundary for the conceptual groundwater-flow model of the panhandle and northwest parts of the Ogallala aquifer, Oklahoma, 1998–2022.

with sandy soils and pervious land cover than in areas with clay-rich soils and impervious land cover (Luckey and Becker, 1998). The distribution of playa lakes and caliche zones also likely affects the timing and distribution of recharge across the Ogallala aquifer focus area (Luckey and Becker, 1998). Precipitation and snowmelt may take years to infiltrate to the Ogallala aquifer's saturated zone (Andrews and others, 2000), which lies more than 200 ft below land surface in some areas (USGS, 2024a). Long lag times between precipitation events and rises in groundwater levels violate an assumption of simple recharge estimation methods like the water-table fluctuation method (Healy and Cook, 2002), which assumes hours to days between a precipitation event and a subsequent rise in groundwater.

Two methods were used in this study to estimate recharge rates to the Ogallala aquifer for the 1998–2022 study period: (1) the groundwater-use regression method (Whittemore and others, 2015; Butler and others, 2016), which was used to estimate spatially distributed recharge rates and (2) the Soil-Water-Balance (SWB) code (Westenbroek and others, 2018).

Recharge estimates from previously published studies, focused within Oklahoma and the surrounding High Plains aquifer, were compiled to use as a composited-average recharge estimate for the Ogallala aquifer focus area and the surrounding High Plains aquifer (table 9).

Groundwater-Use Regression

Annual groundwater-use and groundwater-level change data can be used to estimate mean annual recharge when groundwater discharge to streams is negligible (Whittemore and others, 2015; Butler and others, 2016). Annual groundwater-use data (Codner and others, 2026) were plotted against annual mean groundwater-level change data (McGuire, 2024) for the shared period of record 1988–2019 (fig. 22). Data was not available for 2000 or 2001. A linear regression yielded a coefficient of determination (R^2) of 0.1449, indicating a weak relation between the two datasets (fig. 22). The regression slope was negative, indicating that greater annual groundwater-use rates were correlated with greater annual groundwater-level declines. Years in which annual groundwater use was associated with rises in groundwater levels could be interpreted as years in which the annual recharge rate exceeded the annual groundwater-use rate. Thus, the least-squares-regression line (fig. 22) was used to project and estimate the annual groundwater-use rate that would be associated with no change in groundwater levels. Assuming negligible influences from other inflows or outflows to the aquifer, this groundwater-use value would be equivalent to the mean annual recharge to the aquifer for the analysis period.

Soil-Water-Balance Code

Recharge in the Ogallala aquifer focus area was simulated for the study period 1998–2022 by using the SWB code, version 2.0 (Westenbroek and others, 2018). The input and output data files associated with the SWB-code simulation

for the Ogallala aquifer focus area are included in the data release (Codner and others, 2026) that is associated with this report. The SWB code is based on a modified Thornthwaite and Mather (1957) soil-moisture accounting method that estimates recharge as the daily amount of infiltration that exceeds the storage capacity of the plant root zone. The SWB code uses the following equation (modified from Westenbroek and others [2010]):

$$R = (P + S + R_i) - (Int + R_o + ET) - \Delta Sm, \quad (3)$$

where

R	is recharge, in inches per day;
P	is precipitation, in inches per day;
S	is snowmelt, in inches per day;
R_i	is surface runoff inflow, in inches per day;
Int	is plant interception, in inches per day;
R_o	is surface runoff outflow, in inches per day;
ET	is evapotranspiration, in inches per day; and
ΔSm	is the change in soil moisture, in inches per day.

The SWB code requires landscape-characteristic (land-cover type, soil-water storage capacity, land-surface flow direction, and hydrologic soil group) and climatological (daily temperature and precipitation) input data to estimate spatially distributed recharge over a user-defined grid. The grid used for the implementation of the SWB code described in this report consisted of 566 rows by 783 columns of cells which were each 1,500 by 1,500 ft. The Hargreaves and Samani (1985) method was used to compute reference evapotranspiration. Soil-water storage capacity and hydrologic soil group data were obtained from the Gridded Soil Survey Geographic database (U.S. Department of Agriculture, 2021). The D8 method (Greenlee, 1987) in the ArcGIS Flow Direction tool (Esri, 2024c) was used to calculate flow direction from land-surface altitudes from a 10-m-resolution DEM (USGS, 2015) with filled depressions; depressions in the DEM were filled by using the ArcGIS Fill tool (Esri, 2024b). Daily precipitation, minimum temperature, and maximum temperature grids for the 1998–2022 period were obtained from the Daymet database (version 4; Thornton and others, 2020). Land-cover types from 2021 (Multi-Resolution Land Characteristics Consortium, 2023) were used to assign runoff-curve numbers and plant root-zone depths. Default plant root-zone depths for the SWB code, which were appropriate for permeable glacial deposits in Wisconsin (Westenbroek and others, 2010), were scaled to approximately 60 percent to account for the regional differences in the soils of the study area; SWB-code implementations for nearby aquifers used root-zone depths that ranged from 30 to 80 percent (Ellis and others, 2017, 2020; Ellis, 2018).

SWB-estimated recharge rates were summarized annually in conjunction with precipitation data to calculate recharge efficiency, which is the ratio of recharge to precipitation. The SWB-estimated annual recharge rates for the panhandle

Table 9. Summary of recharge rates for the High Plains (Ogallala) aquifer study area from previously published reports, modified from Stanton and others (2011).

[P, precipitation; S, Streamflow seepage; I, irrigation return flow; U, unspecified; OWRB, Oklahoma Water Resources Board]

Location	Method	Land cover	Recharge rate (inches per year)	Water source	Time period	Reference
Central High Plains	Groundwater-flow model	Undeveloped	0.056–0.84 (mean=0.14)	P, S	Pre-1950	Luckey and others (1986); Sophocleous (2004)
Between Arkansas and Canadian Rivers	Groundwater-flow model	Undeveloped	0.068–0.69 (mean=0.155)	P	Pre-1946	Luckey and others (1986); Sophocleous (2004)
Between Arkansas and Canadian Rivers	Groundwater-flow model	Rangeland, nonirrigated cropland, cropland	0.41	P, I	1946–97	Luckey and others (1986); Sophocleous (2004)
Southwestern Kansas	Groundwater-flow model	Undeveloped	0.0–2.0 (mean=0.24)	P	Pre-1950	Stullken and others (1985); Sophocleous (2004)
Southwestern Kansas	Groundwater-flow model	Undeveloped	0.036–0.045 (median=0.040)	S	Pre-1950	Stullken and others (1985); Sophocleous (2004)
Southwestern Kansas	Groundwater-flow model	Unspecified	0.58	U	1982	Watts (1989); Sophocleous (2004)
Northwestern Oklahoma and southwestern Kansas	Groundwater-flow model	Unspecified	0.23–0.45 (mean=0.34)	P	Pre-1940, 1940–80	Havens and Christenson (1984); Sophocleous (2004)
Kansas	Chloride mass balance	Rangeland	0.2	P	2000–02	McMahon and others (2006)
Kansas	Tritium	Irrigated cropland	1.5–2.1 (mean=1.8)	P, I	2000–02	McMahon and others (2006)
Northern Texas	Zero-flux plane	Nonirrigated cropland and rangeland	0.17	P	1978–79	Klemt (1981)
Northern Texas	Zero-flux plane	Irrigated cropland	1.9	P	1978–79	Klemt (1981)
Southwestern Kansas	Unspecified	Irrigated cropland	1.5	P, S	1975	Gutentag and others (1980); Sophocleous (2004)
Southwestern Kansas	Unspecified	Nonirrigated land	0.15	P, S	1975	Gutentag and others (1980); Sophocleous (2004)
Southwestern Kansas	Unspecified	Irrigated and nonirrigated land	0.6	P, S	1975	Gutentag and others (1980); Sophocleous (2004)
Great Plains	Soil-water-balance model	Nonirrigated land	0.25–5 (median=2.6)	P	1951–80	Dugan and Zelt (2000)
Great Plains	Soil-water-balance model	Irrigated cropland	0.25–7 (median=3.6)	P	1951–80	Dugan and Zelt (2000)
Oklahoma	Unspecified	Unspecified	0.5–0.9 (mean=0.7)	U	2012	OWRB (2012)
Oklahoma	Soil moisture	Unspecified	0.7	U	2018	Wyatt and others (2018)
Oklahoma	Groundwater-flow model	Unspecified	0.06–0.9 (mean=0.18)	U	1946–97	Luckey and Becker (1999)
Oklahoma Panhandle	Observation well	Nonirrigated land	0.25–0.5 (mean=0.38)	P	1938–69	Hart and others (1976)

