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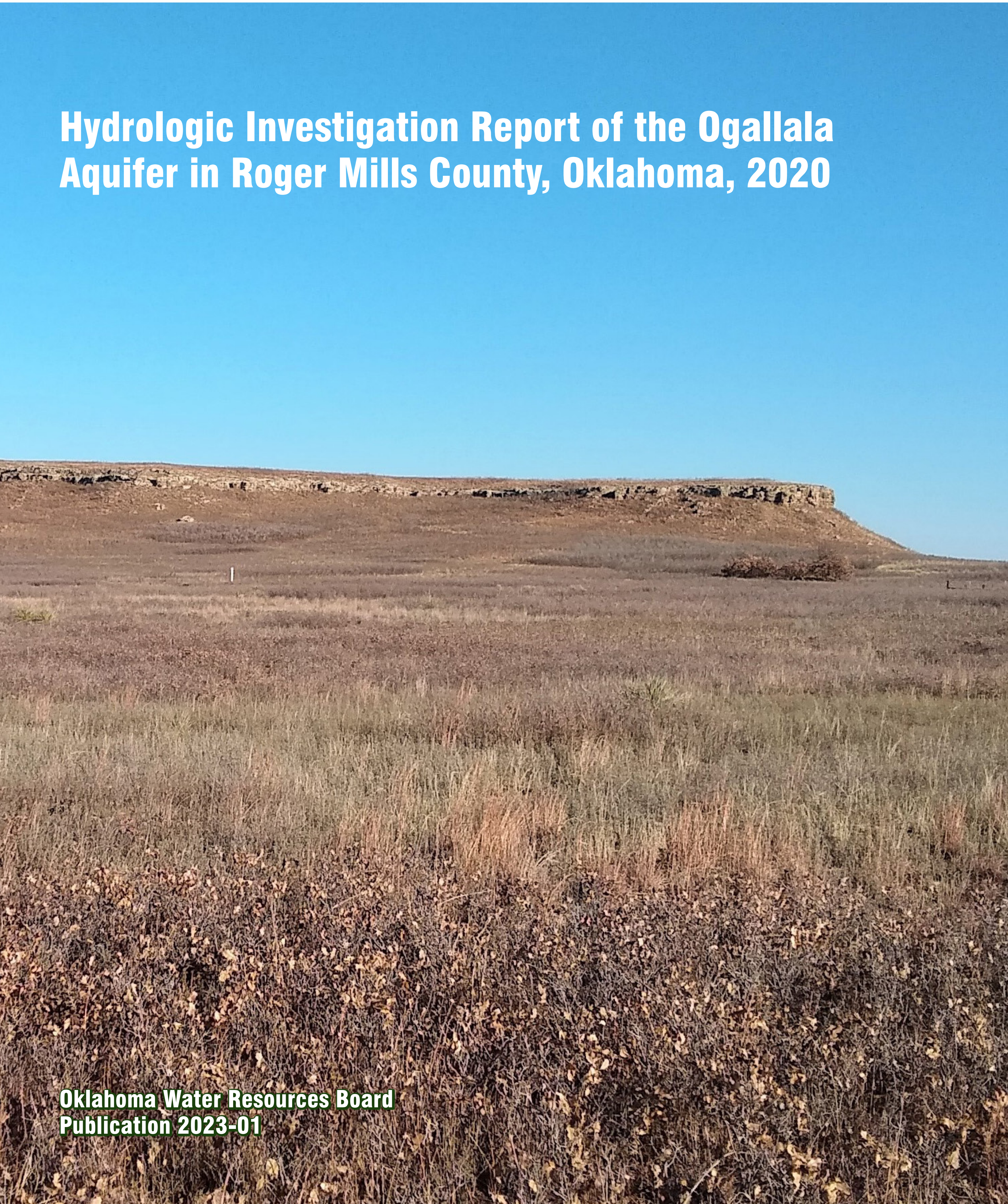
Hydrologic Investigation Report of the Ogallala Aquifer in Roger Mills County, Oklahoma, 2020



Oklahoma Water Resources Board
Publication 2023-01

Cover. Twin Hills in northwest Roger Mills County, Oklahoma. Photograph by Jon Sanford, Oklahoma Water Resources Board, December 19, 2022.

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For more information on the OWRB, Oklahoma's water agency, visit *www.owrb.ok.gov* or call 405-530-8800.

Published January 2023

Acknowledgments

The landowners and rural water districts in Roger Mills County who allowed access to their property and groundwater wells were vital in making this study possible. The author would especially like to thank Karl Sanve, Larry Pennington, Mac Taylor, Rowdy Little, and Glenda Kirk for their support of continuous water-level data collection as well as public water supply managers John Britton (Red Star Rural Water District) and Mr. Martinez (Roger Mills Rural Water, Sewer and Solid Waste Management District #3) for access to wells for aquifer tests.

This investigation would not have been possible without the work of current and former Oklahoma Water Resources Board staff who supported and assisted this investigation. Byron Waltman, Eric Fiorentino, Kevin Blackwood, Derrick Wagner, Sean Hussey, and Kyle Spears provided assistance with field work and site data collection. Internal technical review was provided by Christopher Neel, Derrick Wagner, and Jessica Correll. Internal editorial review was provided by Darla Whitley and Grace Jessup. Shana Mashburn at the U.S. Geological Survey Oklahoma Water Science Center provided external technical review.

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Hydrologic Investigation Report of the Ogallala Aquifer in Roger Mills County, Oklahoma, 2020

By Jon E. Sanford

Abstract

The Oklahoma Water Resources Board (OWRB) conducts hydrologic investigations and surveys of the State's groundwater basins as mandated by the State of Oklahoma to determine maximum annual yield (MAY) and equal proportionate share (EPS). This report details the hydrologic investigation of the Ogallala major groundwater basin in Roger Mills County, referred to in this report as the Ogallala aquifer in Roger Mills County, and provides information necessary for the OWRB to make groundwater management decisions for the aquifer.

The Ogallala aquifer in Roger Mills County is part of the High Plains aquifer which underlies about 174,000 square miles across Oklahoma, Texas, New Mexico, Kansas, Colorado, Nebraska, Wyoming, and South Dakota (McGuire, 2017). The aquifer consists of Neogene-age semi-consolidated, fine- to medium-grained, well-sorted quartz sands with interbedded layers of silt, clay, gravel, volcanic ash, and caliche of the Ogallala Formation that unconformably overlie Permian-age formations. The thickness of the aquifer decreases from west to east across the study area with a maximum thickness of about 335 feet. Groundwater from the aquifer provides water primarily for irrigation, livestock, industrial, municipal, and domestic purposes. Mean annual water use from 1967-2018 was 712 acre-feet per year with irrigation and public supply as the main use types.

Depth to water was measured in 79 groundwater wells in January 2017 to produce a water-table elevation map, which indicates that groundwater flow is predominantly from west to east. However, variations exist where groundwater flows toward the North Fork Red, Washita, and Canadian rivers. Mean saturated thickness in the study area was 45 feet and ranged from 0 to 166 feet. Continuous water-level recorders were installed in six groundwater wells; one well showed seasonal trends and precipitation responses. Aquifer hydraulic properties were estimated from lithology from well completion reports, single-well pumping tests, slug tests, and drawdown data. Transmissivity estimates ranged from 649-1,107 square feet per day; hydraulic conductivity estimates ranged from 10.2-21.3 feet per day; and the mean estimate for specific yield was 0.23. Recharge to the aquifer is primarily due to infiltration of precipitation with other sources being streams and subsurface inflow from the Texas portion of the Ogallala Formation. Mean annual recharge from 1948-2019 was estimated to be 1.00 inches using a Soil-Water Balance (SWB) model. Groundwater quality was analyzed from 54 wells sampled in 2013 and 2017 with water types ranging from calcium bicarbonate to sodium bicarbonate, which is generally considered good for drinking. Total dissolved solid (TDS) concentrations ranged from 188 milligrams per liter to 921 milligrams per liter, with a mean of 411 milligrams per liter and a median of 400 milligrams per liter.

Introduction

The Ogallala major groundwater basin in Roger Mills County, referred to in this report as the Ogallala aquifer in Roger Mills County, is an unconfined major bedrock aquifer underlying about 385 square miles of west-central Oklahoma. The aquifer consists of mostly brown, tan, and white unconsolidated to moderately-cemented layers of fine- to medium-grained, well-sorted quartz sands with interbedded layers of silt, clay, gravel, volcanic ash, and caliche. Groundwater wells in the aquifer have a mean yield of 64 gallons per minute and are primarily used for irrigation and public supply, with minor use for municipal, industrial, livestock, and domestic purposes. Public water suppliers include the Roger Mills Rural Water, Sewer and Solid Waste Management District #3 and the Red Star Rural Water District. Reydon is the largest town located within the aquifer boundary with a population of 210 in 2010 (U.S. Census Bureau, 2018).

The 2012 Oklahoma Comprehensive Water Plan (OCWP) subdivided the state into 82 planning basins to analyze water supply availability (Oklahoma Water Resources Board, 2012a). The aquifer is divided between three planning basins: the portion that discharges to the Canadian River (Basin

59), the portion that discharges to the Washita River (Basin 20), and the portion that discharges to the North Fork Red River (Basin 37) (Figure 1). The OCWP anticipates planning basins 37 and 59, which include the portions of the Ogallala aquifer that discharge to the Canadian River and the North Fork Red River, could have groundwater storage depletions by 2060; however, the depletions will be minimal relative to aquifer storage in the basin (Oklahoma Water Resources Board, 2012b; Oklahoma Water Resources Board, 2012c). Groundwater depletions are not expected through 2060 in planning basin 20, which includes the portion of the aquifer that discharges to the Washita River (Oklahoma Water Resources Board, 2012b).

The extent of the aquifer as defined in this study is the area underlain by the Ogallala Formation in Roger Mills County (Figure 1). The aquifer extent is primarily based on the Oklahoma Geological Survey (OGS) preliminary geologic map of the Foss Reservoir quadrangle (Fay, 2010) and the Elk City quadrangle geologic map (Johnson and others, 2003). Discrepancies between the OGS maps were rectified using satellite imagery and field observations, specifically from 35°24ˈ23ˈˈN to 35°30ˈ55ˈˈN and 99°38ˈ27ˈˈW to 100°0ˈ0ˈˈW. The Ogallala Formation continues west into Texas, which is beyond OWRB jurisdiction, and north of the Canadian River, where it is referred to as the Ogallala–Northwest aquifer by the OWRB.

For this report, the term "study area" refers to the area within the aquifer extent as well as the area surrounding the aquifer where streamflow and climate data were analyzed (Figure 1). The study area is part of the High Plains geomorphic province of Oklahoma (Curtis and others, 2008) and is characterized by grasslands and gently sloping hills with an area of buttes to the north capped with sandstone known as the Antelope Hills and Twin Hills. The study area is predominantly rural with grassland/pasture and shrubland accounting for 61.9 and 24.8 percent of land cover, respectively (National Agricultural Statistics Service, 2020; Figures 2, 3). Crop cover accounts for 8.8 percent of land cover, with winter wheat accounting for 63.2 percent of crops in 2020 (National Agricultural Statistics Service, 2020). Surface elevations range from about 2,150 feet above North American Vertical Datum of 1988 (NAVD 88) near Rush Creek in the east-central part of the study area to about 2,595 feet above NAVD 88 at the Antelope Hills. Larger streams that discharge groundwater from the aquifer include Rush, Croton, Dead Warrior, Buffalo, Middle Buffalo, Meridian, Sandstone, Sergeant Major, and Spring creeks. Rush Creek flows the greatest distance across the aquifer from its headwaters near the Oklahoma-Texas border to about three miles east-northeast of Reydon, where Rush Creek joins the Washita River. Streams originating from the far northern parts of the aquifer flow north toward the Canadian River, which has eroded the Ogallala Formation, exposing Permian-age sediments along the north bank of the river (Figures 1, 6). Multiple terrace deposits are located on the south side of the river. Streams in the central portion of the aquifer flow towards the Washita River, which has completely eroded the Ogallala Formation to near the Oklahoma-Texas border. Streams and drainages originating from the south side of the aquifer generally flow southward toward the North Fork Red River.

Purpose and Scope

The Oklahoma Water Resources Board (OWRB) is required to complete hydrologic investigations of the State's aquifers and complete updates every twenty years in order to provide the necessary data to determine the maximum annual yield and equal proportionate share (Oklahoma Water Resources Board, 2017a). The equal proportionate share is the portion of the maximum annual yield allocated to each acre of land (Oklahoma Water Resources Board, 2017a). The OWRB bases the maximum annual yield on the amount of groundwater that can be withdrawn while allowing a minimum basin life of twenty years from the order establishing the maximum annual yield (Oklahoma Water Resources Board, 2017a). Life of the basin for a bedrock aquifer is defined as the period of time during which the total overlying land of the basin will retain a saturated thickness of 15 feet. The objective of this hydrologic investigation is to provide the OWRB with information about the hydrogeology of the aquifer needed to determine the maximum annual yield based on various proposed management scenarios. Although a report on the Ogallala aquifer in Roger Mills County was completed in 2002 (Belden and Osborn, 2002), an equal proportionate share and maximum annual yield have not been determined to date (2021).

Climate

Oklahoma is separated into nine climate divisions (Oklahoma Climatological Survey, 2019). Roger Mills County is located in Climate Division 4 (west central), which is semi-arid with temperatures and precipitation generally increasing slightly from west to east (Oklahoma Climatological Survey, 2018). Mean daily air temperatures range from 34 degrees Fahrenheit in January to 82 degrees Fahrenheit in July with an annual mean of 58 degrees Fahrenheit (Oklahoma Climatological Survey, 2018). There are generally 80 days with temperatures above 90 degrees Fahrenheit and 13 days with high temperatures below 32 degrees Fahrenheit with a growing season of about 192 days (Oklahoma Climatological Survey, 2018).

Precipitation data were obtained from four Cooperative Observer (COOP) stations (Cheyenne, Cheyenne 11 NW, Reydon 2SSE, and Sweetwater) and one Oklahoma Mesonet station (Cheyenne) located in Roger Mills County (Oklahoma Climatological Survey, 2020; Oklahoma Mesonet, 2018; Figure 1). The National Weather Service Cooperative Observer Program is a network of observation stations with

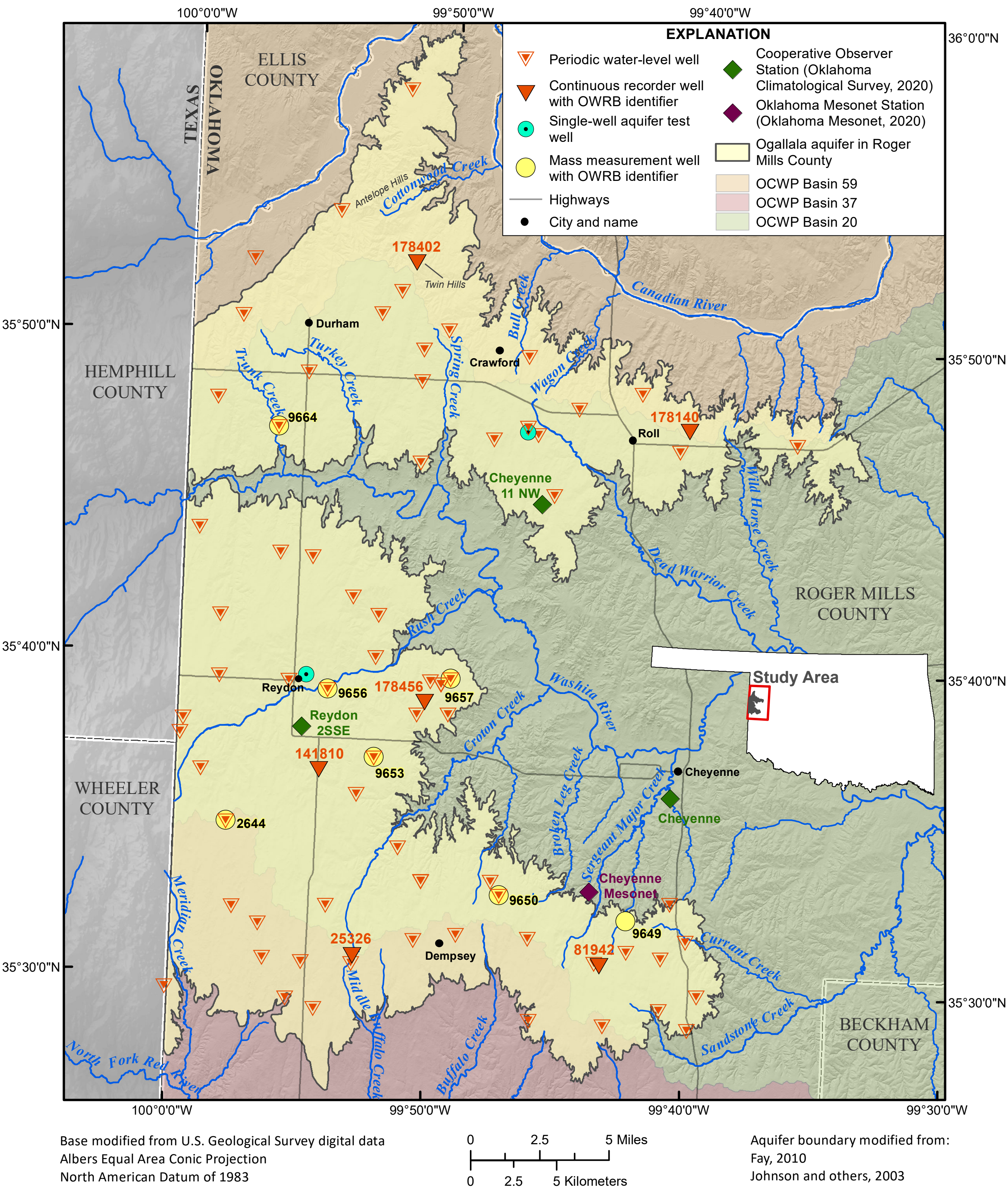


Figure 1. The Ogallala aquifer in Roger Mills County and study area, with locations of continuous water-level recorder wells, water levels collected by the OWRB, weather stations, and OCWP basins.