Table 9. Summary of recharge rates for the High Plains (Ogallala) aquifer study area from previously published reports, modified from Stanton and others (2011).—Continued

[P, precipitation; S, Streamflow seepage; I, irrigation return flow; U, unspecified; OWRB, Oklahoma Water Resources Board]

Location	Method	Land cover	Recharge rate (inches per year)	Water source	Time period	Reference
Texas County, Oklahoma	Groundwater-flow model	Unspecified	0.2–2.2 (mean=1.2)	P, I	1966–72	Morton (1980)
Central High Plains	Soil-water balance model	Unspecified	1.3–1.7 (mean=1.5)	P, I	2000–09	Stanton and others (2011)
Central High Plains	Soil-water-balance model	Unspecified	1.6	P, I	1940–49	Stanton and others (2011)
Oklahoma	Soil-water-balance model	Unspecified	0.18–1.0 (mean=0.59)	P, I	2000–09	Stanton and others (2011)
Oklahoma	Soil-water-balance model	Unspecified	1.6	P, I	1940–49	Stanton and others (2011)

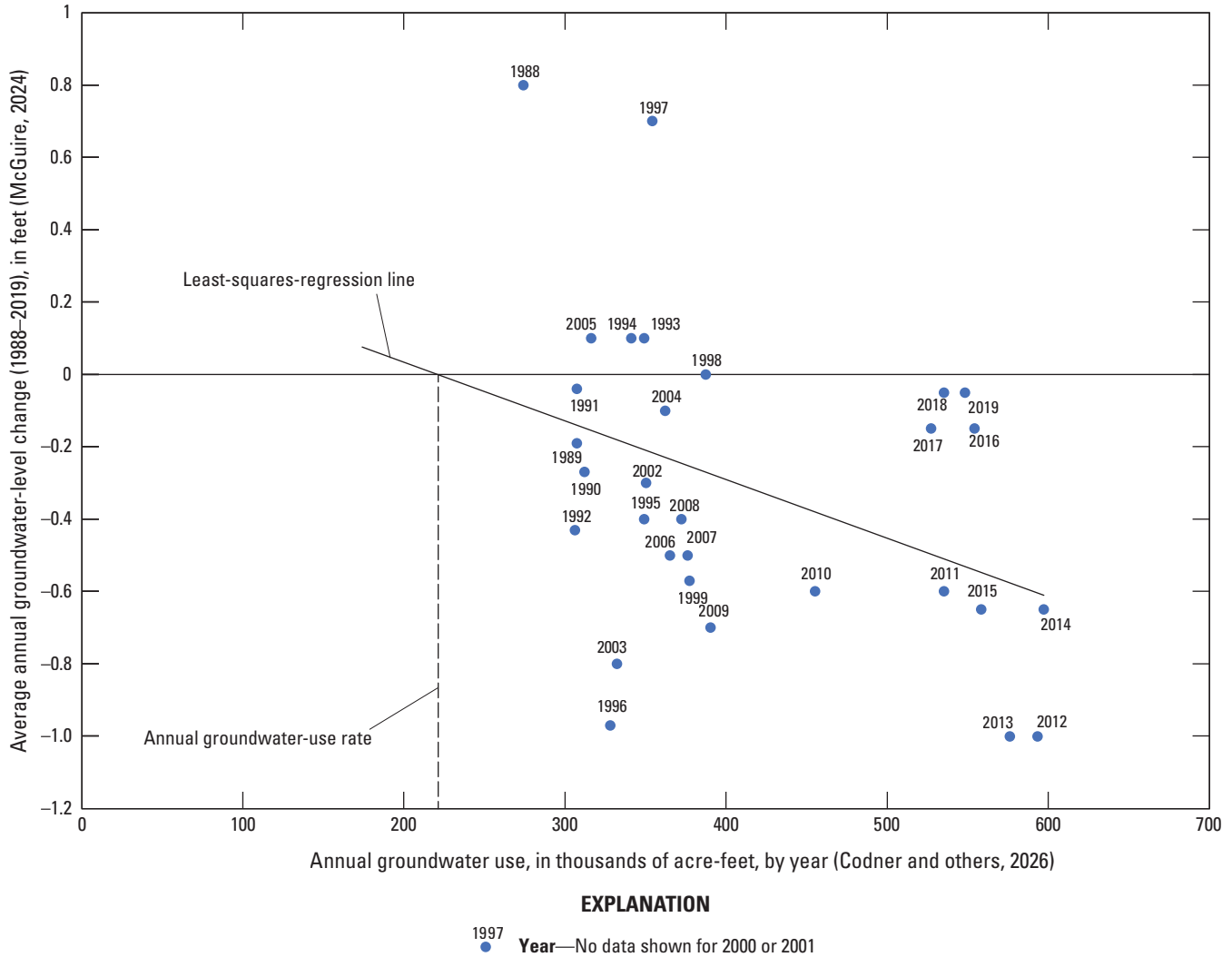


Figure 22. Relation between annual groundwater use and average annual groundwater-level change in the Ogallala aquifer focus area, Oklahoma, 1988–2019.

part of the Ogallala aquifer ranged from 0.07 in/yr (2022) to 2.55 in/yr (2015) for the 1998–2022 study period (fig. 23A). The SWB-estimated annual recharge rates for the northwest part of the Ogallala aquifer ranged from 0.75 in/yr (2011) to 8.15 in/yr (2015) for the 1998–2022 study period (fig. 23B). The SWB-estimated annual recharge rates for the Ogallala aquifer focus area ranged from 0.25 in/yr (2022) to 3.78 in/yr (2015) for the 1998–2022 study period (fig. 23C). During the 1998–2022 study period, annual recharge efficiency was less than 15 percent for all for 25 years of the study period in the panhandle part of the Ogallala aquifer and was greater than 15 percent for 6 years in the northwest part of the Ogallala aquifer.

The SWB-estimated mean annual recharge rates for the 1998–2022 study period in the panhandle and northwest parts of the Ogallala aquifer were 0.78 in/yr and 2.98 in/yr, respectively (table 10; fig. 23A, B). The SWB-estimated mean

annual recharge rate for the 1998–2022 study period in the Ogallala aquifer focus area was 1.27 in/yr, or 5.75 percent of the mean annual precipitation of 22.09 in/yr during the same period (figs. 5A and 21). Spatially, SWB-estimated recharge increases from west to east across the Ogallala aquifer focus area (fig. 24).

Potential recharge was estimated by using the regression method because measured values were available. The SWB-estimated recharge was not calibrated because of the long recharge rates. The estimated mean annual recharge for the Ogallala aquifer focus area was estimated as an inflow of 224,444 acre-ft/yr and accounted for 44.97 percent of the total inflows (fig. 21; table 8). This is equivalent to 0.63 in/yr of recharge for the entire Ogallala aquifer focus area (4,275,122 acres, table 8). Assuming recharge rates were proportional to area, the panhandle part of the Ogallala aquifer

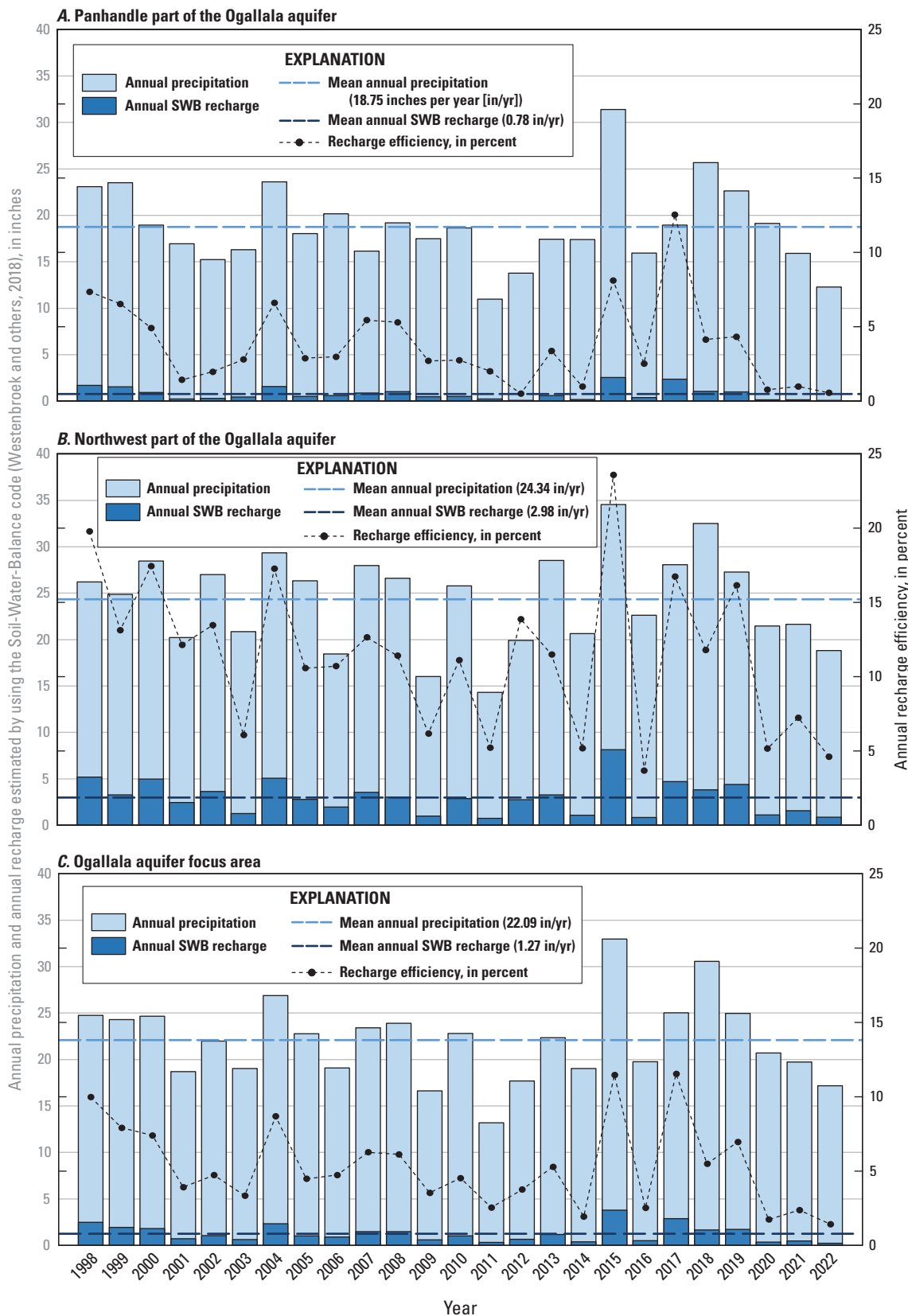


Figure 23. Annual precipitation and annual recharge estimated by using the Soil-Water-Balance (SWB) code (Westenbroek and others, 2018) in *A*, the panhandle part of the Ogallala aquifer, *B*, the northwest part of the Ogallala aquifer, and *C*, the Ogallala aquifer focus area, Oklahoma, 1998–2022.

Table 10. Summary of mean annual recharge estimated by using the Soil-Water-Balance code (Westenbroek and others, 2018) for the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area, 1998–2022.

[in/yr, inch per year]

Region	Area (acres)	Mean annual precipitation (in/yr)	Mean annual recharge (in/yr)	Mean annual recharge, expressed as the percentage of annual precipitation	Mean annual recharge (acre-feet per year)
Panhandle part of the Ogallala aquifer	3,334,636	18.75	0.78	4.16	216,751
Northwest part of the Ogallala aquifer	940,486	24.34	2.98	12.24	233,554
Ogallala aquifer focus area	4,275,122	22.09	1.27	5.75	¹ 450,305

¹This value was calculated as the sum of the aquifer parts and was not calculated from mean annual recharge for the Ogallala aquifer focus area.

(3,334,636 acres) was assigned 175,068 acre-ft/yr of annual recharge, and the northwest part of the Ogallala aquifer (940,486 acres) was assigned 49,376 acre-ft/yr (table 8).

Irrigation Return Flows

The practice of irrigation increases soil moisture and thus can complement recharge through irrigation return flows to groundwater (McMahon and others, 2006) when applied irrigation water exceeds crop-water requirements. The magnitude of irrigation return flows is not well known, and estimates vary (Arnold, 2011). The length of time required for irrigation return flows to reach the saturated zone complicates irrigation-return-flow estimation; it may take years for percolating irrigation water to reach the water table in areas where the saturated zone is hundreds of feet below land surface (Scanlon and others, 2010).

Irrigation efficiency has increased since predevelopment as irrigation practices were gradually converted to center pivots and low energy, precision application systems due to fuel cost increases. In the 1990s, irrigation return flows were estimated to be about 2 percent of the groundwater pumped for irrigation use (Luckey and Becker, 1999), and that percentage was used to estimate irrigation return flows for the conceptual-model water budget in this report. The mean annual irrigation return flows for the panhandle and northwest parts of the Ogallala aquifer were 8,111 and 642 acre-ft/yr, respectively, and together accounted for 1.75 percent of the total inflows during the study period (fig. 21; table 8).

Well Withdrawals

Well withdrawals were assumed to be equivalent to the mean annual reported groundwater use during 1998–2022 for the panhandle part (422,054 acre-ft/yr; table 2) and the northwest part (39,645 acre-ft/yr; table 3) of the Ogallala

aquifer. Together, these well withdrawals account for 461,700 acre-ft/yr or 92.50 percent of the total outflows for the Ogallala aquifer focus area (fig. 21; table 8).

Saturated-Zone Evapotranspiration

Evapotranspiration is the process by which water is transferred to the atmosphere by evaporation from the soil and reservoirs and by transpiration from plants. Most evapotranspiration occurs at the land surface where precipitation pools as surface water or where it infiltrates the soil unsaturated zone and becomes available to plant root zones (Lubczynski, 2008). The surface-water and unsaturated-zone components of evapotranspiration were not considered to be a part of the conceptual model for the Ogallala aquifer focus area because they occur before infiltrating precipitation has reached the saturated zone to become groundwater recharge. However, saturated-zone evapotranspiration, which occurs in lower lying areas or wetlands along streams (Lubczynski, 2008) where the aquifer saturated zone intersects the plant root zone, can be an important component of the conceptual models for some aquifers.