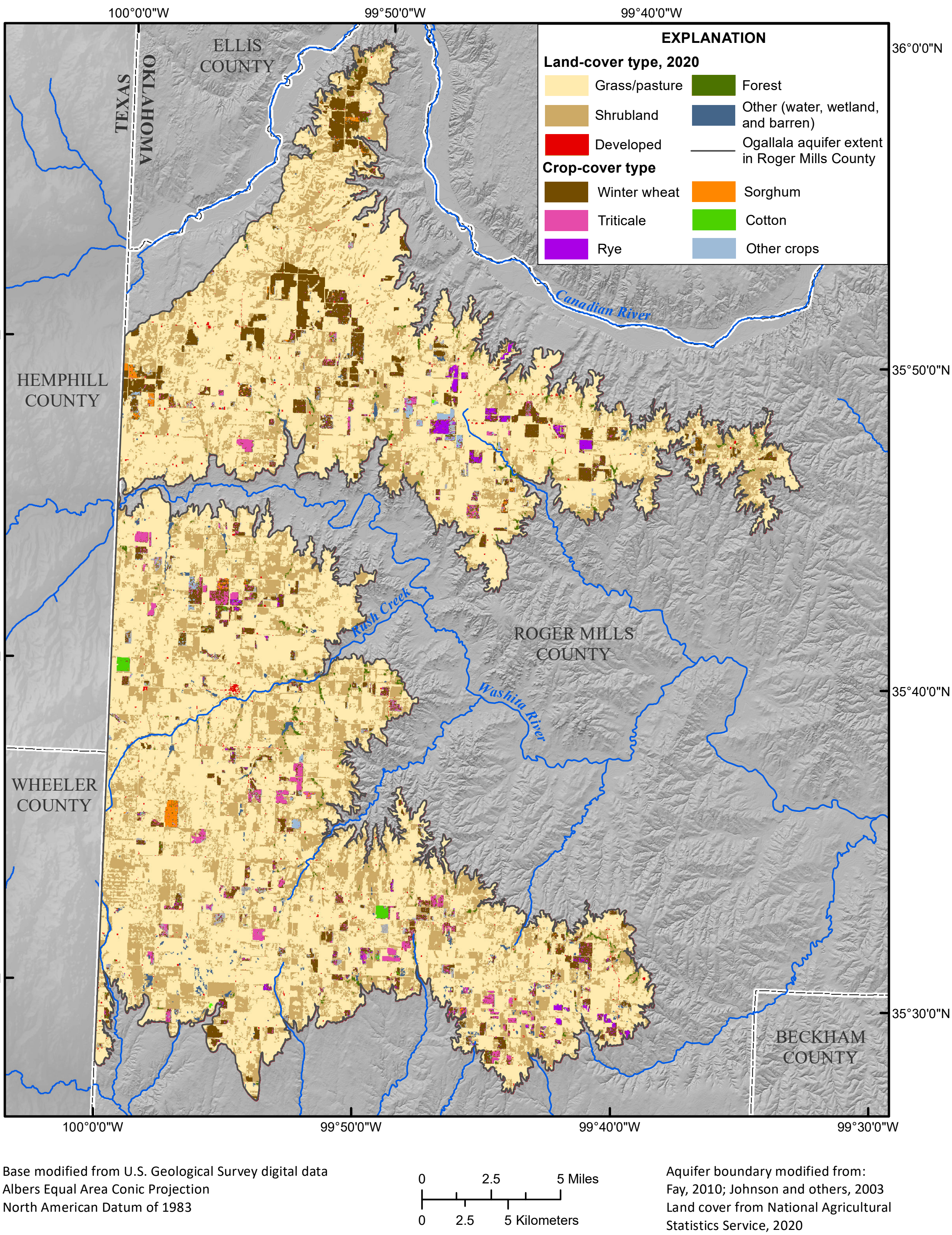


Figure 2. Spatial distribution of land and crop cover over the Ogallala aquifer in Roger Mills County, 2020.

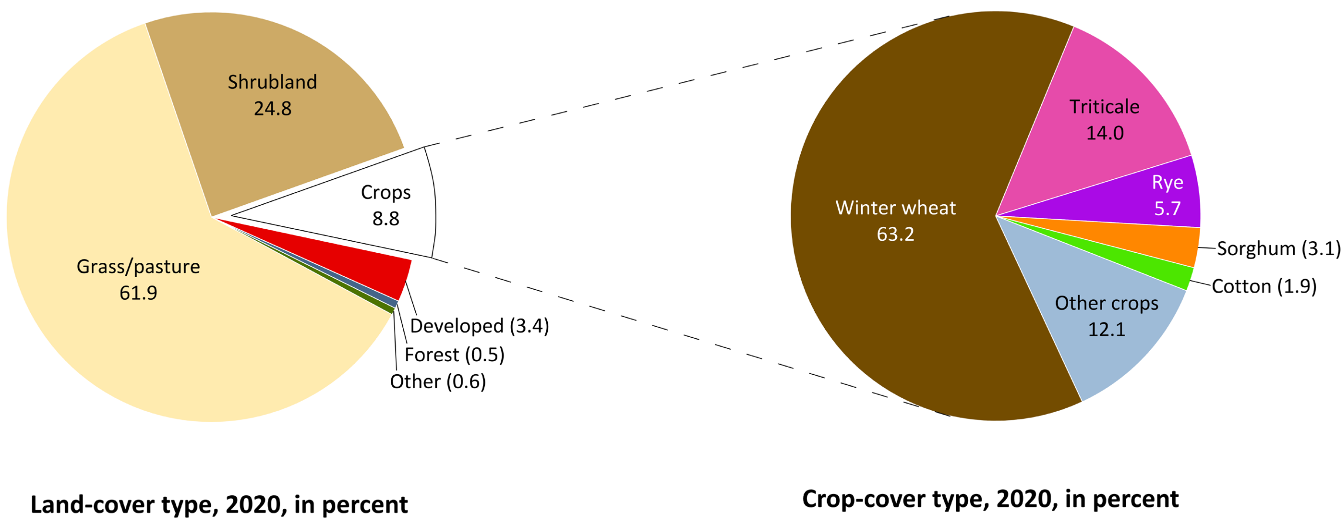


Figure 3. Land cover and crop types over the Ogallala aquifer in Roger Mills County, 2020.

volunteers recording daily temperature and precipitation (National Weather Service, 2018). The Oklahoma Mesonet is a network of 120 automated environmental monitoring stations throughout Oklahoma (Oklahoma Mesonet, 2018). Precipitation data from each station were analyzed for each station from 1924-2019 (Table 1). The mean annual precipitation derived from the COOP data was 24.2 inches from 1924-2008. The Oklahoma Mesonet began recording precipitation data at a station located six miles southwest of Cheyenne in 1994. The mean annual precipitation derived from the Cheyenne Mesonet was 27.6 inches from 1994-2019. Years with one month or more of data missing were omitted from the analysis.

Mean annual precipitation from 1924-2019 in the study area was 24.5 inches. Rainfall trends during the period of record indicate generally below mean precipitation from 1924-72 with a mean of 23.4 inches per year; with three substantial drought periods (Figure 4). The maximum and minimum annual precipitation occurred during this period, with 43.6 inches in 1941 and 12.4 inches in 1966. From 1973-94, variable precipitation occurred with a mean of 24.3 inches per year. Above mean precipitation occurred from 1995-2019 with a mean of 26.6 inches per year; with one substantial drought period from 2011-14.

Maximum monthly precipitation from 1924-2019 occurred in May with a mean of 4.1 inches and minimum monthly precipitation in January with a mean of 0.7 inches (Figure 4). The period from 1973-2019 had greater mean monthly precipitation compared to the period from 1924-72 in every month except February. Overall, the monthly mean precipitation was 1.9 inches from 1924-72 and 2.1 inches from 1973-2019.

Geology

The Ogallala aquifer in Roger Mills County consists of Neogene-age and Quaternary-age alluvium deposits (Figure 6), which lie unconformably over multiple late Permian-age formations, including the Elk City Sandstone in the southern part of the aquifer and the Doxey Shale and Cloud Chief Formation in the central and northern portions of the aquifer (Figure 7). Alluvial terrace deposits of the Canadian River are adjacent to portions of the northern boundary of the aquifer and are part of Reach 1 of the Canadian River alluvial aquifer.

Geologic History and Depositional Environments

The study area is located north of the axis of the Anadarko Basin, a deep foreland basin formed by the collision of the North American and Gondwana plates during the late Paleozoic era (Perry, 1989). The compressional forces caused reactivation of normal faults as reverse faults along the northern flank of the Southern Oklahoma Aulacogen resulting in the uplift of the Wichita Mountains to the south and subsidence of the Anadarko Basin to the north (Perry, 1989). During the Permian period, a shallow inland sea covered much of the southwest United States. Thick layers of shale, siltstone, sandstone, and evaporites were deposited as the seafloor slowly subsided. During the Triassic and Jurassic periods, much of western

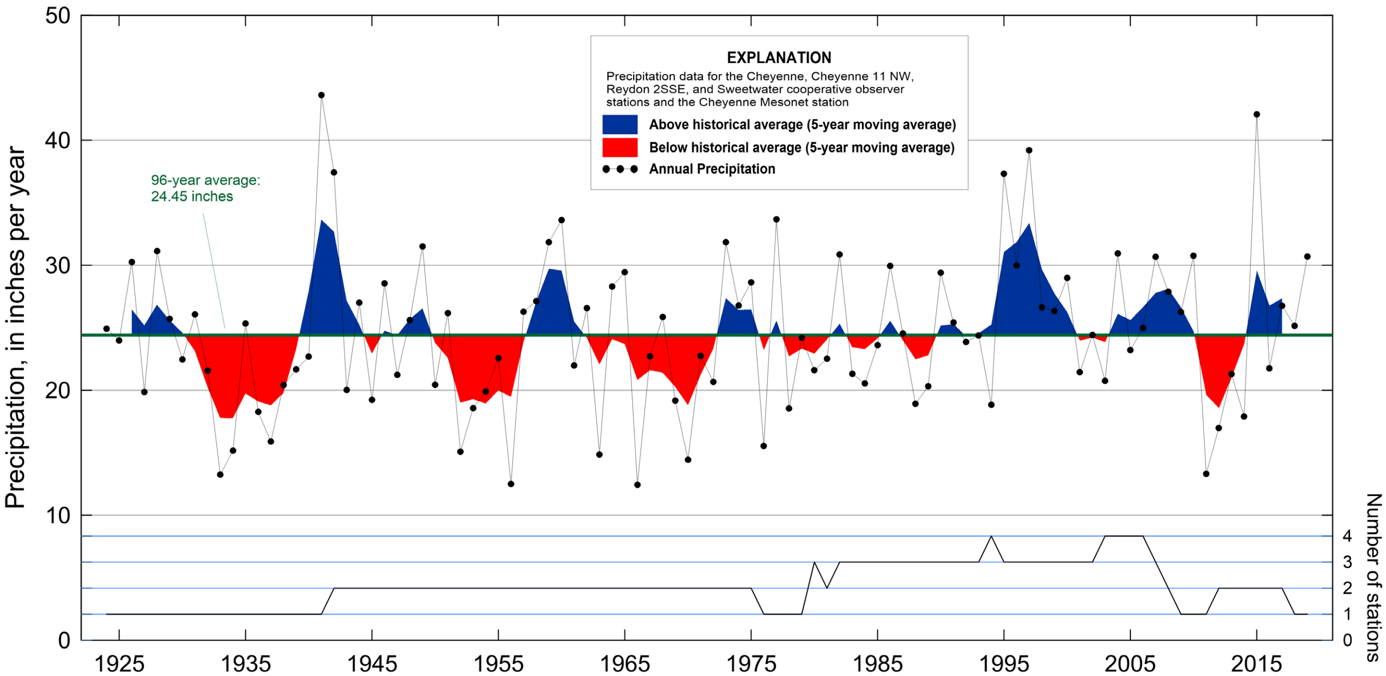


Figure 4. Annual precipitation 1924-2019, wet and dry periods defined as the departure of the 5-year moving average from the mean annual precipitation, and the number of climate stations recording during each year.

Table 1. Mean annual precipitation and data collection time periods of precipitation at the Oklahoma Mesonet station and Cooperative Observer stations used in the analysis of the study area.

Station number	Climate station name	Period of analysis[1]	Number of years	Mean annual precipitation, in inches
7579	Reydon 2SSE	1942-2006	67	23.2
1738	Cheyenne	1924-1994	71	23.6
8652	Sweetwater	1982-2008	27	24.3
1743	Cheyenne Mesonet	1994-2019	26	27.6
1744	Cheyenne 11 NW	2003-2017	15	26.5

[1]Not Continuous

Oklahoma was likely above sea level and any strata deposited during this time has been eroded (Johnson, 2008). During the Cretaceous period, a large interior seaway resulted in the deposition of sandstone and shale (Luckey and Becker, 1999). Periods of uplift associated with the Laramide orogeny began about 70 million years ago during the Late Cretaceous period (Gutentag and others, 1984), and as a result, Cretaceous strata were eroded from the study area and in nearly all of western Oklahoma. Continued uplift and erosion during the Neogene period led to extensive deposition of clastic sediments east of the Rocky Mountains. Sediments were primarily deposited by broad coalescing alluvial fans and streams (Luckey and Becker, 1999).

Quaternary-Age Deposits

Quaternary-age alluvium and terrace deposits consist of eolian sand and alluvial sand, silt, clay, and gravel along the channels of streams flowing across the study area. The alluvium and terraces deposits are reworked sediments of the Ogallala Formation and therefore have similar hydrologic properties. Prominent alluvium and terrace deposits are located along the south side of the Canadian River and adjacent to the northern aquifer boundary. The terrace deposits resulted from three erosional and depositional cycles that occurred during the Quaternary period (Kitts, 1959). The terrace deposits consist of medium- to coarse-grained cross-bedded quartz sand along with gravel, clay, and silt with a maximum combined thickness

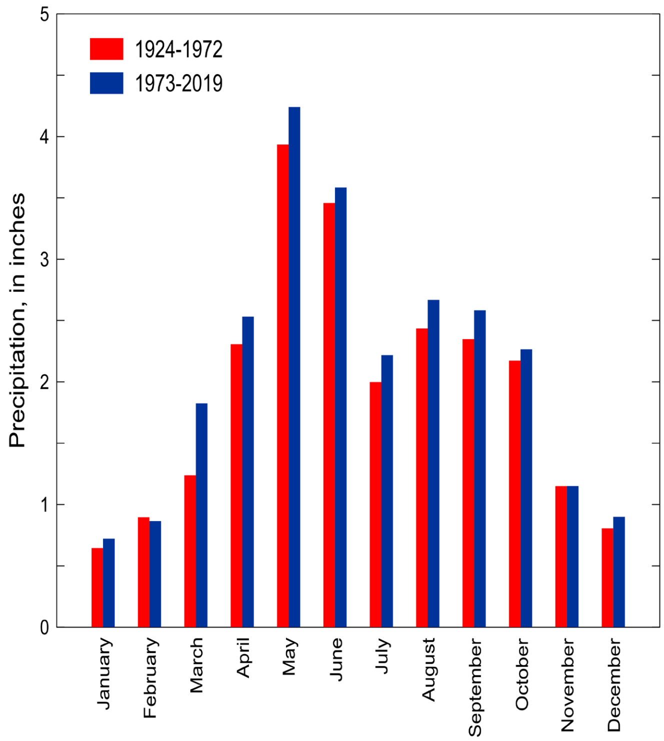


Figure 5. Mean monthly precipitation during the time periods of 1924-72 and 1973-2019.

up to 190 feet (Kitts, 1959). The three terrace deposits are widest near the Oklahoma-Texas border with a combined width extending over two miles from the current location of the Canadian River (Kitts, 1959). High terrace deposits can be difficult to distinguish from the Ogallala Formation due to erosion and because of their lithologic similarities (Kitts, 1959).