Saturated-zone evapotranspiration was not expected to be a major component of the conceptual-model water budget for the panhandle and northwest parts of the Ogallala aquifer because groundwater in the aquifer saturated zone is generally far below land surface and thus unavailable to plant roots. About 52,000 acres of the 4,275,122-acre Ogallala aquifer focus area were classified as wetlands (including riverine wetlands, freshwater emergent wetlands, and freshwater forested/shrub wetlands) by the National Wetlands Inventory (U.S. Fish and Wildlife Service, 2024). Many of the areas were classified as wetlands in the Ogallala aquifer focus area, however, were upland playa lakes that do not intersect the groundwater saturated zone. The wetland classification that could intersect the groundwater saturated zone is the riverine

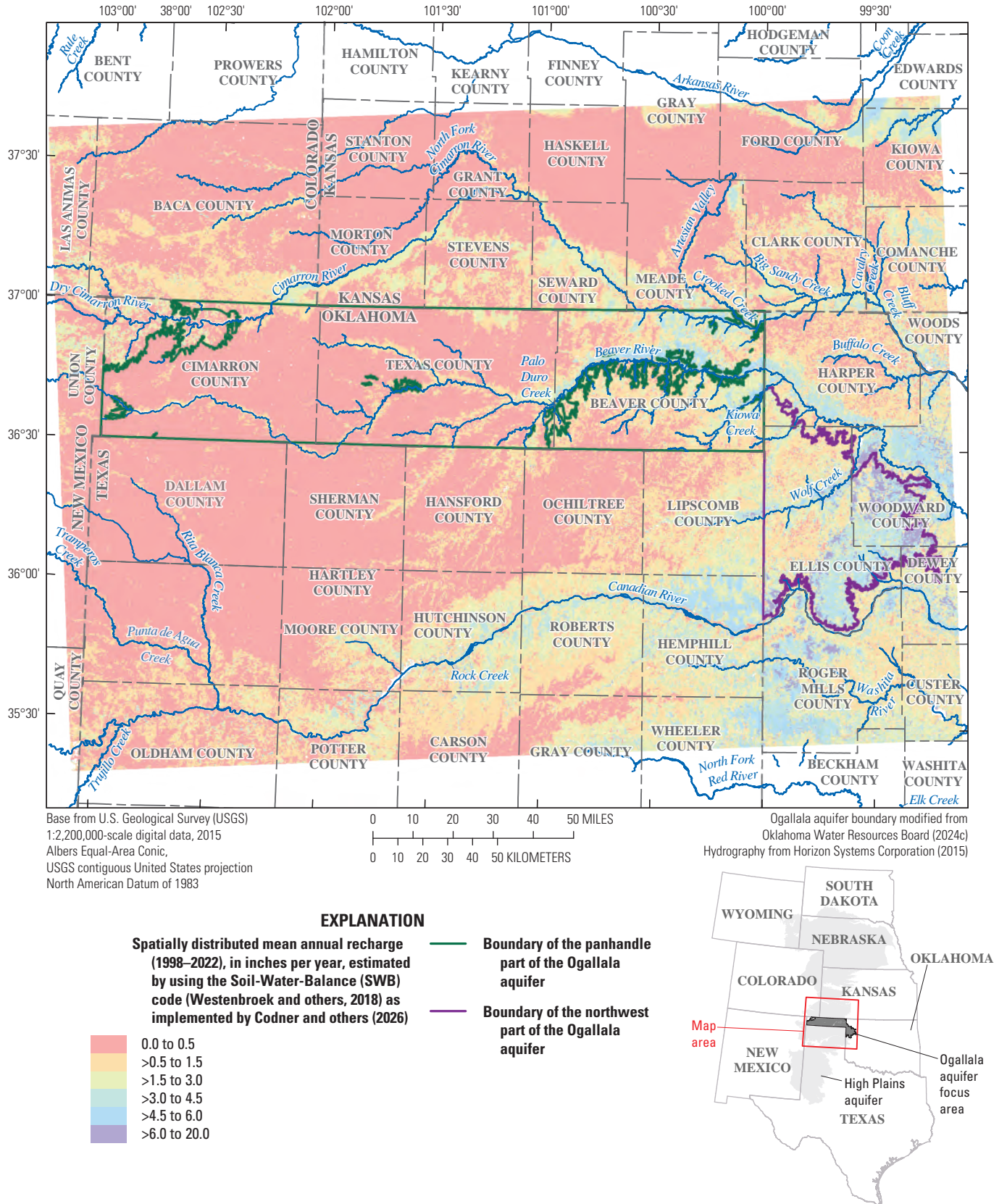


Figure 24. Spatially distributed mean annual recharge for the 1998–2022 study period estimated by using the Soil-Water-Balance (SWB) code (Westenbroek and others, 2018) for the High Plains (Ogallala) aquifer study area, southeastern Colorado, southwestern Kansas, northeastern New Mexico, northwestern Oklahoma, and northwestern Texas.

wetlands. Only 26,375 acres in the panhandle and 1,600 acres in the northwest part of the Ogallala aquifer were assumed to contribute to saturated-zone evapotranspiration. These areas account for less than 1 percent of the respective aquifer areas; therefore, the saturated-zone component of evapotranspiration was considered a negligible component of the conceptual-model water budget for the Ogallala aquifer focus area.

Streambed Seepage

Synoptic base-flow measurements (or seepage-run measurements) were collected at discrete and continuous streamflow measurement sites (table 1) by using the methods of Rantz and others (1982) during January 17–26, 2023, which was a period of minimal runoff (USGS, 2024a). This period of minimal runoff was chosen to isolate the base-flow component of streamflow while groundwater withdrawals for irrigation were minimal. Of the 27 base-flow measurement sites visited, 22 had no flow, and the remaining 5 sites (S19, S22, S29, S30, and S32) each had measured base flows less than 16 ft³/s (fig. 25). The synoptic base-flow measurements indicated that in January 2023 (1) the Beaver River had no flow at all sites measured, (2) the Cimarron River was a losing stream (decreasing base flow downstream) in northeastern Beaver County between sites S22 and S19, and (3) Wolf Creek was a gaining stream (increasing base flow downstream) between sites S18 and S32 and a losing stream between sites S32 and S23.

Continuous-record streamgages USGS 07234000 Beaver River at Beaver, Okla. (map identifier S21), and USGS 07235600 Wolf Creek near Gage, Okla. (map identifier S32; figs. 1 and 25; table 1), were used in an analysis of no-flow days, which were defined in this report as days with daily streamflow less than 1 ft³/s. The streamgage on Beaver River had a period of record covering the entire 1998–2022 study period (fig. 11A; table 1) and was used to represent groundwater discharge from the panhandle part of the Ogallala aquifer during the study period. The streamgage on Wolf Creek had a period of record covering 13 years (2010–22) of the 1998–2022 study period (fig. 12B; table 1) and was used to represent groundwater discharge from the northwest part of the Ogallala aquifer during the study period. USGS 07234000 Beaver River at Beaver, Okla. (map identifier S21, figs. 1 and 26), typically has no flow for much of the year. During the study period, 19 of 25 years had at least 180 no-flow days, and 6 of 25 years had at least 360 no-flow days. Only 1999 had fewer than 135 no-flow days, with 51 days with no flow (fig. 25). USGS 07235600 Wolf Creek near Gage, Okla. (map identifier S32, figs. 1 and 25), typically has 0 no-flow days, at least according to available records from 2010 to 2022. Only 3 of those 13 years had no-flow days, and only 2012 had more than 45 no-flow days.

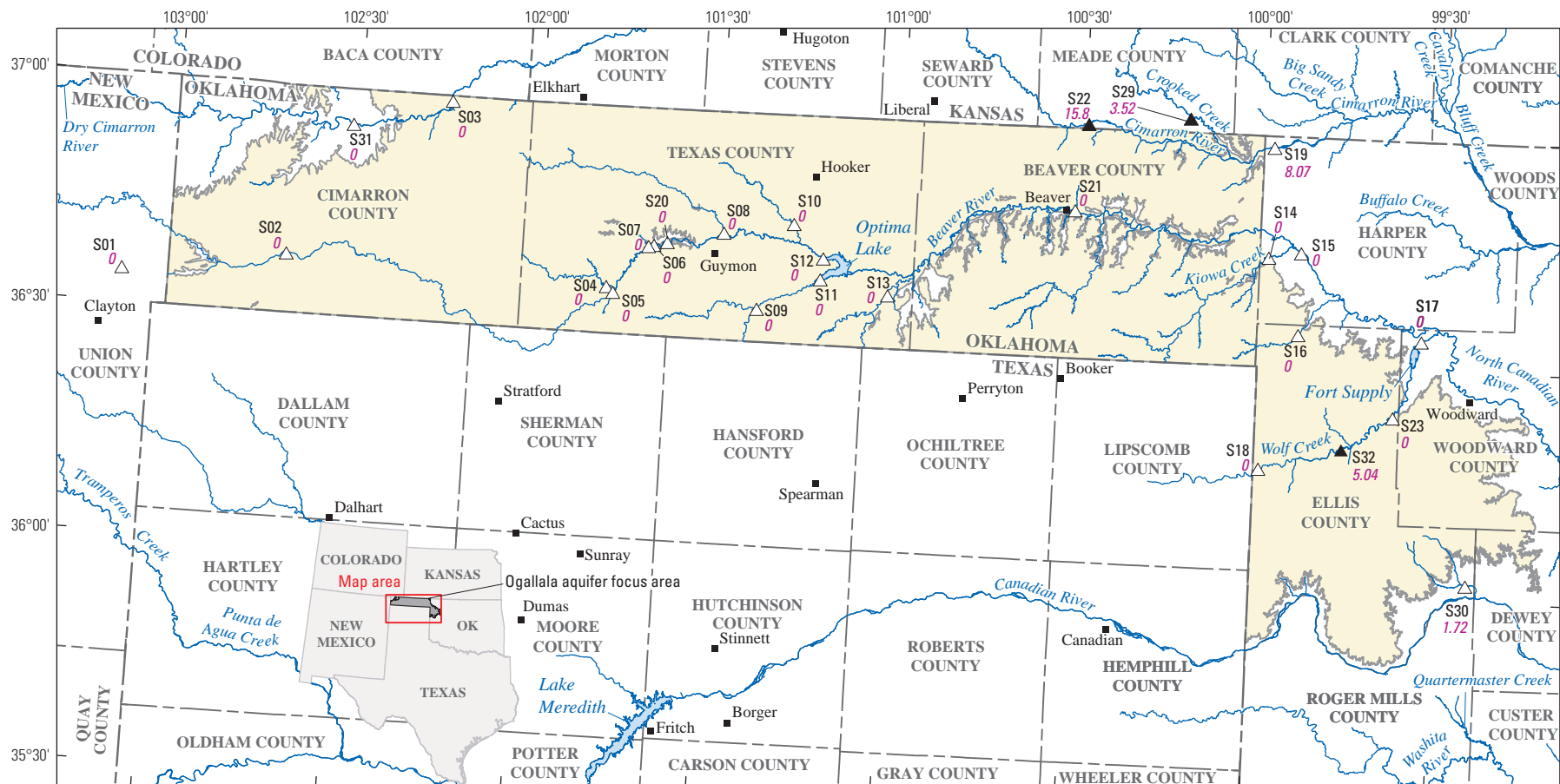
Based on synoptic base-flow measurements and analysis of continuous-record streamgage data (figs. 25–26), streambed seepage was assumed to be a negligible part of the conceptual-model water budget for the panhandle part of the Ogallala

aquifer for the 1998–2022 study period. Streambed seepage was not considered a negligible part of the conceptual-model water budget for the northwest part of the Ogallala aquifer. The mean annual base flow for 2010–22 at USGS 07235600 Wolf Creek near Gage, Okla., was 7.64 ft³/s (fig. 12B). This base-flow discharge was assumed to be a net outflow for the northwest part of the Ogallala aquifer and converts to 5,535 acre-ft/yr. This outflow accounts for 1.11 percent of the total outflows for the Ogallala aquifer focus area (table 8).

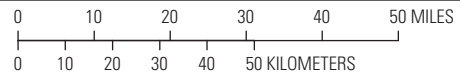
Change in Groundwater Storage

Changes in groundwater storage were summarized for two periods: (1) predevelopment–2019 and (2) 1998–2019. The groundwater-level changes for the predevelopment–2019 period were determined by clipping the raster data of McGuire and Strauch (2024a, b) to the Ogallala aquifer focus area (fig. 27). The clipped groundwater-level change raster was used to calculate the change in groundwater storage for the predevelopment–2019 period by multiplying the area of the aquifer and the mean estimated specific yield (0.09) by the mean change in groundwater level (table 11). The groundwater-level changes for this period ranged from rises of more than 10 ft, mostly in Ellis County, Okla., to declines of more than 100 ft in parts of Texas County, Okla. (fig. 27).

A groundwater-level change map for the 1998–2019 period (fig. 28) was created by using groundwater-level measurements taken in 79 wells at approximately the same time each year (McGuire and Strauch, 2024b; USGS, 2024a). The 2017–2019 groundwater-level change raster from McGuire and Strauch (2024b) was contoured at a 10-ft interval by using the ArcGIS Contour tool (Esri, 2024a). Those 10-ft contours and points representing the 1998–2019 groundwater-level change for the 79 wells were used as inputs to the ArcGIS Topo to Raster tool (Esri, 2024d). The output groundwater-level change raster was used to calculate the change in groundwater storage for the 1998–2019 period by multiplying the area of the aquifer and the mean estimated specific yield (0.09) by the mean change in groundwater level (table 11). A decline in groundwater levels and net loss in storage occurred in both the panhandle and northwest parts of the Ogallala aquifer during the 1998–2019 period. The groundwater levels decreased by averages of 18.2 and 1.45 ft, respectively, across the panhandle and northwest parts of the Ogallala aquifer from 1998 to 2019 (McGuire and Strauch, 2024b). Groundwater storage decreased 260,102 acre-ft/yr in the panhandle part and 5,844 acre-ft/yr in the northwest part of the Ogallala aquifer. The assumption was made that the groundwater-storage change was about the same for the 1998–2019 period of record as for the 1998–2022 study period, and these values were applied to the conceptual-model water budget for 1998–2022. The resulting changes in storage were considered net inflows of 260,102 acre-ft/yr for the panhandle part of the Ogallala aquifer and 5,844 acre-ft/yr for the northwest part of the Ogallala aquifer. This net loss in groundwater storage was considered an inflow to the aquifer



Base from U.S. Geological Survey (USGS)
 1:1,600,000-scale digital data
 Albers Equal-Area Conic,
 USGS contiguous United States projection
 North American Datum of 1983