Ogallala Formation

The Ogallala Formation in the study area is generally composed of fine- to medium-grained, well-sorted quartz sands with interbedded layers of silt, clay, gravel, volcanic ash, and caliche (Kitts, 1959). Sediments are tan, brown, and light gray to white in color and are poorly to moderately cemented by calcium carbonate (Belden and Osborn, 2002) with thin layers of white to tan sandstone in some areas. The sandstone layers are generally less than one foot in thickness and consist of moderately to well-cemented, fine- to medium-grained sand. Gravel observed in the study area consists of rounded pebbles of quartz and metamorphic rock. The maximum thickness of the Ogallala Formation in the study area is about 350 feet but generally ranges from 0-250 feet and thins to the east. The thickness is controlled by the underlying topography, erosion, and collapse structures due to salt dissolution in the underlying Permian-age rocks (Belden and Osborn, 2002). The uppermost 200 feet of the Ogallala Formation is exposed in the Antelope Hills area and consists primarily of unconsolidated and loosely consolidated, fine- to medium-grained quartz sand (Kitts, 1959). A sandstone bed cemented with calcium carbonate caps the Antelope Hills and Twin Hills and contains fossilized seeds. An eroded bed of unconsolidated fine-grained sand up to 25 feet thick overlies the sandstone cap (Kitts, 1959). The age of Ogallala sediments in Roger Mills County are estimated to range in age from middle Clarendonian-age to middle Hemphillian-age (7.6-11.9 Ma) based on faunal evidence; fossilized bone and plant material were found within the Ogallala Formation (Kitts, 1959).

Permian-Age Formations

Permian-age shale, siltstone, and sandstone unconformably underlie the Ogallala Formation (Figure 7). The Permian-age units are easily distinguished from the Ogallala Formation by their red color and typically finer-grained composition. From youngest to oldest, the Permian-age units in the study area are the Elk City Sandstone, Doxey Shale, Cloud Chief Formation, and the Rush Springs Formation. The Elk City Sandstone consists of up to 260 feet of red, friable sandstone (Kent and others, 1982; Wagner and others, 2021) and underlies the southern portions of the Ogallala – Roger Mills aquifer. The Doxey Shale and Cloud Chief Formation underlie the majority of the aquifer and act as lower confining units. The Doxey Shale consists of 160 to 195 feet of blocky, red and maroon silty shale with thin layers of interbedded siltstone (Kent and others, 1982). The Cloud Chief Formation consists of 175 to 400 feet of generally orange to red-brown shale with interbedded sandstone and siltstone and a gypsum bed called the Moccasin Creek at the base of the formation (Carr and Bergman, 1976). The Rush Springs Formation consists of 300 to 400 feet of orange-brown to red fine-grained sandstone with interbedded dolomite and gypsum (Carr and Bergman, 1976).

Characteristics of the Ogallala Aquifer in Roger Mills County

Streamflow and Base Flow

Streams originating within the aquifer boundary and to the west in the Texas panhandle include Sandstone, Sergeant Major, Buffalo, Meridian, Croton, Rush, Spring, Wagon, and Dead Warrior creeks. The Washita River is the largest stream in the study area and has eroded into the underlying Permian formations across most of the study area. The portion of streamflow that results from groundwater discharge is called base flow. Streamflow is maintained by base flow in the larger streams during the fall, winter, and spring months. However, most of the streams were observed having low flow during the

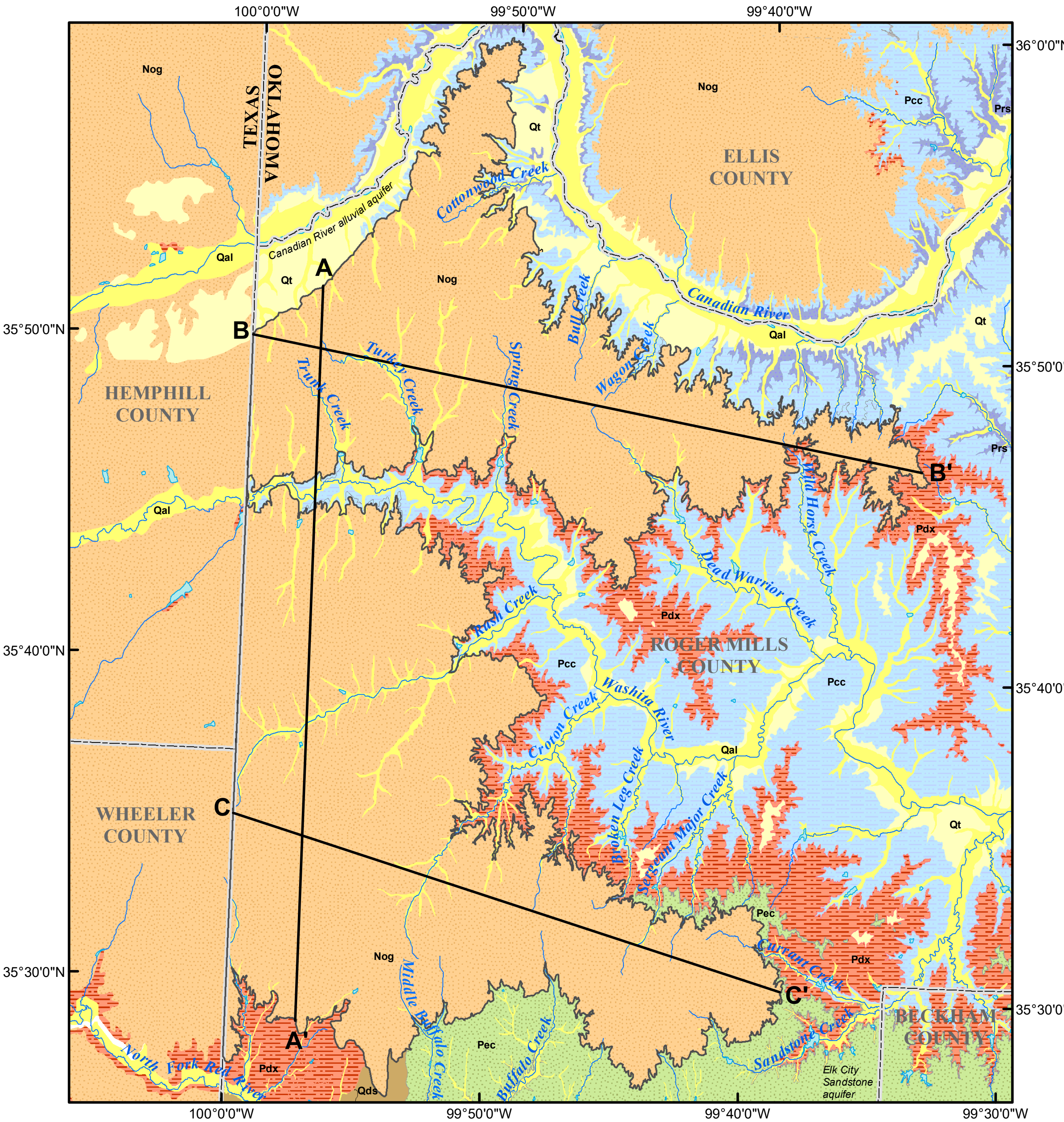


Figure 6. Surficial geologic units in the study area.

Era	Period	Geologic Unit	Description	Thickness, in feet	Hydrogeologic Unit
Cenozoic	Quaternary	Alluvial & Terrace Deposits	Unconsolidated sand, silt, clay and gravel	[a]0 - 190	
Cenozoic	Neogene	Ogallala Formation	Miocene-age fine to medium grained semi-consolidated layers of sand interbedded with silt, clay, gravel, volcanic ash and caliche. Thin layers of sandstone are poorly to moderately cemented by calcium carbonate. Sediments are tan, brown, and light gray to white in color	[b]0 - 335	Ogallala aquifer in Roger Mills County
Paleozoic	Permian	Elk City Sandstone	Late Permian-age reddish, fine grained sandstone with minor amounts of silt and clay, weakly cemented by iron oxide, calcium carbonate, and gypsum	[c]0 - 260	Elk City Sandstone aquifer
Paleozoic	Permian	Doxey Shale	Blocky, red and maroon silty shale and siltstone	[c]160 - 195	Confining
Paleozoic	Permian	Cloud Chief Formation	Red-brown to orange-brown shale, with interbedded fine to medium grained cross-bedded sandstone and siltstone in the middle section, the base of the formation is marked by a gypsum bed called the Moccasin Creek	[d]175 - 400	Confining
Paleozoic	Permian	Rush Springs Formation	Red to orange-brown cross-bedded, fine-grained, quartz sandstone interbedded with dolomite and gypsum, with minor silt	[e]300 - 400	Rush Springs aquifer

[a]Kitts, 1959
[b]Belden and Osborn, 2002
[c]Kent and others, 1982
[d]Carr and Bergman, 1976
[e]Fay, 2010

Figure 7. Stratigraphic column of geologic and hydrogeologic units in the study area.

summer because of high temperatures and low precipitation as well as increased evapotranspiration and groundwater use.

Streamflow was measured at 25 sites on 12 different streams to gain insight to understand interactions between the aquifer and streamflow (Figures 8, 9). Sites were chosen based on the lack of nearby impoundments and access to the stream. Of the 25 sites measured, 16 were located either within or near the aquifer boundary and eight measurements were on the Washita River. Five other sites had little to no streamflow. The measurement locations were selected to demonstrate the base-flow contributions from the aquifer and its effect on streamflow in the Washita River. Multiple measurements were taken for comparison purposes on December 19-20, 2017; February 2, 2018; and March 5-6, 2020, when the streams were assumed to be under base-flow conditions (Table 2).

All of the streams measured within the aquifer boundary were gaining as flow increased at each downstream measurement station. Rush Creek flows the greatest distance and had the most discharge of any creek that originates within the aquifer boundary. In December 2017, measurements were taken at three locations (upstream, midpoint, and downstream) on Rush Creek with streamflow increasing from 1.78 cubic feet per second (Rsh1) to 4.78 cubic feet per second (Rsh3), or gaining approximately 0.45 cubic feet per second per mile (Figure 8). In March 2020, measurements were made at the upstream and downstream locations on Rush Creek with streamflow increasing from 1.73 cubic feet per second (Rsh1) to 5.32 cubic feet per second (Rsh3), or gaining approximately 0.54 cubic feet per second per mile (Figure 9). Multiple measurements were also taken on Croton Creek and Dead Warrior Creek near the aquifer boundary. Streamflow in Croton Creek increased 0.56 cubic feet per second per mile in 2017. Streamflow in Dead Warrior Creek increased 0.60 cubic feet per second per mile in 2017, and 0.79 cubic feet per second per mile in 2020.

In February 2018, streamflow was measured at eight sites on the Washita River from Hemphill County, Texas to near Cheyenne, Oklahoma with an increase from 4.19 cubic feet per second (Wsh1) to 16.72 cubic feet per second (Wsh8) (Figure 8). Streamflow increased with each successive downstream measurement with the exception of Wsh2 to Wsh3, where there was a decrease of 0.20 cubic feet per second. In March 2020, streamflow was measured at six sites on the Washita River from Hemphill County, Texas to five miles northwest of Cheyenne, Oklahoma (Figure 9). In addition, data from a United States Geological Survey (USGS) streamflow gauge near Cheyenne, Oklahoma (USGS 07316500) was utilized to show that streamflow increased from 10.44 cubic feet per second (Wsh1) to 18.70 cubic feet per second (Wsh 8) between the upstream and downstream measurements. A decrease of 0.09 cubic feet per second per mile occurred between Wsh2 and Wsh4 and a decrease of 0.02 cubic feet per second per mile occurred between Wsh4 and Wsh5. Another decrease of 4.23 cubic feet per second occurred between the measurement made at five miles northwest of Cheyenne, Oklahoma and the USGS stream gauge (USGS 07316500) measurement near Cheyenne, Oklahoma, which could be caused by differences in data collection methods.

The primary difference between the February 2018 and March 2020 measurements is the higher streamflow in the Washita River in March 2020. The higher streamflow measured in March 2020 ranged from 1.98 cubic feet per second (Wsh8) to 8.56 cubic feet per second (Wsh7). Comparing the February 2018 and March 2020 measurements, there was over seven inches more precipitation in the twelve months prior to the March 2020 measurements, leading to higher groundwater levels and base-flow discharge in the proximity of the study area. Evidence for this can be seen in three continuous water-level recorders within the aquifer (see Water-Level section of this report). They each recorded generally stable water levels from January 2017 to June 2019, with no precipitation response. However, all three sites had increasing water levels from June 2019 to January 2020.

The Washita River from Hemphill County, Texas (Wsh1) to one mile east of the Oklahoma-Texas border (Wsh2), a distance of about eight miles where the Washita River mostly flows over the Ogallala Formation, increased 2.53 cubic feet per second in 2018 and 1.89 cubic feet per second in 2020. Over the next seven miles (Wsh2 to Wsh7), as the river flows over the Cloud Chief Formation and has minimal inflow from tributaries, an increase of 1.08 cubic feet per second was measured in 2018 and a decrease of 0.45 cubic feet per second was measured in 2020. This indicates base flow from the Ogallala Formation provides most of the water flowing in the Washita River in the study area during times when no runoff is occurring. Evidence of this can be seen in measurements of Rush, Croton, and Sergeant Major creeks, which originate on the aquifer and flow northeast to the Washita River. Streamflow was measured near the aquifer boundary and downstream of the confluence with the Washita River to show their contributions and resulting increases in streamflow (Figure 8, 9). Streamflow in the Washita River from about 5 miles upstream of the confluence of Rush Creek (Wsh5) to about 0.5 miles downstream from the confluence of Sergeant Major Creek (Wsh8) increased 8.92 cubic feet per second in 2018 and 6.82 cubic feet per second in 2020. The combined streamflow measured from the three streams at the boundary of the Ogallala formation was 9.43 cubic feet per second in 2018 and 9.64 cubic feet per second in 2020. This indicates that Rush, Croton, and Sergeant Major creeks are the major contributors to increases in streamflow and provide the majority of flow in the Washita River under base-flow conditions. Several smaller creeks also flow into this stretch of the Washita River which may contribute to flow as well. Measurements made on Sergeant Major Creek near the edge of the aquifer boundary (Sgm1) and at a location about six miles downstream prior to entering the Washita River (Sgm2)