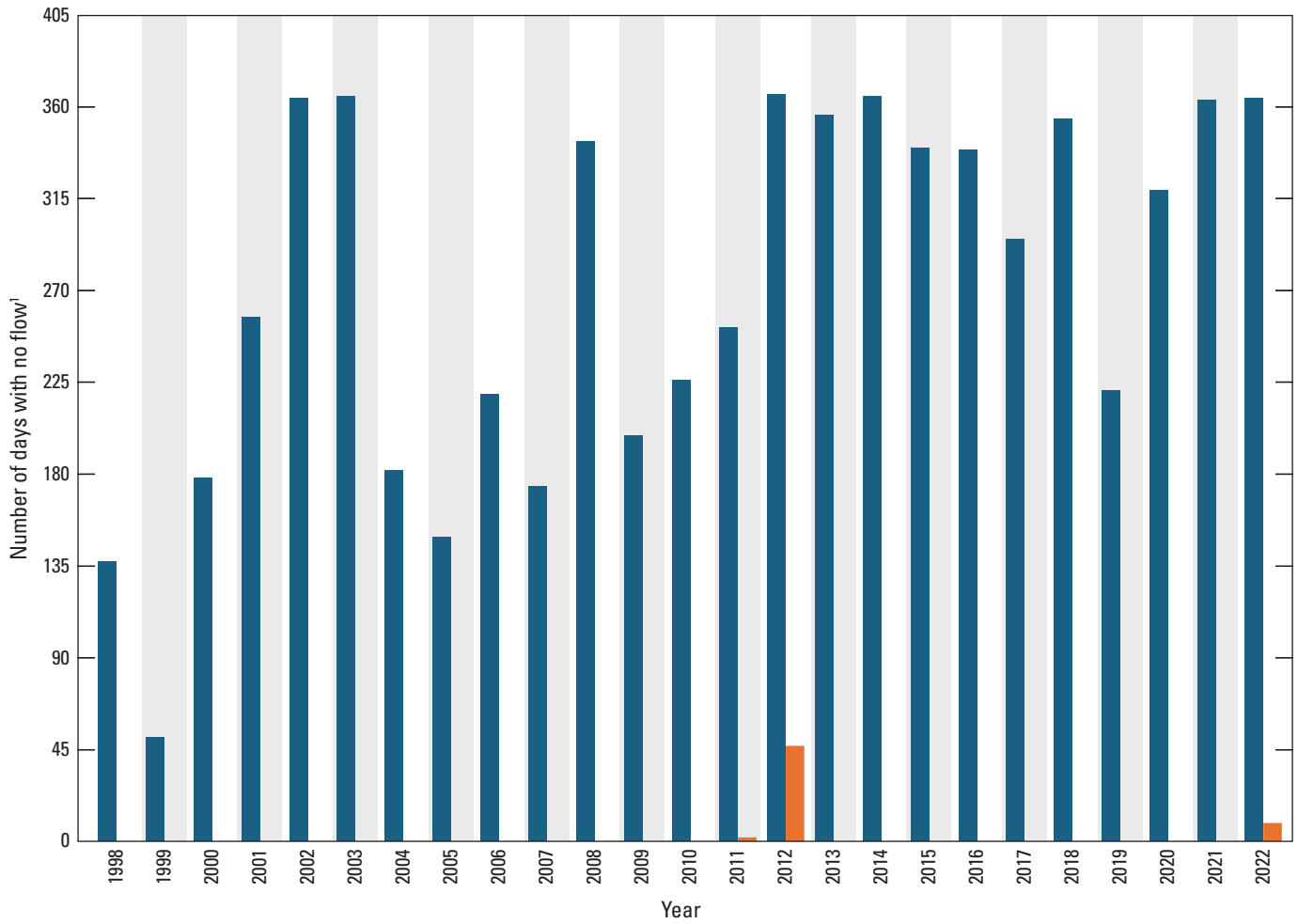
Ogallala aquifer boundary modified from Qi (2010) and
 Oklahoma Water Resources Board (2024c)
 Hydrography from Horizon Systems Corporation (2015)

Ogallala aquifer focus area

EXPLANATION

- Streamgage or streamflow measurement site used for collection of synoptic base-flow (seepage-run) data and map identifier and value of base-flow measurement, in cubic feet per second, January 17–26, 2023 (fig. 1; table 1; USGS, 2024a)**—Base-flow measurement is shown in purple italicized font
- S23 0 △ Measurement collected at discrete USGS streamflow measurement site
 - S32 5.04 ▲ Measurement collected at continuous-record USGS streamgage

Figure 25. Seepage-run measurements for selected streams that overlie the Ogallala aquifer focus area, Oklahoma, January 17–26, 2023.



EXPLANATION

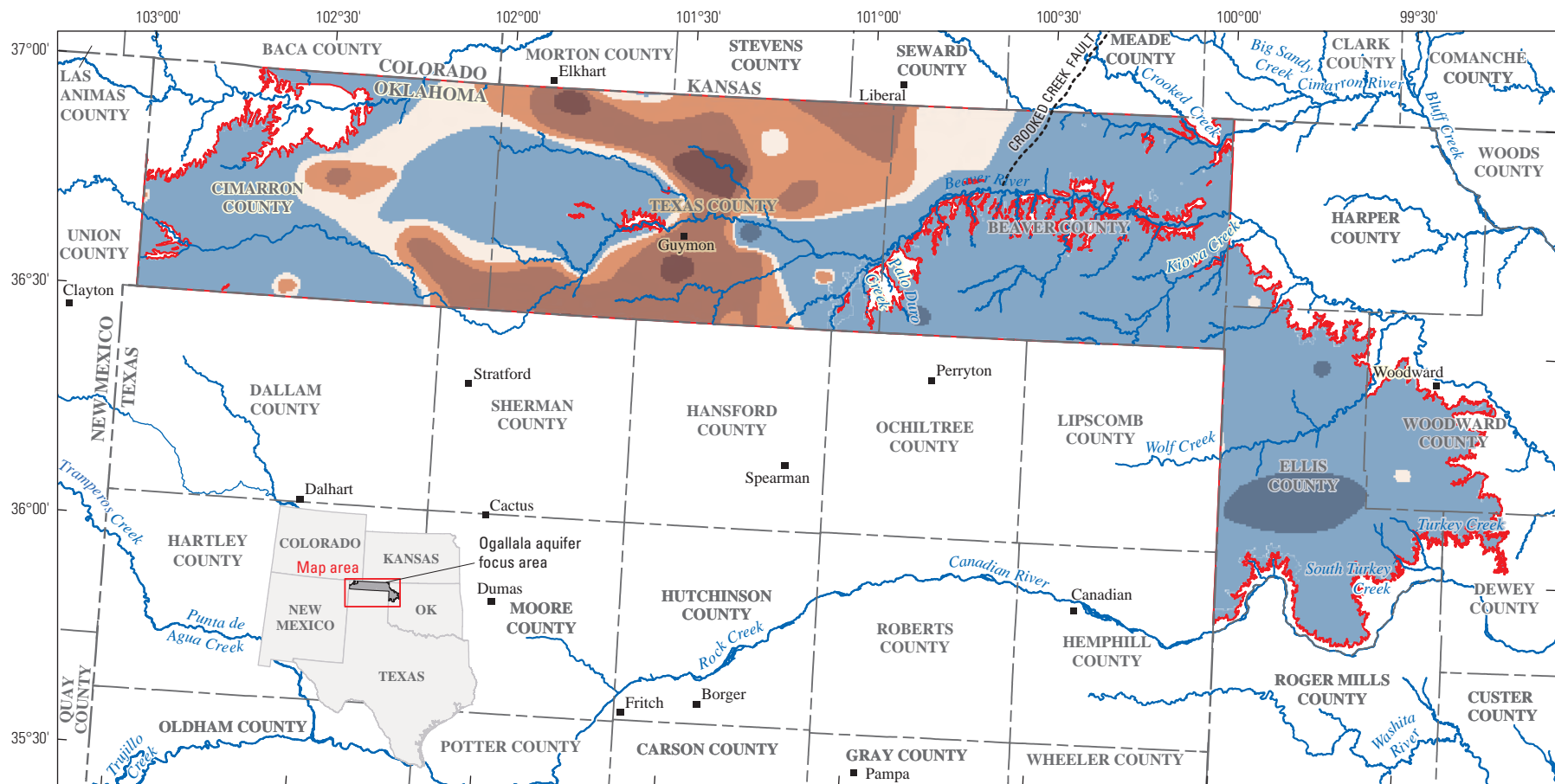
Number of no-flow days for selected continuous-record streamgage (U.S. Geological Survey [USGS], 2024a)

- USGS 07234000 Beaver River at Beaver, Okla. (map identifier S21; table 1; fig. 1)
- USGS 07235600 Wolf Creek near Gage, Okla.² (map identifier S32; table 1; fig. 1)

¹“No flow” was considered anything less than 1 cubic foot per second to account for instrumentation error.