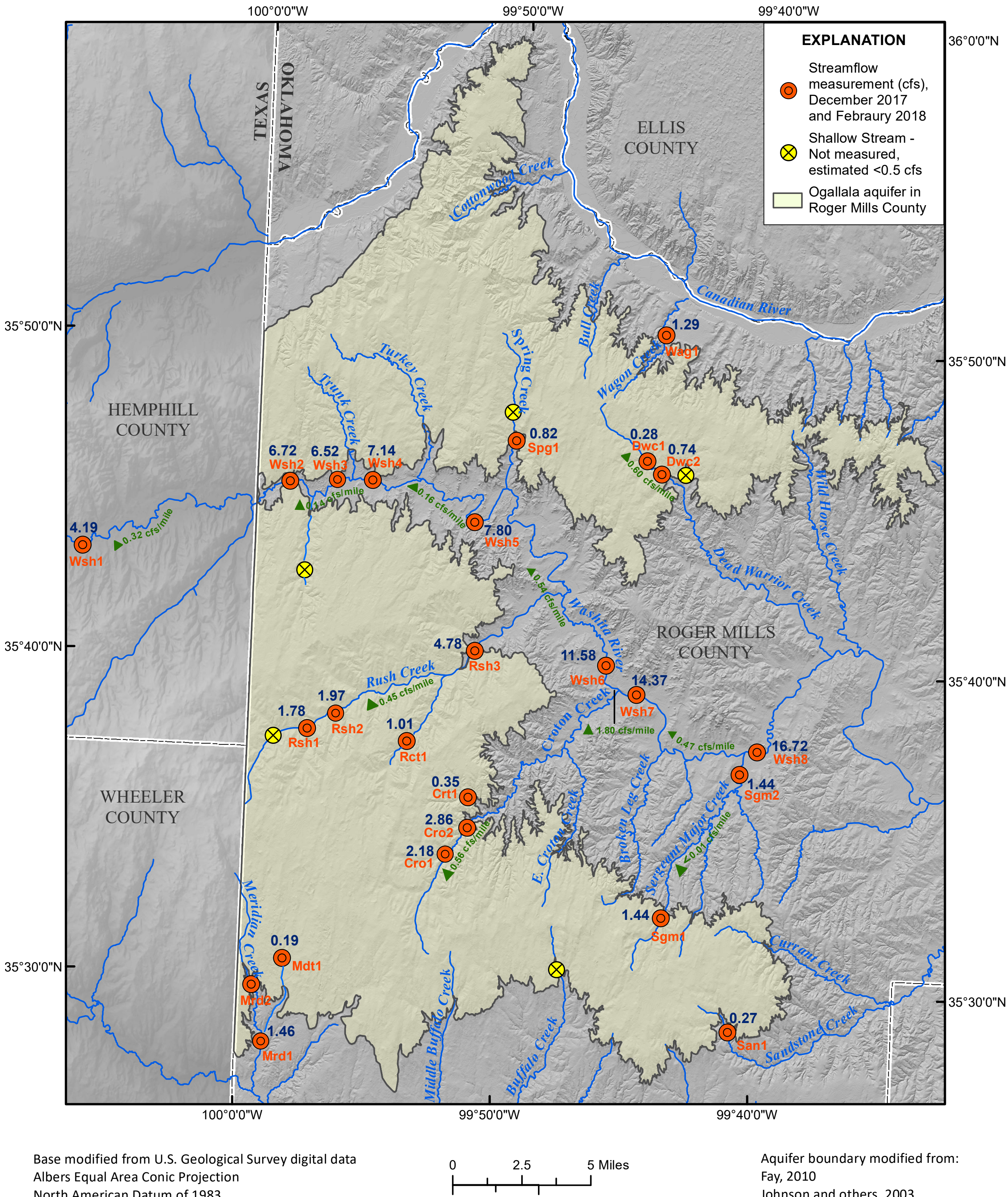
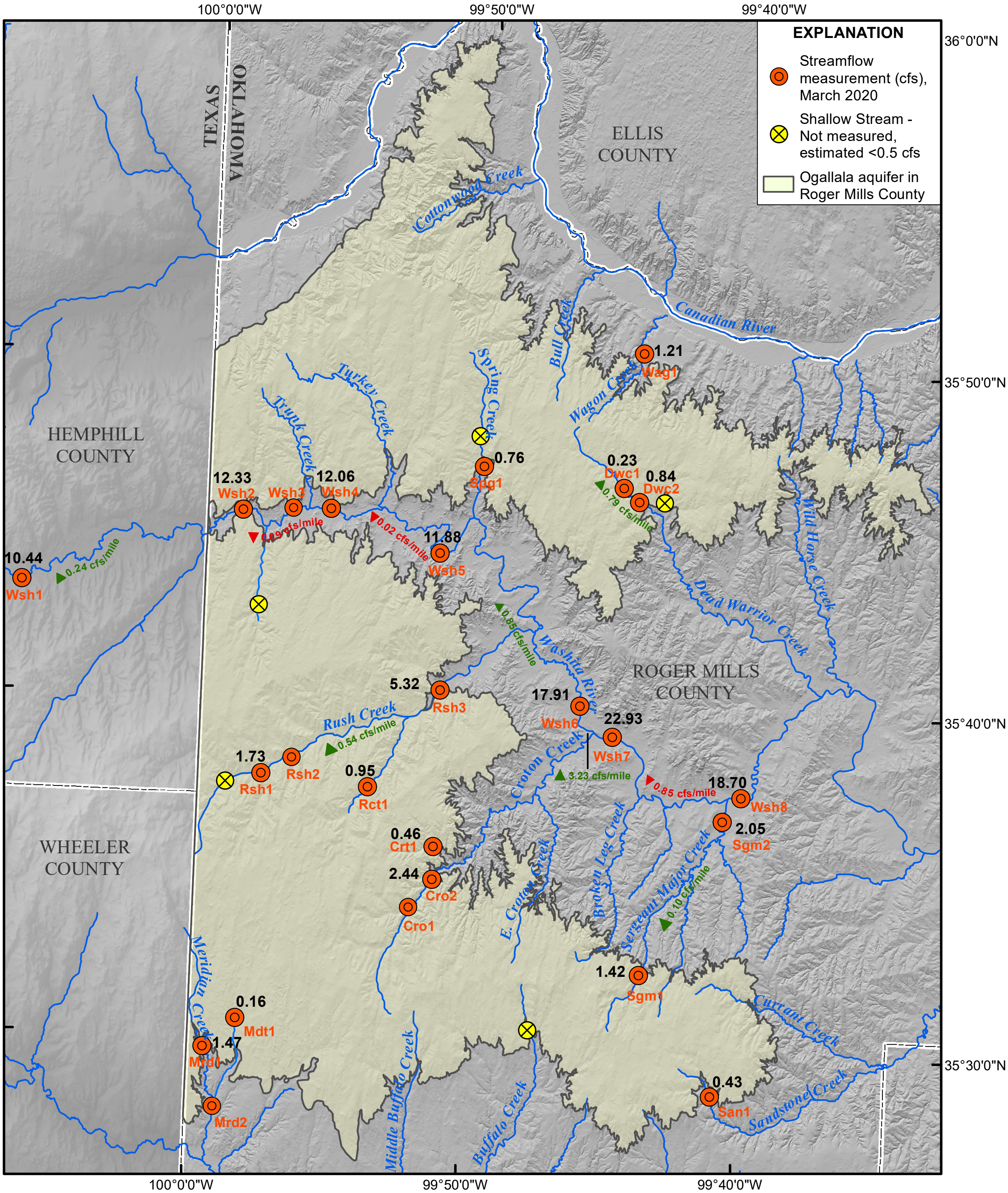


Figure 8. Streamflow measurements in cubic feet per second and locations, December 2017 and February 2018.



Base modified from U.S. Geological Survey digital data
Albers Equal Area Conic Projection
North American Datum of 1983

0 2.5 5 Miles
0 2.5 5 Kilometers

Aquifer boundary modified from:
Fay, 2010
Johnson and others, 2003

Figure 9. Streamflow measurements in cubic feet per second and locations, March 2020.

Table 2. Streamflow measurements in the study area.

Stream Name	Latitude	Longitude	Dec. 2017/Feb. 2018	March 2020
Washita River (Wsh1)	35.720	-100.113	4.185	10.444
Washita River (Wsh2)	35.758	-99.979	6.717	12.331
Washita River (Wsh3)	35.760	-99.949	6.516	--
Washita River (Wsh4)	35.760	-99.926	7.137	12.055
Washita River (Wsh5)	35.740	-99.858	7.801	11.883
Washita River (Wsh6)	35.668	-99.769	11.580	17.912
Washita River (Wsh7)	35.654	-99.749	14.370	22.925
Washita River (Wsh8)	35.626	-99.669	16.721	18.700
Rush Creek (Rsh1)	35.629	-99.962	1.776	1.730
Rush Creek (Rsh2)	35.638	-99.944	1.967	--
Rush Creek (Rsh3)	35.673	-99.855	4.781	5.317
Rush Creek Tributary (Rct1)	35.625	-99.897	1.007	0.952
Croton Creek (Cro1)	35.567	-99.869	2.176	--
Croton Creek (Cro2)	35.581	-99.855	2.861	2.437
Croton Creek Tributary (Crt1)	35.597	-99.855	0.345	0.460
Meridian Creek (Mrd1)	35.495	-99.991	--	1.469
Meridian Creek (Mrd2)	35.466	-99.983	1.458	--
Meridian Creek Tributary (Mdt1)	35.509	-99.972	0.186	0.164
Dead Warrior Creek (Dwc1)	35.776	-99.747	0.280	0.233
Dead Warrior Creek (Dwc2)	35.769	-99.738	0.737	0.843
Sergeant Major Creek (Sgm1)	35.538	-99.727	1.440	1.424
Sergeant Major Creek (Sgm2)	35.614	-99.680	1.441	2.046

were nearly identical in December 2017 and increased 0.62 cubic feet per second between Sgm1 and Sgm2 in March 2020. These streamflow measurements indicate very minor contributions from groundwater discharging from Permian formations to streams between the aquifer boundary and the Washita River.

Water-level Fluctuations

Water-level observations can be useful for characterizing the response of the aquifer to different stresses, such as climate variations and groundwater pumping. The response of groundwater levels to precipitation events can also provide insight into recharge of the aquifer and the interaction between surface water and groundwater. Long-term water-level observations are useful for assessing regional groundwater supply by monitoring changes in storage caused by development of the aquifer and climate variability. Continuous short-term water-level observations are useful for showing seasonal pumping trends and responses to precipitation events.

Historical Water Levels

Long-term periodic water-level observations were collected in the Ogallala aquifer in Roger Mills County by the OWRB since the early 1980s. These data are stored by the OWRB using OWRB well identifiers and in the USGS National Water Information System database using unique USGS site numbers. As of 2020, 16 wells in the study area are measured annually for groundwater levels with an additional 30 wells with historical groundwater-level observations that were discontinued for various reasons such as obstructions or landowner changes. Seven wells with long-term measurements between 1980 and 2019 were analyzed for this investigation (Figure 10). These seven wells were chosen because they had the longest periods of record and lacked data gaps.

Trends in groundwater-level data show fluctuations primarily with climate cycles. Water levels were typically above normal for the observed historical wet period (mid-1980s through the late 2000s) and below normal during the observed historical dry period (2011–2015). Groundwater levels during the period 1980-2019, groundwater levels

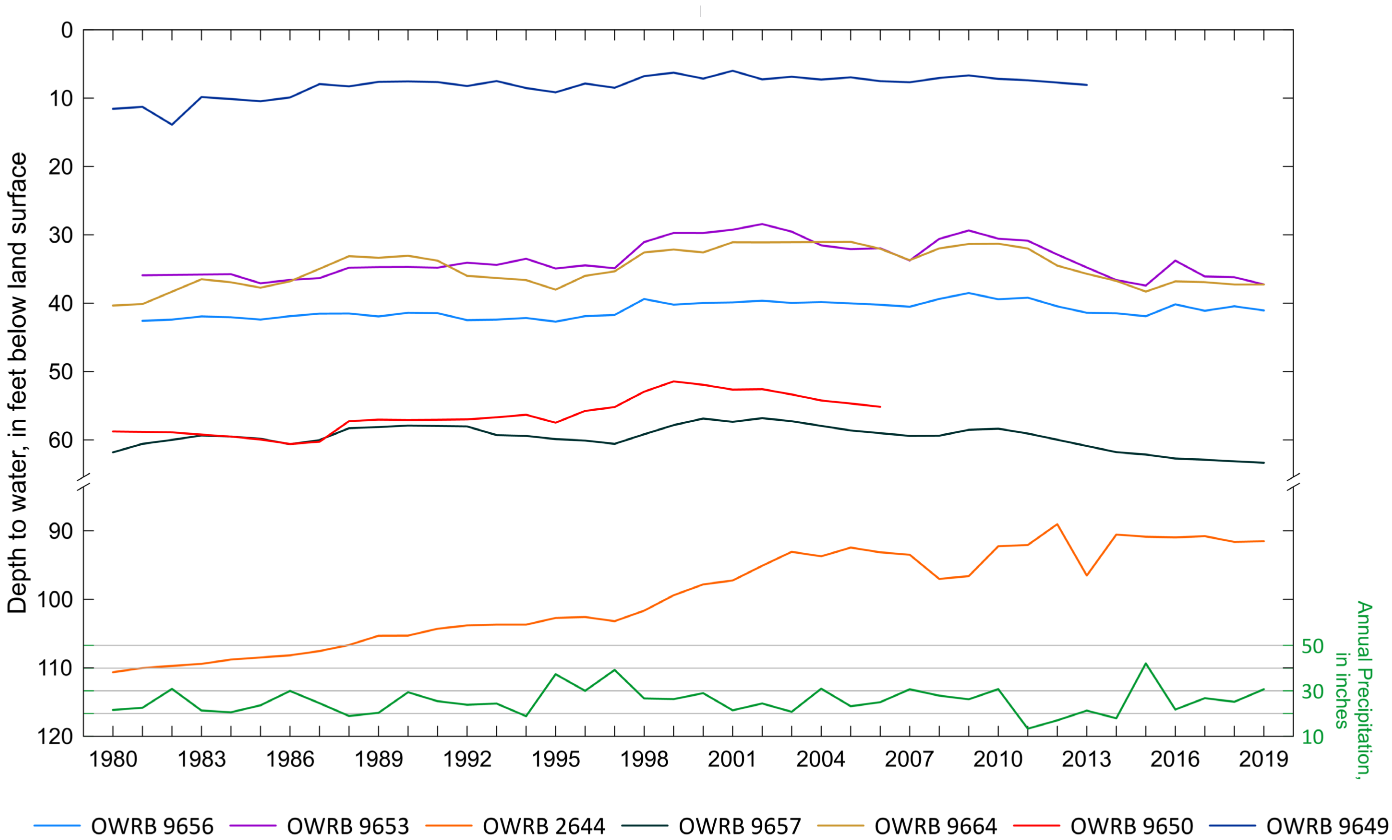


Figure 10. Water levels from OWRB Mass Measurement Program wells showing long-term responses (see Figure 1 for locations).

increased at five sites and decreased at two sites with a mean increase in water levels of 6.17 feet and a mean decrease of 1.43 feet (Figure 10). During the observed historical wet period (1980-2010), the mean water level increased 6.77 feet. The mean water level decreased 3.49 feet during the historical dry period (2011-15). Water levels in three wells increased in 2016 in response to above mean precipitation in 2015. However, the mean water level in the wells decreased 1.21 feet from 2016-19.

Continuous Water Levels

Depth to water was recorded continuously at 1-hour intervals at six groundwater wells. Water-level recorders were installed in five wells (OWRB 25326, 141810, 178140, 178402, 178456) between December 2016 and February 2017 and in one well (OWRB 81942) in December 2017 (Table 3). Two water-level recorders (OWRB 178402, 178456) were discontinued in March 2019. One well (OWRB 141810) is located in an area with a shallow water table (4-7 feet below land surface) and showed rapid, short-term water-level responses to precipitation (Figure 11). A seasonal pattern of decreasing water levels reflects stresses to the aquifer during the summer months (June-September) from groundwater pumping and baseflow discharge. Increases in evapotranspiration and runoff following precipitation during the summer also contribute to decreases in recharge. Water levels began increasing during October and were relatively stable during the winter months when pumping and evapotranspiration were at a minimum. Wells with deeper water tables (OWRB 25326, 81942, 178140, 178402, 178456), 47-87 feet below land surface, had more stable water levels with only minor changes from 2017 through early 2019 (Figure 12). These water levels then began increasing in June 2019 following above mean precipitation, including 8.56 inches in May 2019, which indicates that the water levels likely do not respond to short-term precipitation events or follow seasonal patterns and instead respond to sustained above mean precipitation.

Groundwater Flow

Groundwater in the aquifer is unconfined and predominantly flows from west to east. The direction of horizontal groundwater flow can be determined from water-table elevation maps of the aquifer. The water-table elevation map of an aquifer is an estimated surface of the water table and reflects the estimated height to which a

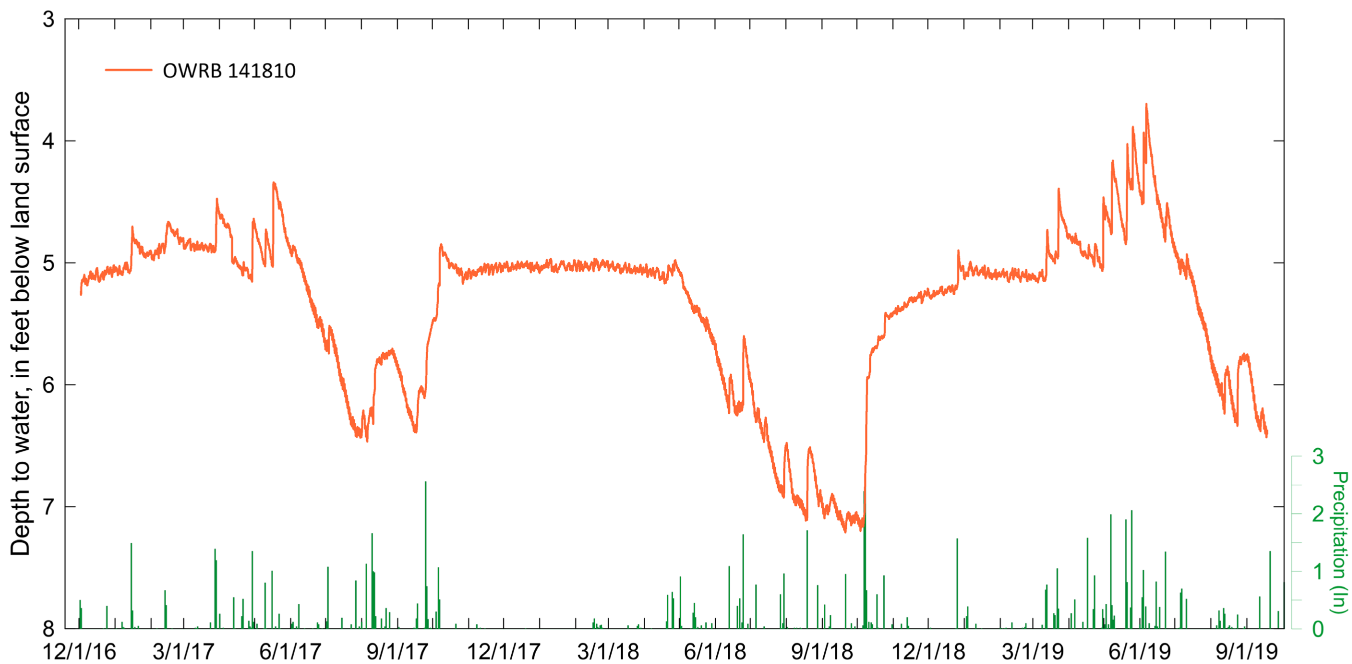


Figure 11. Water levels from OWRB continuous water-level well and precipitation data from the Cheyenne Mesonet station showing short-term responses to precipitation and seasonal patterns (see Figure 1 for location).

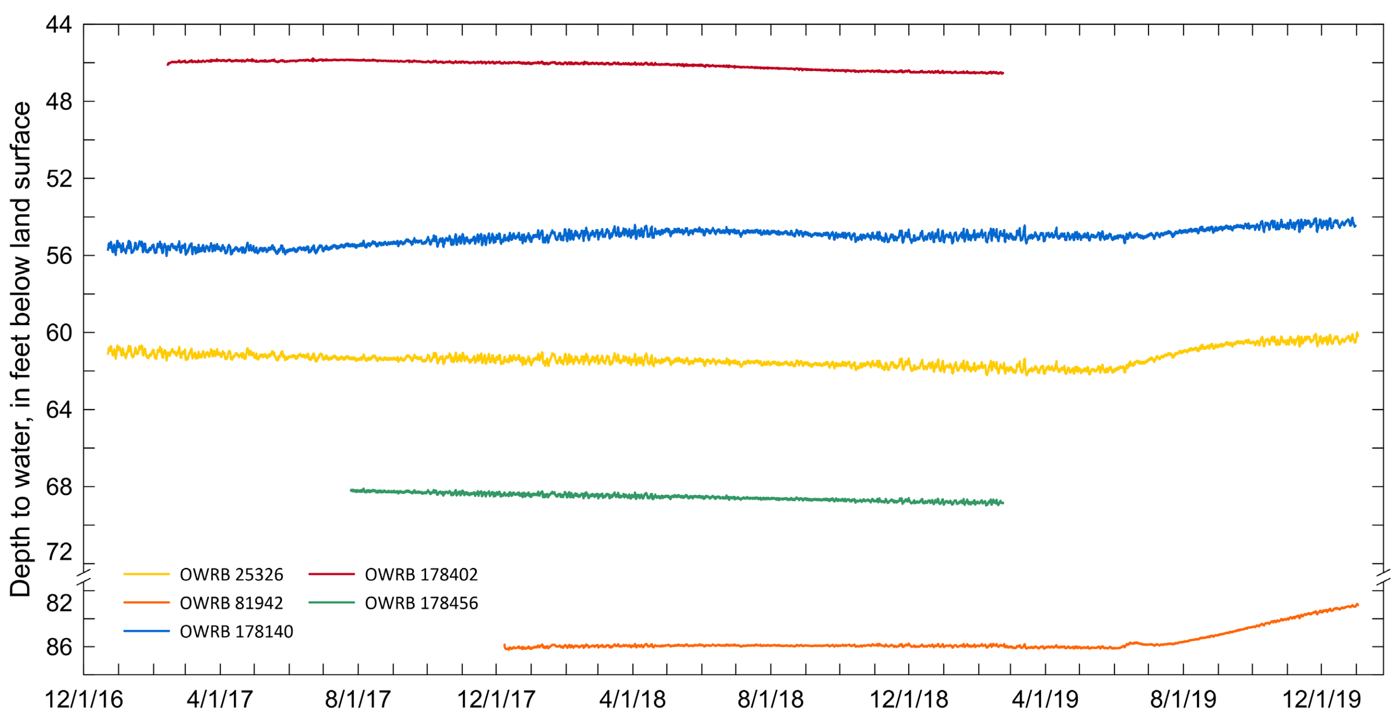


Figure 12. Water levels from OWRB continuous water-level recorder wells (see Figure 1 for locations).

Table 3. Groundwater well sites with continuous water-level recorders in the Ogallala aquifer in Roger Mills County.

OWRB Well ID	Latitude	Longitude	Total well depth, in feet below land surface	Period of analysis
25326	35.512	-99.881	143	12/22/2016 - present*
81942	35.512	-99.722	98	12/8/2017 - present*
141810	35.608	-99.908	60	12/2/2016 - 9/18/2019
178140	35.790	-99.676	115	12/22/2016 - present*
178402	35.873	-99.857	90	2/13/2017 - 2/22/2019
178456	35.645	-99.841	95	2/13/2017 - 2/22/2019

*recording at time of publication

column of water will rise in a cased well at any point. A water-table map is constructed by contouring static water-level measurements in wells and can be used to determine the direction of groundwater flow. The water table in an unconfined aquifer is defined by the upper limit of the zone of saturation. In 2000, water levels were measured in wells in a previous study by the OWRB (Belden and Osborn, 2002). As part of this investigation, water levels were measured in wells distributed across the aquifer in 2017 to produce water table elevation and saturated thickness maps using water levels from 79 wells, 62 more wells than the 2000 measurement.

2000 Water-Table Elevation

A water-table elevation map was compiled by Belden and Osborn (2002) from water levels measured in 17 wells in March 2000. The mean depth to water was 39 feet below land surface with a mean hydraulic gradient of approximately 20 feet per mile (Belden and Osborn, 2002). Water-table elevation contours are drawn perpendicular to groundwater flow and predominately decrease from west to east with some local variation. The water table elevation map shows a “V” pattern pointing upstream along Rush Creek, which indicates that groundwater is draining to the creek. The map also shows groundwater flow divides between the Washita and Canadian rivers as well as the Washita and North Fork Red rivers.

2017 Water-Table Elevation

In January 2017, water-levels were measured from 79 wells as a part of this investigation. The majority of the water levels were obtained from wells used for domestic supply, livestock, and mining. Depth to water ranged from 4.9 to 169.8 feet below land surface with a median depth of 60.7 feet below land surface. Land surface elevations were collected at each well site using high-precision GPS receivers with decimeter accuracy. The depth-to-water measurements were subtracted from land surface elevations (NAVD 88) to estimate the water-table elevations and contours were interpolated to illustrate groundwater flow (Figure 13). Similar to the 2000 water-table elevation map, groundwater flow is predominately from west to east and a “V” pattern occurs along Rush Creek. However, variations exist especially where groundwater flows toward the North Fork Red, Washita, and Canadian rivers. There is also a “V” pattern indicating groundwater flow toward Dead Warrior, Croton, Spring, Turkey, Trunk, Buffalo, Sergeant Major, Sandstone, and Meridian creeks and an unnamed tributary of Rush Creek.

Groundwater Use

Groundwater from the Ogallala aquifer in Roger Mills County is primarily used for irrigation, public supply, and mining. Reported groundwater use for industrial; commercial; agricultural; domestic; and fish, recreation, and wildlife were combined for this report. The term “public water supply” is used to describe groundwater use by municipalities, rural water districts, housing additions, trailer parks, churches, and schools. Public water suppliers that utilize the aquifer include the Red Star Rural Water District and the Roger Mills Rural Water, Sewer, and Solid Waste Management District #3. As of 2019, the OWRB had over 600 well completion reports for groundwater wells screened or partially screened in the Ogallala Formation within the aquifer boundary. Approximately half of the wells were drilled for domestic use and half were drilled for agricultural, municipal, industrial, oil and gas drilling, and commercial uses. Mean well yields are about 64 gallons per minute and range from 5-400 gallons per minute. Non-domestic water uses such as irrigation; public supply; industrial; power; mining; commercial; agricultural; and recreation, fish, & wildlife are self-reported to the OWRB annually with complete records beginning around 1967. Water use reports are not required to be reported to the OWRB for domestic groundwater use. Prior to 1980, irrigation water use amounts were based on crop type, acres, and frequency of application. In 1980, the method was changed to include inches applied to increase accuracy of the estimated irrigation use (Oklahoma Water Resources Board, 2017a).

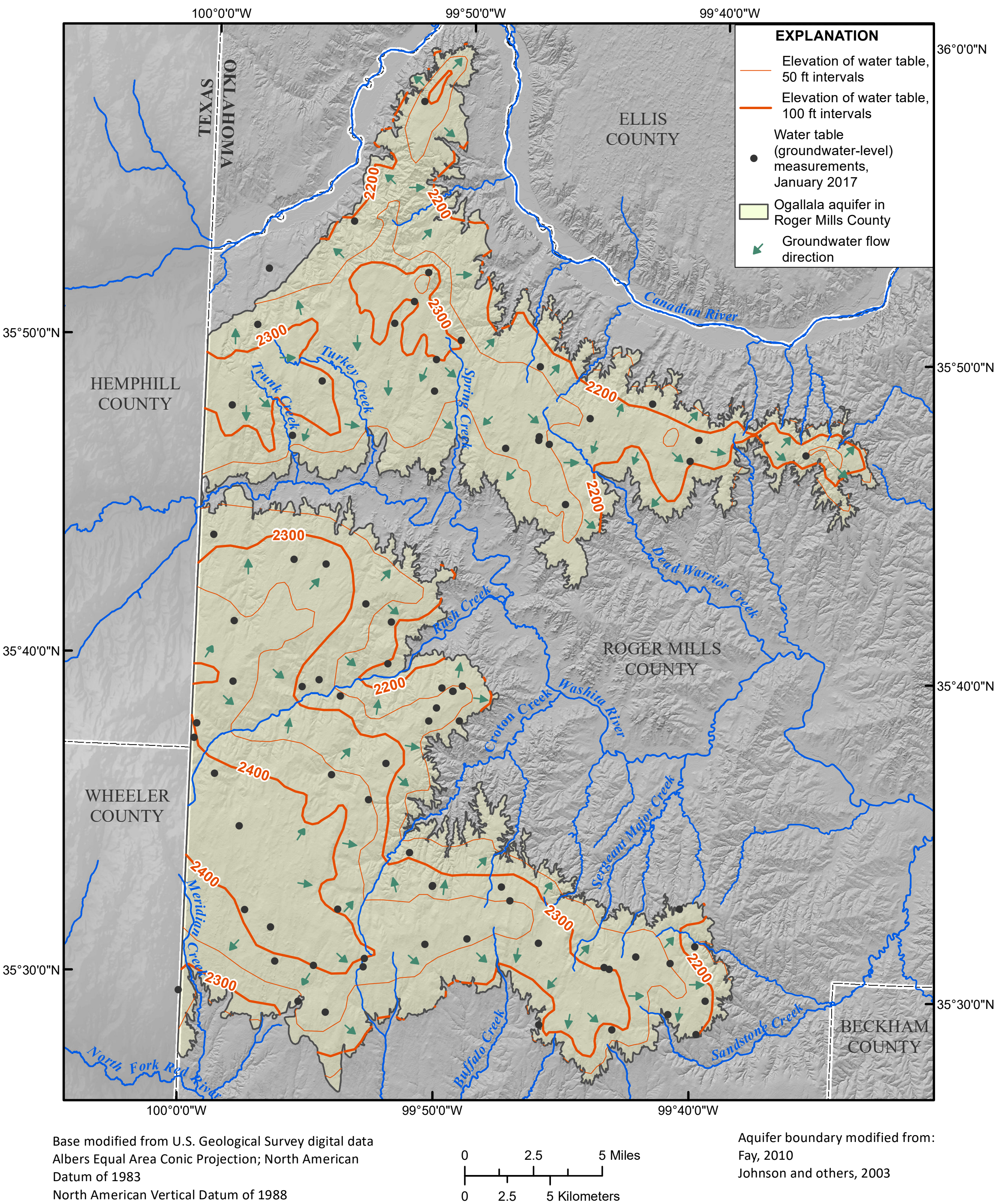


Figure 13. Water table elevation contours (2017) in the Ogallala aquifer in Roger Mills County.

Long-term permitted groundwater use

There were 115 active long-term temporary groundwater permits or prior rights in 2019 with an additional 29 inactive within the aquifer boundary (Figure 14). Annual groundwater use was reported for 57 permits to the OWRB by permitted users during the period of 1967-2019 (Figure 15). Irrigation accounted for 58.9 percent, public water supply accounted for 38.5 percent, mining accounted for 2.4 percent of use while industrial, commercial, and agricultural uses accounted for less than one percent (Table 4). The mean reported groundwater use from 1967-2019 was 619 acre-feet per year with a median of 573 acre-feet per year. The maximum and minimum reported groundwater use was 1,536 acre-feet in 2014 and 131 acre-feet in 1973.

Reported groundwater use trends were identified for two time periods based on the amount of use: 1967-90 and 1991-2019 (Table 5). For 1967-90, reported groundwater use was lower with a mean of 448 acre-feet per year. Prior to 1980, irrigators were required to report the number of acres irrigated and the number of times irrigation occurred, but not the amount of water applied to the land. These assumptions regarding the amount of water used based on crop type may have resulted in overestimations of water use. This could explain the higher reported irrigation use during that time compared to 1980-90. Reported groundwater use increased from 1991-2019 with a mean of 760 acre-feet per year. The increase is mostly attributed to new permits and increased groundwater use for irrigation.

Table 4. Reported mean annual groundwater use by type in the Ogallala aquifer in Roger Mills County, 1967-2019.

Time span	Mean annual reported water use by type, in acre-feet per year			
	Irrigation	Public water supply	Mining	Other
1967-2019	365	238	15	10
1967-1990	329	115	4	0.2
1991-2019	515	339	24	0.2

Table 5. Summary statistics of reported groundwater use in the Ogallala aquifer in Roger Mills County, 1967-2019.

	Reported annual groundwater use, in acre-feet per day		
Statistic	1967-2019	1967-1990	1991-2019
Mean	619	448	760
Median	573	420	736
Minimum	131	131	405
Maximum	1,536	822	1,536

Provisional-temporary groundwater permits

The OWRB issues provisional-temporary groundwater permits that expire 90 days after issuance. These permits are used to provide a short-term water supply or supplement the water supply of existing permit holders. Unlike long-term permits, water use reports are not required for provisional-temporary permits with volumes assumed not to exceed the authorized amount. The OWRB has records for provisional-temporary permits dating back to 1992. A more detailed description of provisional-temporary permits is available in OWRB Rules Chapter 30: Taking and Use of Groundwater (Oklahoma Water Resources Board, 2017a).