²Data available for Wolf Creek near Gage, Okla., are from 2010–2022.

Figure 26. Observed number of no-flow days for selected continuous-record streamgages in the Ogallala aquifer focus area, Oklahoma, 1998–2022.



Base from U.S. Geological Survey (USGS)
 1:1,600,000-scale digital data
 Albers Equal-Area Conic,
 USGS contiguous United States projection
 North American Datum of 1983

Ogallala aquifer boundary modified from Qi (2010) and
 Oklahoma Water Resources Board (2024c)
 Hydrography from Horizon Systems Corporation (2015)

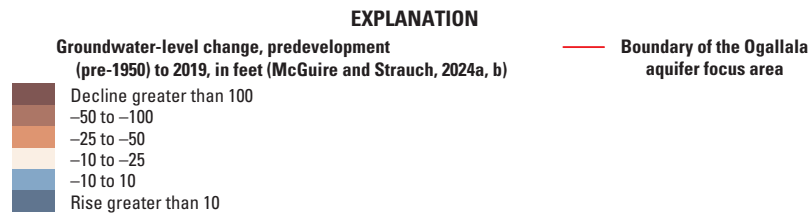


Figure 27. Groundwater-level changes in the Ogallala aquifer focus area, Oklahoma, predevelopment–2019. Modified from McGuire and Strauch (2024a).

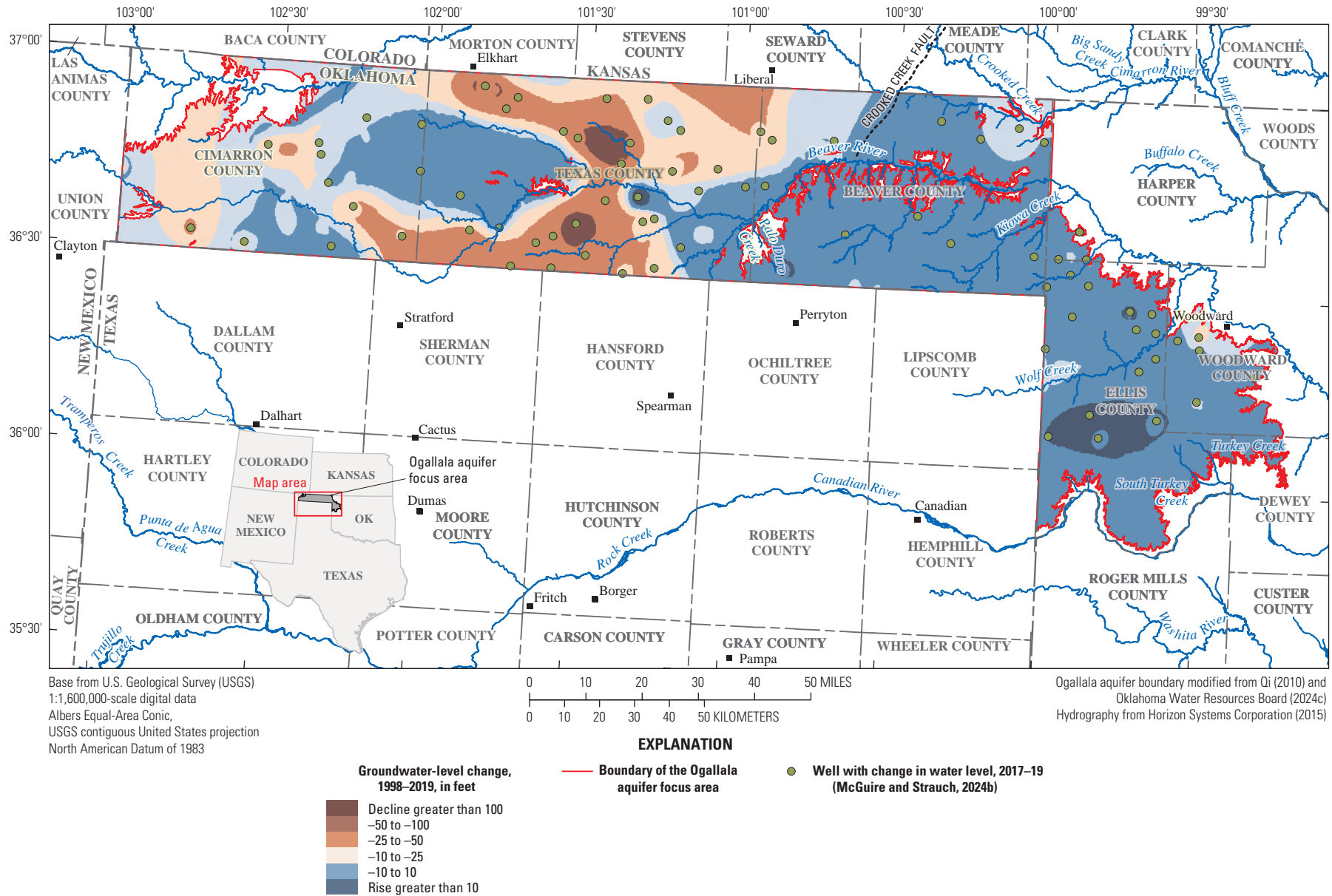


Figure 28. Groundwater-level changes in the Ogallala aquifer focus area, Oklahoma, 1998–2019.

Table 11. Summary of change in groundwater storage for the panhandle and northwest parts of the Ogallala aquifer in Oklahoma, which together compose the Ogallala aquifer focus area, predevelopment–2019 and 1998–2019.

[Mean estimated specific yield value of 0.09 (table 6) used for calculation of groundwater storage. Values may not sum to total because of independent rounding]

Region	Area (acres)	Mean change in groundwater levels, predevelopment–2019 (feet)	Change in groundwater storage, predevelopment–2019 (acre-feet)	Mean change in groundwater levels, 1998–2019 (feet)	Change in groundwater storage, 1998–2019 (acre-feet)	Mean annual change in groundwater storage, 1998–2019 (acre-feet per year)
Panhandle part of the Ogallala aquifer	3,334,636	-20.28	-6,086,378	-18.2	-5,462,134	-260,102
Northwest part of the Ogallala aquifer	940,486	-1.93	-163,362	-1.45	-122,733	-5,844
Ogallala aquifer focus area	4,275,122	-15.5	-5,963,795	-14.5	-5,579,034	¹ -265,946

¹This value was calculated as the sum of the aquifer parts and was not calculated from mean change in groundwater levels for the Ogallala aquifer focus area.

for mass balance purposes and accounted for 53.28 percent of the inflows for the Ogallala aquifer focus area for the 1998–2022 study period (fig. 21; table 8).

Lateral Groundwater Flows

Net lateral groundwater flows were calculated as the difference between the nonzero aquifer inflows (recharge, irrigation return flows, and net change in groundwater storage) and the aquifer outflows (well withdrawals) and were used to balance the conceptual-model water budget because no data were available to estimate lateral groundwater flows, which in this study were defined as flows across political boundaries of the Ogallala aquifer focus area to or from adjacent parts of the High Plains aquifer. Net lateral groundwater flows for the panhandle and northwest parts of the Ogallala aquifer were calculated to be net outflows of 21,227 and 10,682 acre-ft/yr, respectively, and together accounted for 6.39 percent of the total outflows for the Ogallala aquifer focus area (fig. 21; table 8).

Vertical Leakage

Vertical leakage, which is the exchange of groundwater between the Ogallala aquifer and the underlying hydrogeologic units, was assumed to be small compared to lateral groundwater flows across the political boundaries of the Ogallala aquifer focus area. Most of the Ogallala aquifer focus area overlies units which produce minimal amounts of

water used for stock wells (Hart and others, 1976). Therefore, vertical leakage was assumed to be a negligible part of the conceptual-model water budget (fig. 21; table 8).