Between 1992 and 2019, 250 provisional-temporary permits were issued in the Ogallala aquifer in Roger Mills County. Oil, gas, and mining accounted for 248 permits and 96.2 percent of authorized use; irrigation accounted for two permits and 3.8 percent of authorized use (Figure 16). The mean authorized use for the entire period was 56 acre-feet per year. Permitted use for provisional-temporary permits can be split into two periods. A period of lower authorized use from provisional-temporary permits occurred from 1992 to 2010, with a mean of 23 acre-feet per year from a total of 129 provisional-temporary permits. Permitted use from provisional-temporary permits increased substantially from 2011 to 2019, with a mean of 126 acre-feet per year from a total of 122 provisional-temporary permits which incorporates a drought period.

Hydrogeology

Base of the Ogallala Formation

The base of the aquifer is the contact between the Ogallala Formation and underlying Permian formations, including the Cloud Chief Formation, Doxey Shale, and Elk City Sandstone. The base is typically easy to distinguish in lithologic logs and in outcrops by a change in color and lithology. Lithology descriptions at the base typically include a transition from sands, clays, or gravels that are white, tan, gray, and brown (Ogallala Formation) to red shales, clays, and sandstones (Permian formations).

A previous OWRB report determined the aquifer base elevation using lithologic descriptions from over 200 well driller's logs which showed generally decreasing base

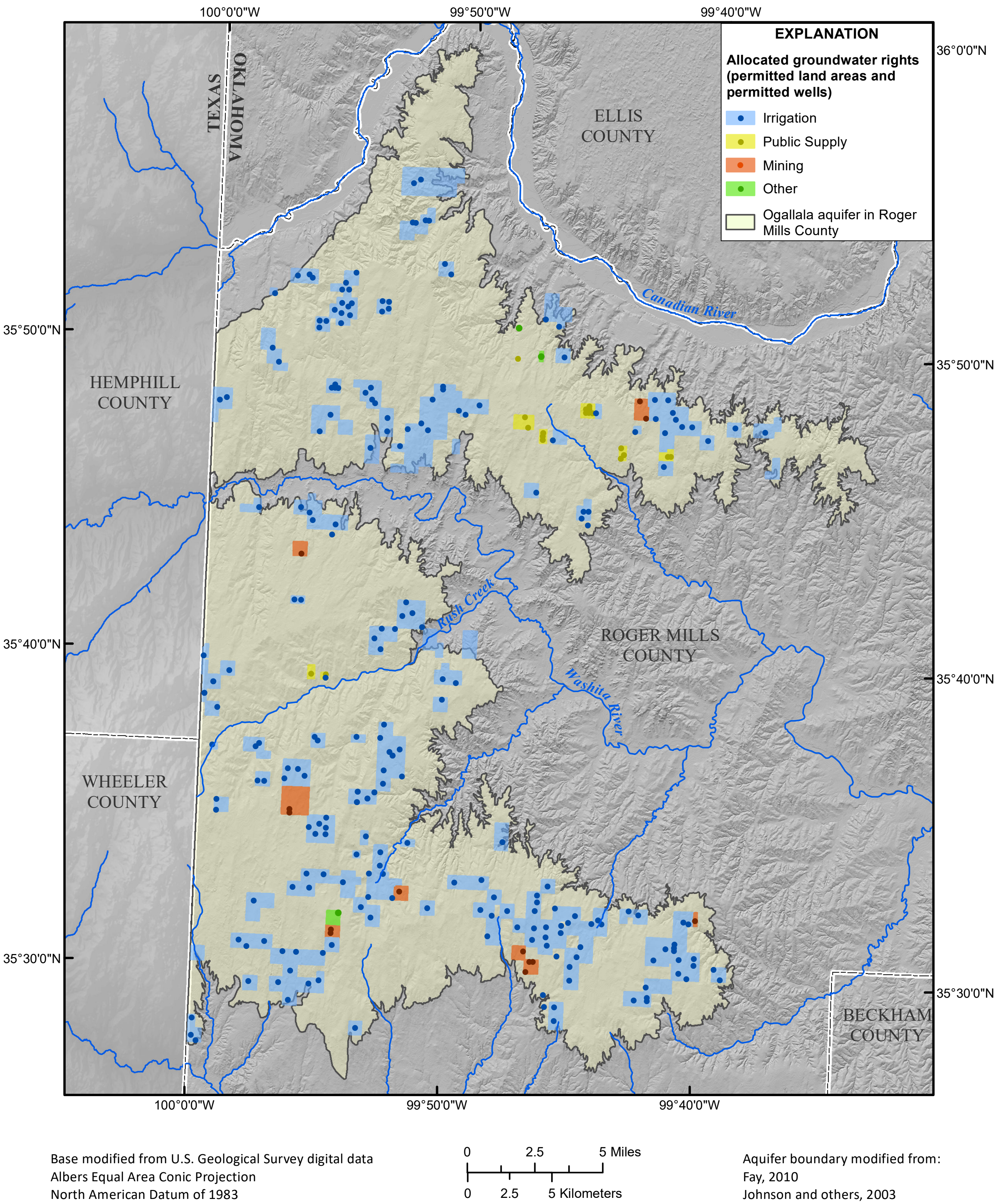


Figure 14. Land areas and well locations permitted for groundwater use, 2019.

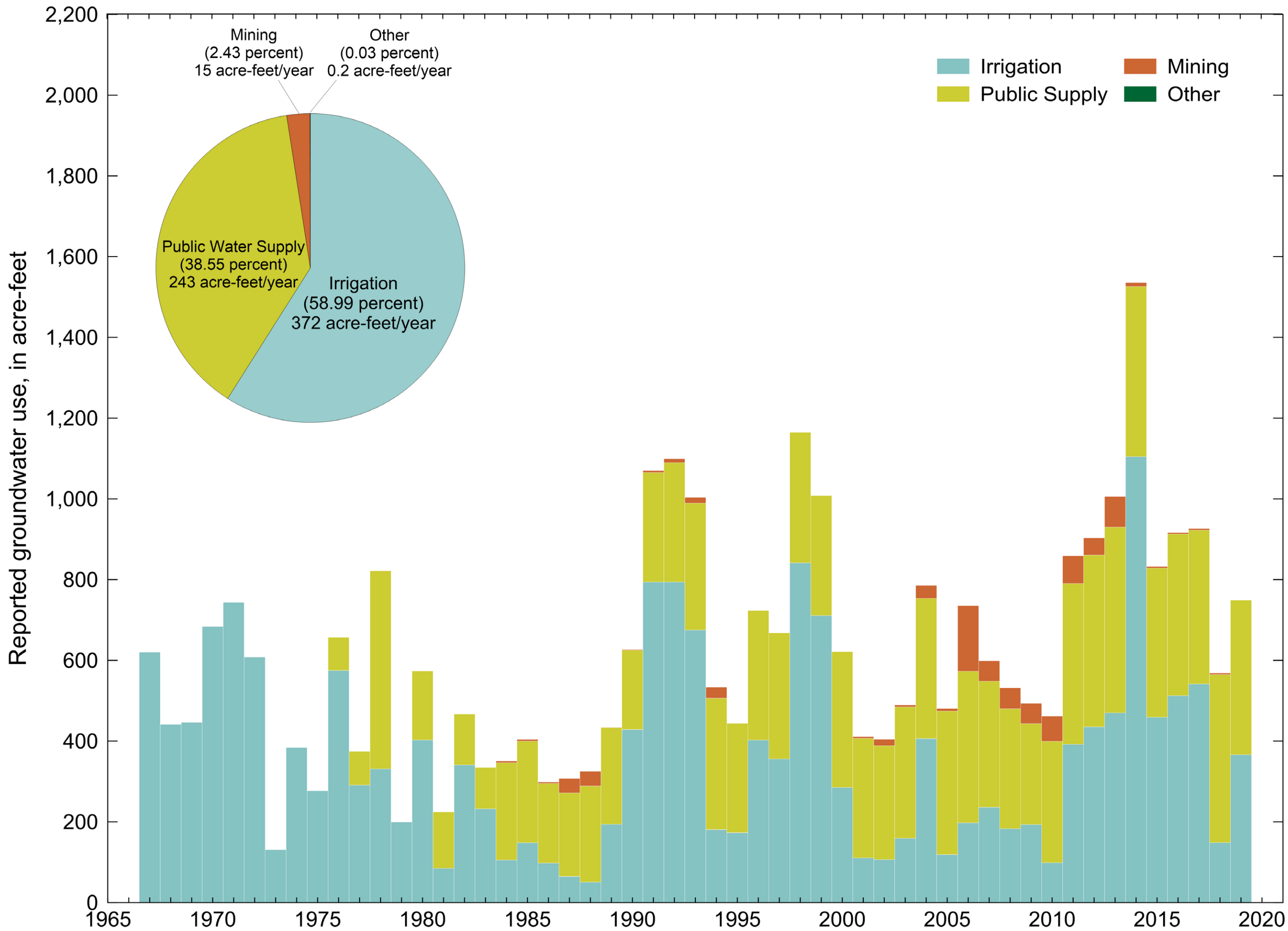


Figure 15. Annual reported groundwater use in the Ogallala aquifer in Roger Mills County, 1967-2019.

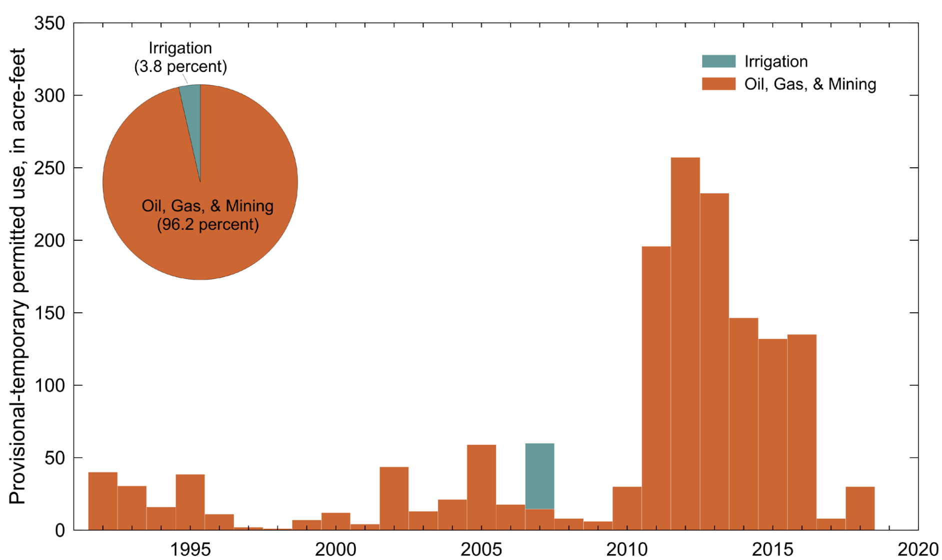


Figure 16. Groundwater use authorized for provisional-temporary permits, 1992-2019.

elevations from west to east ranging from about 2,400-2,150 feet above NAVD 88 (Belden and Osborn, 2002). The base elevation of the aquifer was reanalyzed for this investigation using an additional 353 well driller's logs from the OWRB groundwater well records database for a total of 553 well driller's logs (Oklahoma Water Resources Board, 2018; Figure 17). The base elevation generally decreases from west to east similar to the aquifer base elevation from the previous study. Local variations are likely caused by the unconformable contact with the underlying Permian formations. The base ranges from about 2,380 feet above NAVD 88 in the southwest part of the aquifer to about 2,125 feet above NAVD 88 in the southeast part of the aquifer about seven miles south of Cheyenne, Oklahoma.

Aquifer Saturated Thickness

The saturated thickness represents the vertical thickness of the aquifer that is saturated and is important for understanding the availability and changes in the groundwater resources of an aquifer. The saturated thickness of the Ogallala aquifer in Roger Mills County (Figure 18) was estimated by subtracting the base elevation of the Ogallala Formation (Figure 17) from the 2017 water-table elevation (Figure 11). The maximum saturated thickness is 166 feet with a mean of 45 feet; the saturated thickness generally coincides with the sediment thickness and decreases to zero at the contact with the underlying Permian formations. The maximum saturated thickness occurs about seven miles south-southwest of the town of Reydon, Oklahoma. Other thick portions of the aquifer are located near the Oklahoma-Texas border between Rush Creek and the Washita River as well as the north-central parts of the aquifer with saturated thicknesses ranging from 120-160 feet. The saturated thickness decreases toward streams, most notably Rush Creek and Croton Creek, due to erosion of the Ogallala Formation by the streams. Along the northwest boundary of the aquifer, the Ogallala Formation is hydrologically connected with the Canadian River alluvial terrace deposits; the saturated thickness ranges from 5-30 feet along that portion of the boundary.

Cross Sections

Three cross sections of the Ogallala aquifer in Roger Mills County (Figure 19) were created for the study showing the base of the Ogallala Formation (Figure 17) and the 2017 water-table elevation datasets (Figure 13). Several streams intersect the water-table elevation, indicating likely contributions to base flow from the aquifer. Cross-section A-A' runs from north to south along the western portion of the aquifer and shows a slight increase in the aquifer base elevation in the southern portion of the aquifer with the water table intersecting the Washita River and Rush Creek. Cross-section A-A' also shows the downcutting of the Washita River through the Ogallala Formation and about 50-80 feet into the underlying Doxey Shale and Cloud Chief Formation. Cross-section B-B' runs from west to east across the aquifer, north of the Washita River and generally shows thinning of the aquifer from west to east. The Ogallala Formation has been completely eroded near the narrowest part of the aquifer about four miles east of the town of Roll, OK. Base-flow was not observed during the winter of 2017 in the drainages seen along cross-section B-B', indicating the water-table was not discharging during field observations. A groundwater divide is also located about 13 miles east of the Texas-Oklahoma border along the cross section. Cross-section C-C' runs from west to east along the thickest portion of the southern part of the aquifer. The C-C' cross-section shows a thick, less eroded section of the Ogallala Formation extending about 5.5 miles to the east from the Oklahoma-Texas border, with a significant amount of erosion in the vicinity of Croton Creek, where groundwater was observed discharging to the surface. Erosion can also be seen along other drainages that do not intersect the water table. The eastern half of cross-section C-C' generally shows a decrease in the base elevation and thickness of the aquifer from west to east.

Recharge

Groundwater recharge for this investigation is defined as the process of precipitation entering the groundwater flow system and is the primary means of inflow into the aquifer. The rate of recharge is controlled by various factors such as precipitation, soil type, aquifer lithology, vegetation, land use, and land-surface gradient. Recharge rates are often difficult to quantify because of high spatial and temporal variability. Two techniques were utilized for this study: (1) a hydrograph-based water-table fluctuation method used to estimate localized recharge rates and (2) a code-based water-balance technique called the soil-water balance code (SWB), which uses precipitation and physical attributes to estimate recharge rates for the period of 1948-2019.

Water-Table Fluctuation Method

The Water-Table Fluctuation (WTF) method (Healy and Cook, 2002) has been used in other groundwater studies in Oklahoma (Canadian, North Fork Red River, Elk City; Ellis and others, 2017; Smith and others, 2017; Wagner and others, 2021). The WTF method is based on short-term rises in groundwater levels over a few hours or days that are caused by precipitation events in unconfined aquifers. The method is best applied to groundwater wells with shallow water tables that rise sharply after precipitation events. The WTF method estimates recharge using the change in groundwater head, related to a precipitation event, multiplied by the specific yield of the aquifer. There are several uncertainties when using the WTF method. Specific yield values are typically estimated and assumed to be constant which does not take

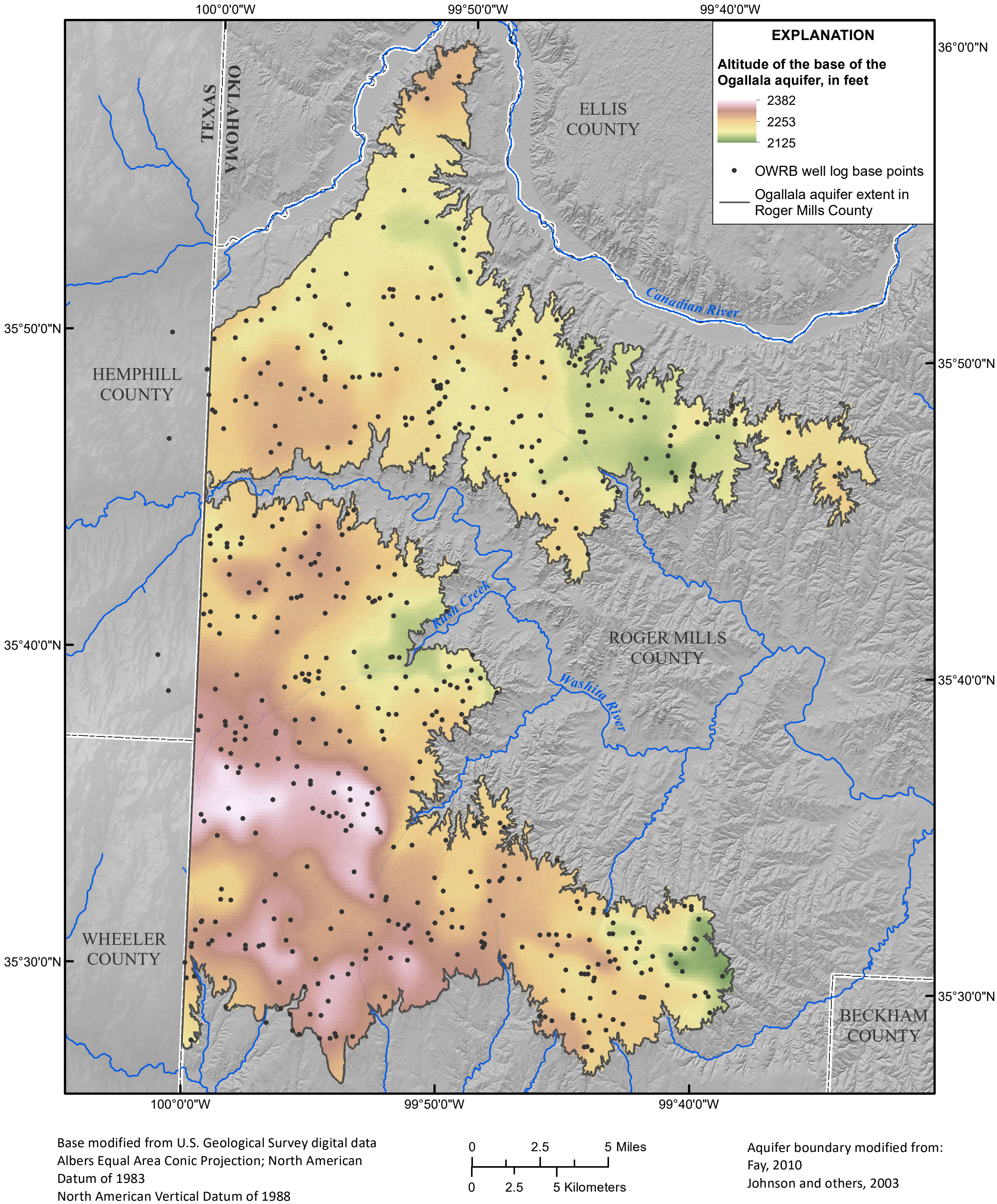


Figure 17. Elevation of the base of the Ogallala aquifer in Roger Mills County derived using lithologic logs.

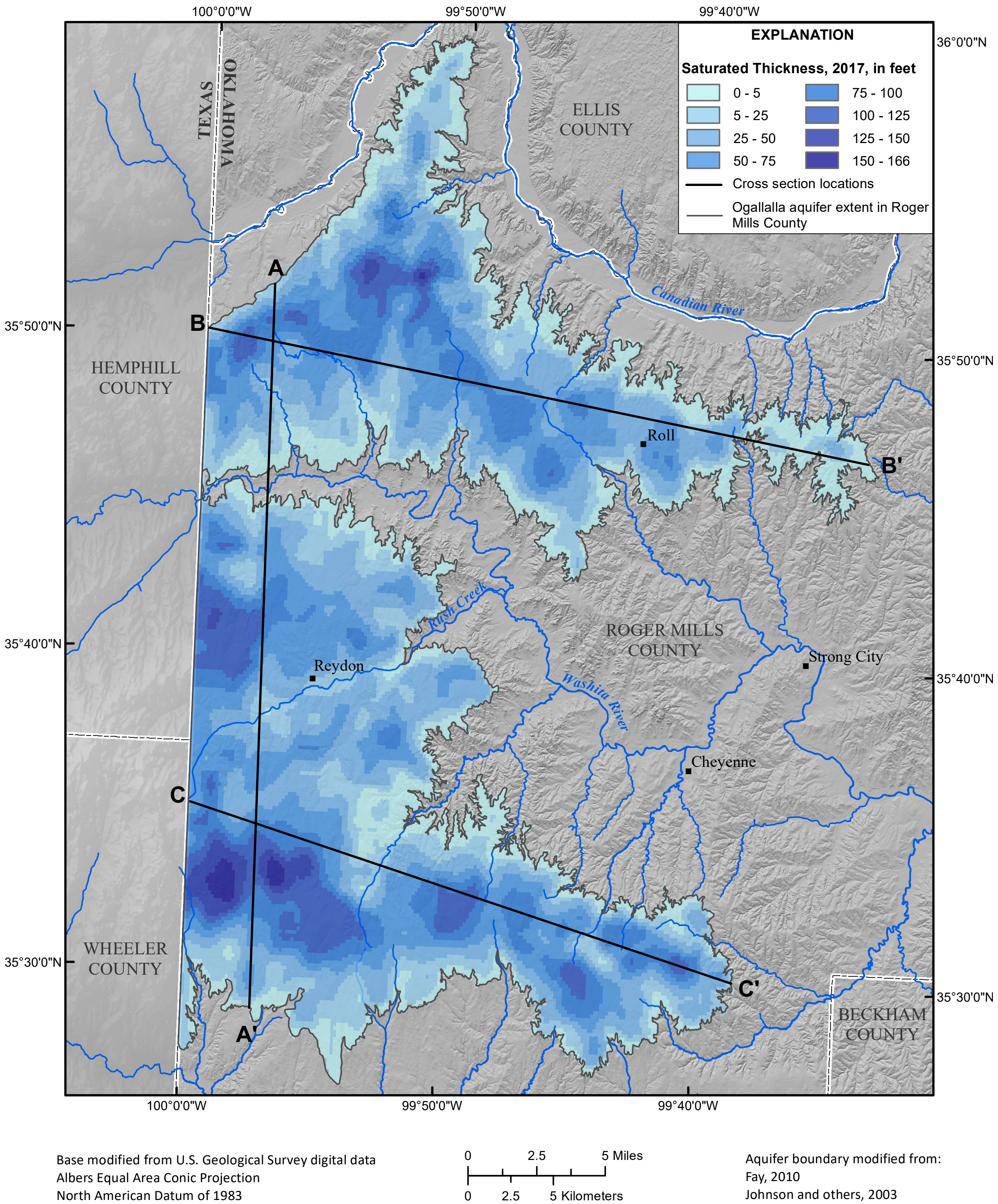


Figure 18. Saturated thickness (2017) and cross-section locations in the Ogallala aquifer in Roger Mills County.

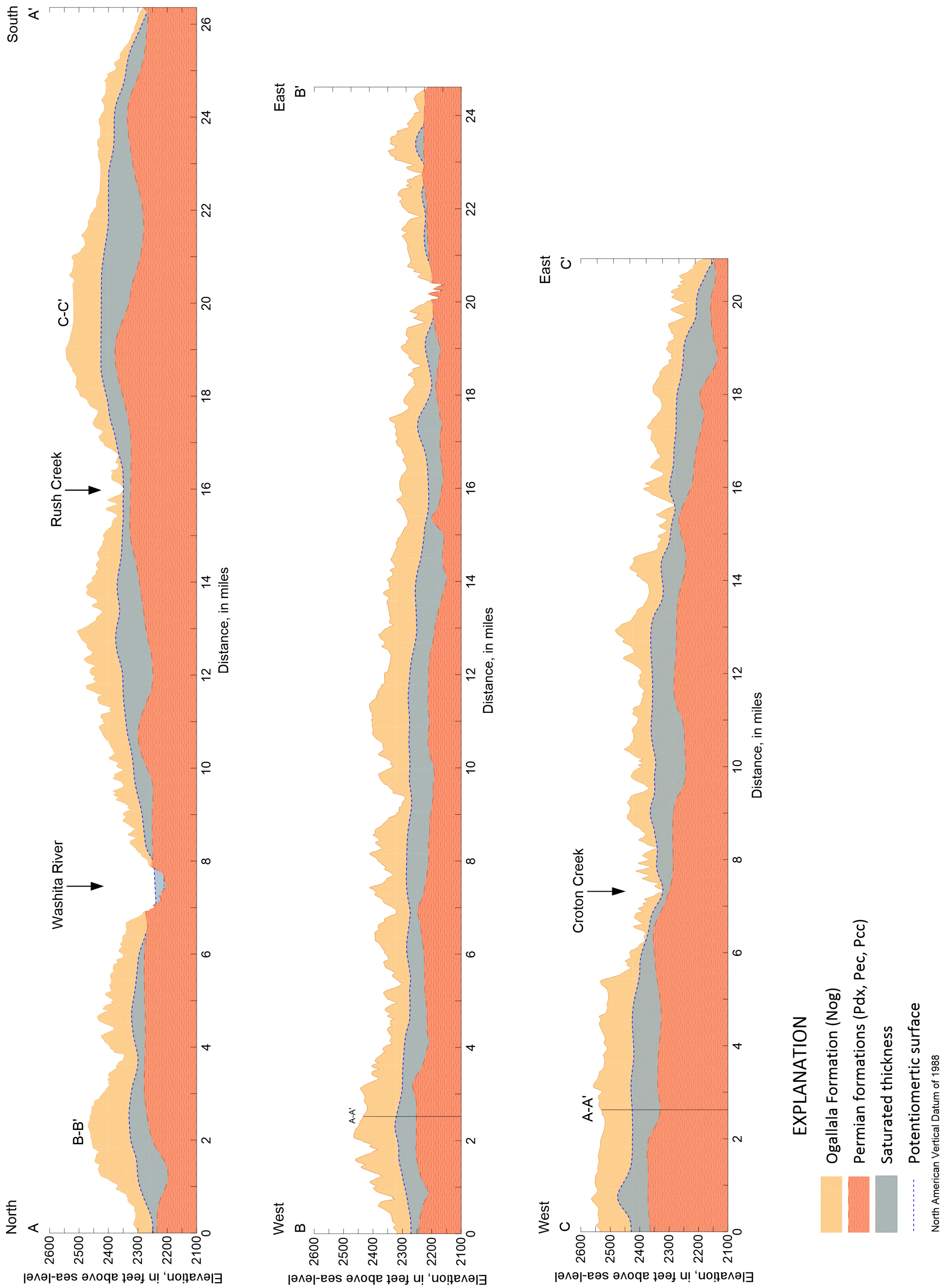


Figure 19. Cross-sections A-A', B-B', and C-C' showing the geologic units, 2017 water table elevation, and saturated thickness.

into account variability in specific yield due to moisture retention in the unsaturated zone between recharge events and could lead to greatly overestimated recharge rates (Healy and Cook, 2002; Crosbie and others, 2005). Recharge can also be overestimated due to the Lisse effect, which occurs when air trapped in the unsaturated zone during rapid recharge events causes a rapid rise in water levels that is greater than expected for the amount of precipitation followed by a rapid decrease in water levels (Crosbie and others, 2005). There can also be a source of error in the WTF method with wells in closer proximity to a stream due to the effects of bank storage. Bank storage occurs when a stream rises above the water table and water infiltrates into the surrounding aquifer before flowing back to the stream when the water level drops (Singh, 1968; Todd, 1980). The method also does not consider other variables such as surface runoff, pumping, surface water infiltration, and evapotranspiration.

A water-level hydrograph for OWRB 141810 (Figure 11), located three miles south-southeast of Reydon, OK, was analyzed using the WTF method during 2017 and 2018. This well met all criteria for shallow depth to water and groundwater responses and was equipped with a continuous water-level recorder that recorded the groundwater level in 1-hour intervals. The water-level trend seen in the hydrograph prior to precipitation events was extrapolated below the peak in water levels following precipitation. This gives an estimate of what the water level would have been without any precipitation and provides a more accurate estimate for recharge. The specific yield was estimated to be 0.18, based on percent coarse analysis (see Hydraulic Properties section of this report). Annual precipitation was 26.95 inches in 2017 and 23.19 inches in 2018, measured at the Cheyenne Oklahoma Mesonet station located 11 miles southeast of the well. Using the WTF method, the estimated recharge was 9.95 inches (37 percent of precipitation) in 2017 and 8.53 inches (37 percent of precipitation) in 2018. The estimated recharge using the WTF method was greater than 70 percent of precipitation during five precipitation events and greater than 100 percent of precipitation following two precipitation events during these years. Therefore, the WTF method may be overestimating recharge due to the high percentage of precipitation as recharge. This could be caused by a combination of factors including variability in the specific yield, the Lisse effect, and bank storage.

Soil-Water Balance Code

The soil-water balance (SWB) code provides an estimation of groundwater recharge at a regional scale using a modified Thornthwaite-Mather soil-water balance approach in conjunction with land cover, soil characteristics, and climatological data (Westenbroek and others, 2010). The SWB code estimates recharge as the difference between the change in soil moisture and the sources and sinks of water at each grid cell in the model domain at a daily time step (Westenbroek and others, 2010). The SWB code estimates losses caused by interception, ET, and runoff at daily time steps and removes the volume from the estimated soil moisture. Interception is a user-defined amount of water utilized by vegetation that may be specified for each land-use type and season (growing or dormant). Spatially variable potential ET is estimated in the SWB code using climate data, such as air temperature, relative humidity, and wind speed. For this investigation, the Hargreaves-Samani method (Hargreaves, 1985) was used for two reasons: (1) this method utilizes data from multiple climate stations as spatially-gridded datasets and (2) this method estimates ET using the minimum and maximum air temperature in addition to daily precipitation.

The SWB code only considers water input in the form of precipitation and runoff entering the grid cell from up-gradient. The daily precipitation value for a grid cell must exceed the interception and estimated potential evapotranspiration before water is assumed to contribute to soil moisture (Westenbroek and others, 2010). Once soil moisture exceeds the maximum water capacity for the soil type, the grid cell is considered saturated and excess is converted to recharge (Westenbroek and others, 2010). Additional water applied to a grid cell is converted to runoff, which is either routed to an adjacent cell or out of the model domain completely. Runoff was estimated using the U.S. Department of Agriculture Natural Resources Conservation Service (NRCS) curve-number precipitation-runoff relation. Curve numbers are a baseline percentage of saturation that are modified at daily time steps using the precipitation history of the previous five days, vegetation dormancy, and, optionally, the frozen ground index (Westenbroek and others, 2010). The slope of the land surface is used only to direct estimated runoff to adjacent cells (Westenbroek and others, 2010).

There are some limitations of the SWB code: (1) curve numbers, maximum soil recharge, interception, root zone depth, available water capacities, and infiltration rates are based on the mean for land and soil types and were not directly measured for this study; (2) depth from the bottom of the root zone to the top of the water table are not factored in, resulting in recharge estimations that can be anomalously high in areas where the water table is close to the surface (Westenbroek and others, 2010); (3) ET from the groundwater table is not computed and can be underestimated in areas where groundwater occurs near land surface; and (4) soil type and maximum water capacity have the greatest impact on recharge estimation, most notably where surface water cuts through sandy soils.

Soil data was obtained from the National Resources Conservation Service (NRCS) SSURGO dataset (National Resources Conservation Service, 2014). Soils are represented by four hydrologic soil groups (A-D) and were categorized based on infiltration capacity, with ‘A’ soils having the highest infiltration capacity and ‘D’ soils having very low infiltration capacity (Westenbroek and others, 2010). Each soil type was assigned an available soil-water capacity based on soil texture and range from 1.20-3.60 inches per foot of thickness (Westenbroek and others, 2010). Land use data were obtained from the National Land Cover Database (NLCD), which provides 16 different classes for land cover (Multi-Resolution Land Characteristics Consortium, 2016). At the 100-meter cell size, the land-use class for some cells containing county roads were classified as "commercial/industrial transportation", which caused artificially low recharge values for these cells caused by increased runoff from impermeable surfaces. The cells were changed to match the land-use class of surrounding cells to more accurately reflect the land-use and recharge of those areas. Land-use data, in conjunction with available soil-water capacity, were used to calculate surface run-off and maximum soil-moisture holding capacity (Westenbroek and others, 2010). The SWB model uses a land-use lookup table provided by the NRCS with curve numbers, precipitation interception, maximum daily recharge values, and root-zone depths specific to each land-use type (Westenbroek and others, 2010). Characteristics such as available water capacities, infiltration rates, root-zone depth, maximum soil recharge, interception, and curve numbers are based on the mean for each land and soil type. A flow direction grid was used to determine the routing of overland flow between cells. The flow direction grid was generated from a 10-m digital elevation model of Oklahoma using the D8 method. The D8 method assigns flow from each grid cell to one of the eight surrounding cells in the direction of the steepest slope (O'Callaghan and Mark, 1984).