Conceptual-Model Water Budget

A conceptual-model water budget estimating mean annual inflows to and outflows from the panhandle and northwest parts of the Ogallala aquifer, together called the Ogallala aquifer focus area, for the 1998–2022 study period (fig. 21; table 8) was developed from the conceptual model. The balanced total inflows and outflows for the Ogallala aquifer focus area were estimated 499,143 acre-ft/yr for the 1998–2022 study period. The components of the conceptual-model water budget were estimated from analyses of available data; however, where data were unavailable or inadequate, assumptions were made from previous investigations as described in the “Hydrologic Boundaries” section. The inflow percentages for the Ogallala aquifer focus area are 44.97 percent for recharge, 1.75 percent for recharge due to irrigation return flow, and 53.28 percent for net change in groundwater storage. The outflow percentages for the Ogallala aquifer focus area are 6.39 percent for net lateral groundwater flow, 1.11 percent for net streambed seepage, and 92.50 percent for well withdrawals. Vertical leakage and saturated-zone evapotranspiration were assumed to be negligible outflow components of the conceptual-model water budget.

Summary

The 1973 Oklahoma Groundwater Law (Oklahoma Statute § 82-1020.5) requires the Oklahoma Water Resources Board (OWRB) to conduct hydrologic investigations of the State’s aquifers (referred to as “groundwater basins” in the statutes) to support a determination of the maximum annual yield (MAY) for each aquifer. The MAY is defined as the amount of fresh groundwater that can be withdrawn annually while ensuring a minimum 20-year life of the aquifer. For bedrock aquifers, the groundwater-basin-life requirement is satisfied if, after 20 years of MAY withdrawals, 50 percent of the groundwater basin (hereinafter referred to as an “aquifer”) retains a saturated thickness of at least 15 feet (ft). The MAY is divided by the total land area overlying the aquifer to determine the annual volume of groundwater allocated per acre of land, or the equal-proportionate-share (EPS) pumping rate. Most of the High Plains aquifer in Oklahoma is part of a lobe of the aquifer that extends from the Arkansas River to the Canadian River and includes parts of southeastern Colorado, southwestern Kansas, northeastern New Mexico, northwestern Oklahoma, and northwestern Texas. The OWRB (as well as water-regulating agencies in neighboring States) refers to the High Plains aquifer as the “Ogallala aquifer.” Consequently, this report uses “Ogallala aquifer” when referring to the High Plains aquifer in Oklahoma. For purposes of permitting, the OWRB has divided the Ogallala aquifer into three parts: panhandle, northwest, and Roger Mills. The OWRB issued final orders on March 12, 2002, that established MAYs and EPS pumping rates for the panhandle part and the northwest part of the Ogallala aquifer. For the panhandle part of the Ogallala aquifer, the MAY was established at 6,773,760 acre-feet per year (acre-ft/yr), and the EPS pumping rate was determined to be 2.0 acre-feet per acre per year. For the northwest part of the Ogallala aquifer, the MAY was established at 1,189,500 acre-ft/yr, and the EPS pumping rate was determined to be 1.4 acre-feet per acre per year. Because more than 20 years have elapsed since the March 12, 2002, final orders, the U.S. Geological Survey, in cooperation with the OWRB, carried out a hydrologic investigation to update the hydrogeologic framework and conceptual flow model and water budget for the panhandle and northwest parts of the Ogallala aquifer for the study period 1998–2022.

In the Ogallala aquifer focus area in 2022, the predominant land-cover type was grass/pasture (43.3 percent of land cover in the panhandle part of the Ogallala aquifer and 66.6 percent of land cover in the northwest part). The predominant crop type was winter wheat (31.9 percent of cropland in the panhandle part of the Ogallala aquifer and 65.2 percent for the northwest part).

For the period 1998–2022, the mean annual precipitation was 18.75 inches in the panhandle part of the Ogallala aquifer, and the mean annual temperature was 57.47 degrees Fahrenheit. The mean annual precipitation was 24.34 inches in the northwest part of the Ogallala aquifer, and the mean annual temperature was 61.78 degrees Fahrenheit. The mean

annual reported groundwater use was 422,054 acre-ft/yr in the panhandle part of the Ogallala aquifer and 39,645 acre-ft/yr in the northwest part. The predominant category of groundwater use in the study area was irrigation.

The geographic aquifer extent of the Ogallala aquifer focus area was established by the OWRB. The area of the panhandle part of the Ogallala aquifer is 3,334,636 acres, and the area of the northwest part of the Ogallala aquifer is 940,486 acres. The altitude of the base of the Ogallala aquifer in the focus area was modified from a previous report to incorporate the altitude of the top of the underlying Permian and Cretaceous bedrock contacts interpreted from completed drillers’ lithologic log reports. The base of the aquifer dips from west to east from 4,800 ft to 2,000 ft in altitude relative to North American Vertical Datum of 1988. A potentiometric surface was constructed by using synoptic groundwater-level measurements. The saturated thickness of the Ogallala aquifer focus area was determined by subtracting the altitude of the base of the aquifer from the potentiometric surface. The mean saturated thickness of the Ogallala aquifer within the Ogallala aquifer focus area was 125 ft in March 2021.

Textural and hydraulic properties for the Ogallala aquifer focus area were estimated by using nuclear magnetic resonance (NMR) measurements, slug tests, and analyses of lithologic log descriptions. Mean estimated horizontal hydraulic conductivity values from NMR measurements were 5.9–144.8 feet per day. Specific yield values from NMR measurements were estimated to be 0.053–0.134, with a mean of about 0.092. Transmissivity values from slug tests were 177.0–1,705.5 feet square per day.

A conceptual model for the Ogallala aquifer focus area included a water budget for the panhandle and northwest parts of the Ogallala aquifer. The conceptual-model water budget was used to quantify net groundwater flows across each identified hydrologic boundary for the 1998–2022 study period. Recharge was a principal inflow to the panhandle part and the predominant inflow to the northwest part of the Ogallala aquifer. The mean annual recharge rates for the panhandle and northwest parts of the Ogallala aquifer were estimated, using the regression method, to be 175,068 and 49,376 acre-ft/yr, respectively. Recharge from irrigation return flows was estimated to be about 2 percent of the irrigation well withdrawals, or 8,111 and 642 acre-ft/yr, respectively, for the panhandle and northwest parts of the Ogallala aquifer. Groundwater levels decreased by averages of 18.2 and 1.45 ft, respectively, across the panhandle and northwest parts of the Ogallala aquifer from 1998 to 2019. The resulting changes in storage were considered net inflows of 260,102 acre-ft/yr for the panhandle part of the Ogallala aquifer and 5,844 acre-ft/yr for the northwest part. Well withdrawals from the Ogallala aquifer focus area were estimated from the average reported groundwater use of 422,054 acre-ft/yr for the panhandle part of the Ogallala aquifer and 39,645 acre-ft/yr for the northwest part during 1998–2022. Well withdrawals were the largest outflow component in both the panhandle and northwest parts of the Ogallala aquifer. Streambed seepage flows for the

panhandle part of the Ogallala aquifer were assumed to be a negligible component of the conceptual-model water budget because most of the streams draining that part of the aquifer were dry during a large part of the study period. However, the northwest part of the Ogallala aquifer was assigned a net outflow of 5,535 acre-ft/yr based on base-flow estimates for Wolf Creek. Net lateral groundwater flows were used to balance the conceptual-model water budget and were considered net outflows of 21,227 acre-ft/yr for the panhandle part of the Ogallala aquifer and 10,682 acre-ft/yr for the northwest part. Vertical leakage was assumed to be a negligible component of the conceptual-model water budget based on the relatively low permeability materials that compose the geologic units underlying most of the Ogallala aquifer focus area.

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