The SWB code was used to estimate spatially distributed groundwater recharge from 1948-2019 over the Ogallala aquifer in Roger Mills County. This 72-year time period was chosen based on the availability of precipitation data from multiple stations. The model requires tabular climate data and four gridded datasets: (1) soil-water capacity, (2) land-use classification, (3) hydrologic soil group, (4) flow direction (Westenbroek and others, 2010). Climate data consisting of daily precipitation, daily minimum temperature, and daily maximum temperature were obtained from ten COOP stations and four Oklahoma Mesonet stations located in the study area (Oklahoma Climatological Survey, 2020; Oklahoma Mesonet, 2020). Each dataset was sampled and clipped to a 100 square-meter grid covering the extent of the Ogallala – Roger Mills aquifer. Estimated recharge results were clipped to the outline of the aquifer and statistics for the mean monthly and annual recharge were tabulated.

The results of the SWB code were calculated with monthly and annual recharge grids. Figure 20 shows the spatial variability in estimated mean annual recharge for 1948-2019. Estimated annual recharge in the aquifer during this time period was 1.00 inches. Higher recharge values occur in much of the central and southern portions of the aquifer. The soils in those areas are predominately sand and have lower available water capacity allowing a greater percentage of precipitation to contribute to recharge. Areas with less recharge are primarily located in the northern part of the aquifer along with smaller areas around Croton Creek and the extreme southwestern part of the aquifer. These areas generally are more eroded and have finer-grained sediments that have higher available water capacities.

The highest estimated annual recharge (4.9 inches) occurred in 2015, the wettest year on record in the study area from 1948-2019 (Figure 21). The central and southern portions of the aquifer had the highest estimated recharge with more than two inches in most areas and more than seven inches in much of the southeast portion with a maximum of 32 inches. The northwestern and northernmost portions of the aquifer were estimated to have the lowest recharge in 2015 with less than 0.25 inches in a few areas. The estimated recharge in 2014 was one of the lowest during the period of record (Figure 22). The recharge in 2014 was less than 0.01 inches with the majority of the aquifer showing zero recharge.

Figure 23 shows the estimated annual recharge and annual precipitation for 1948-2019. Three time periods were selected based on trends of below or above mean recharge estimates: (1) 1948-94, (2) 1995-2008, and (3) 2009-19 (Table 6). The period of 1948-94 had below mean estimated annual recharge of 0.87 inches and median recharge of 0.33 inches. Only 15 of the 47 years had above mean recharge. The longest period of above mean estimated recharge occurred from 1995-2008, with an annual mean of 1.56 inches and a median of 1.64 inches. The period of 2009-19 had below mean recharge of 0.85 inches. Only three years during this period had above mean recharge.

Mean monthly recharge trends were analyzed for the period of record and for three time periods: (1) 1948-2019, (2) 1948-94, (3) 1995-2008, and (4) 2009-19 (Figure 24). During 1948-2019, estimated monthly recharge was greatest during May with mean recharge of 0.22 inches. Higher amounts of estimated recharge during the spring and winter months are likely caused by higher precipitation amounts and lower amounts of evapotranspiration. The lowest amount of monthly recharge occurred during July with a mean of less than 0.01 inches. Estimated recharge remains low in August as evapotranspiration and temperatures peak. Estimated monthly recharge for the 1948-94 period is similar to the trend of the period of record analyzed, with the greatest recharge occurring in May and the least recharge occurring in July. For the time period 1995-2008, the greatest estimated monthly recharge occurred in October with 0.36 inches of recharge which is more than double the mean amount of recharge that occurred in May. For the time period 2009-19, estimated recharge was greatest in May with 0.35 inches, respectively, while November had the lowest monthly recharge estimate of less than 0.01 inches.

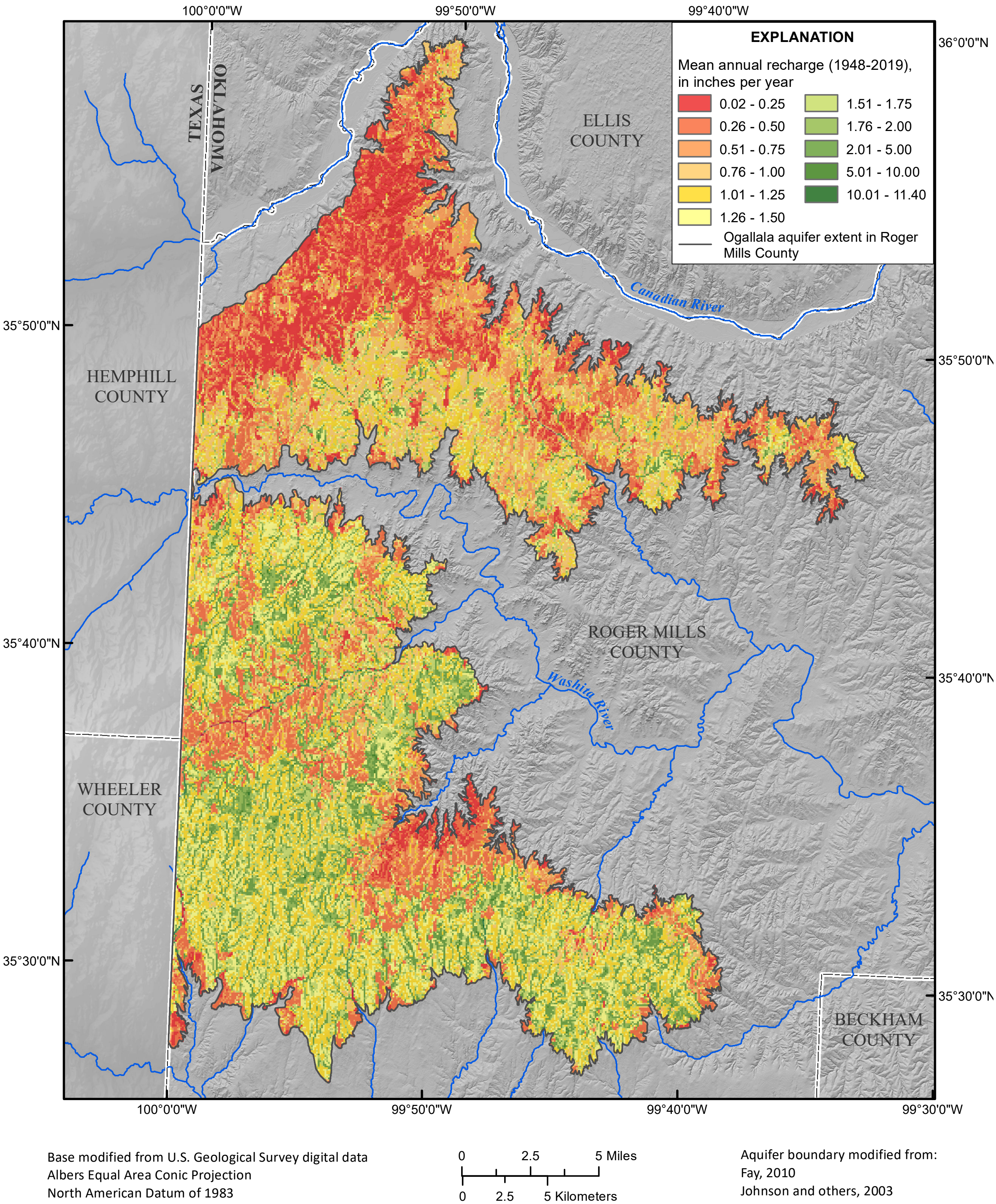
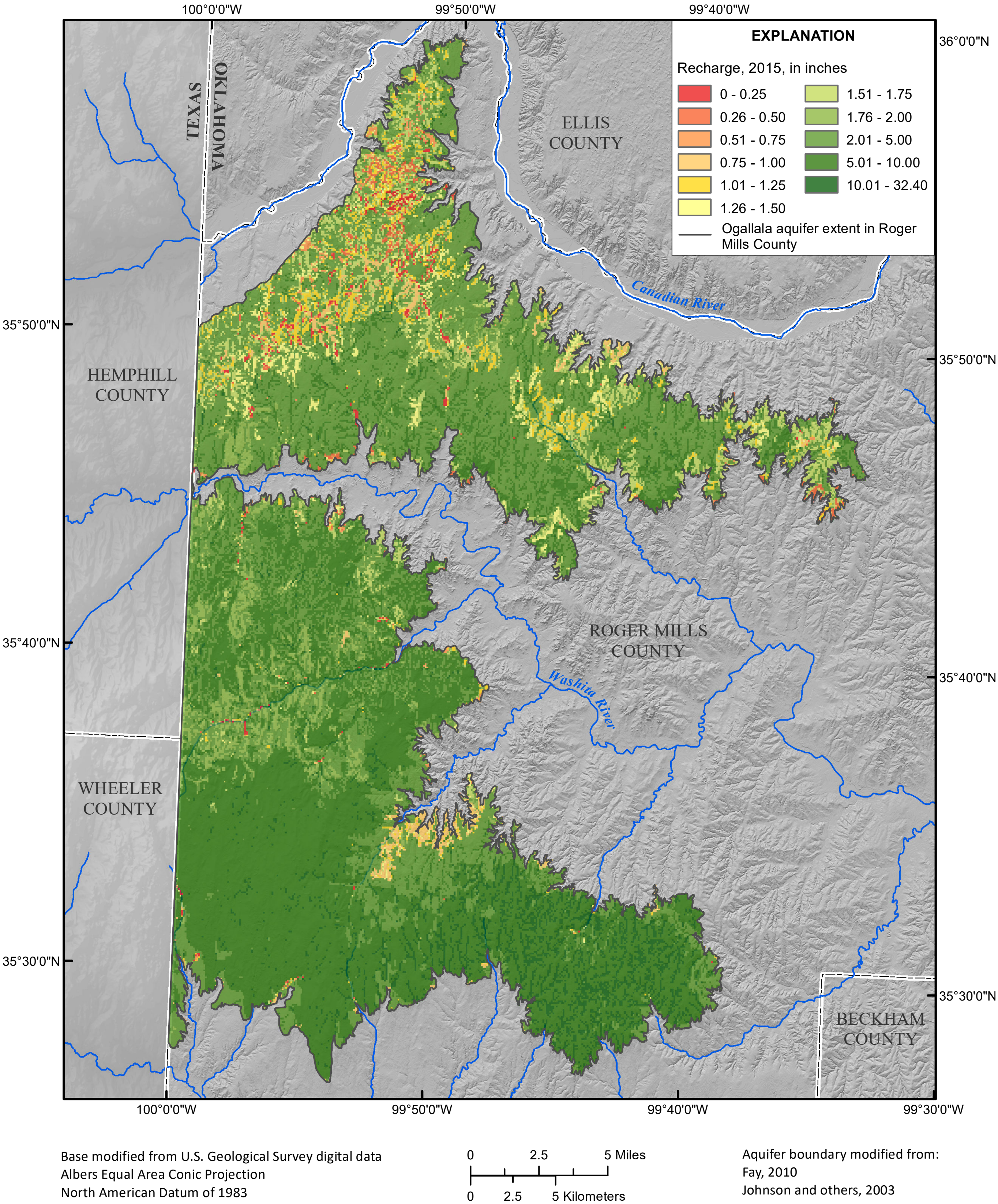


Figure 20. Mean annual recharge estimated by using the SWB code for the Ogallala aquifer in Roger Mills County, 1948-2019.



Base modified from U.S. Geological Survey digital data
Albers Equal Area Conic Projection
North American Datum of 1983

Aquifer boundary modified from:
Fay, 2010
Johnson and others, 2003

Figure 21. Mean annual recharge estimated by using the SWB code for the Ogallala aquifer in Roger Mills County in 2015, a year of above mean recharge.

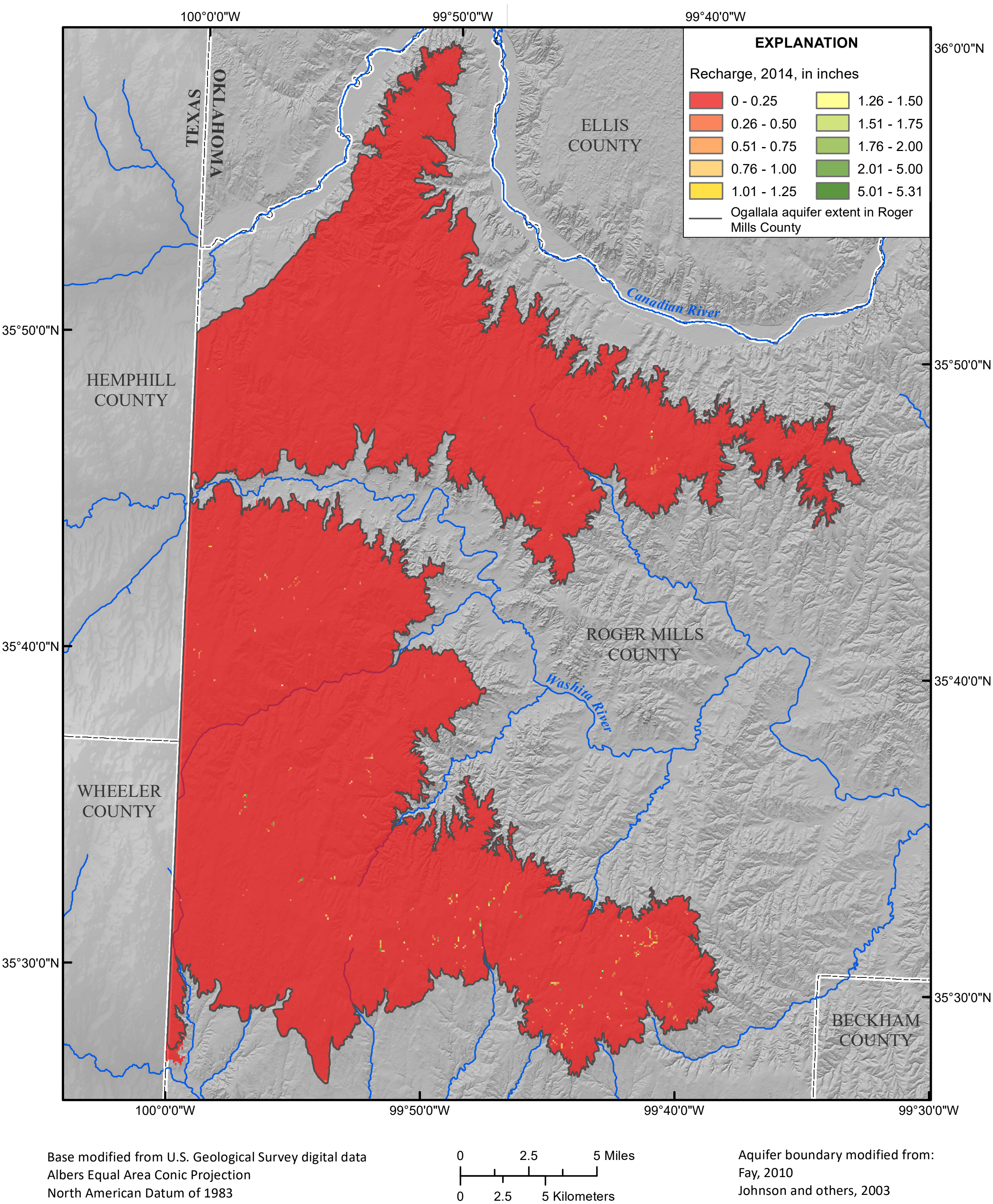


Figure 22. Mean annual recharge estimated by using the SWB code for the Ogallala aquifer in Roger Mills County in 2014, a year of below mean recharge.

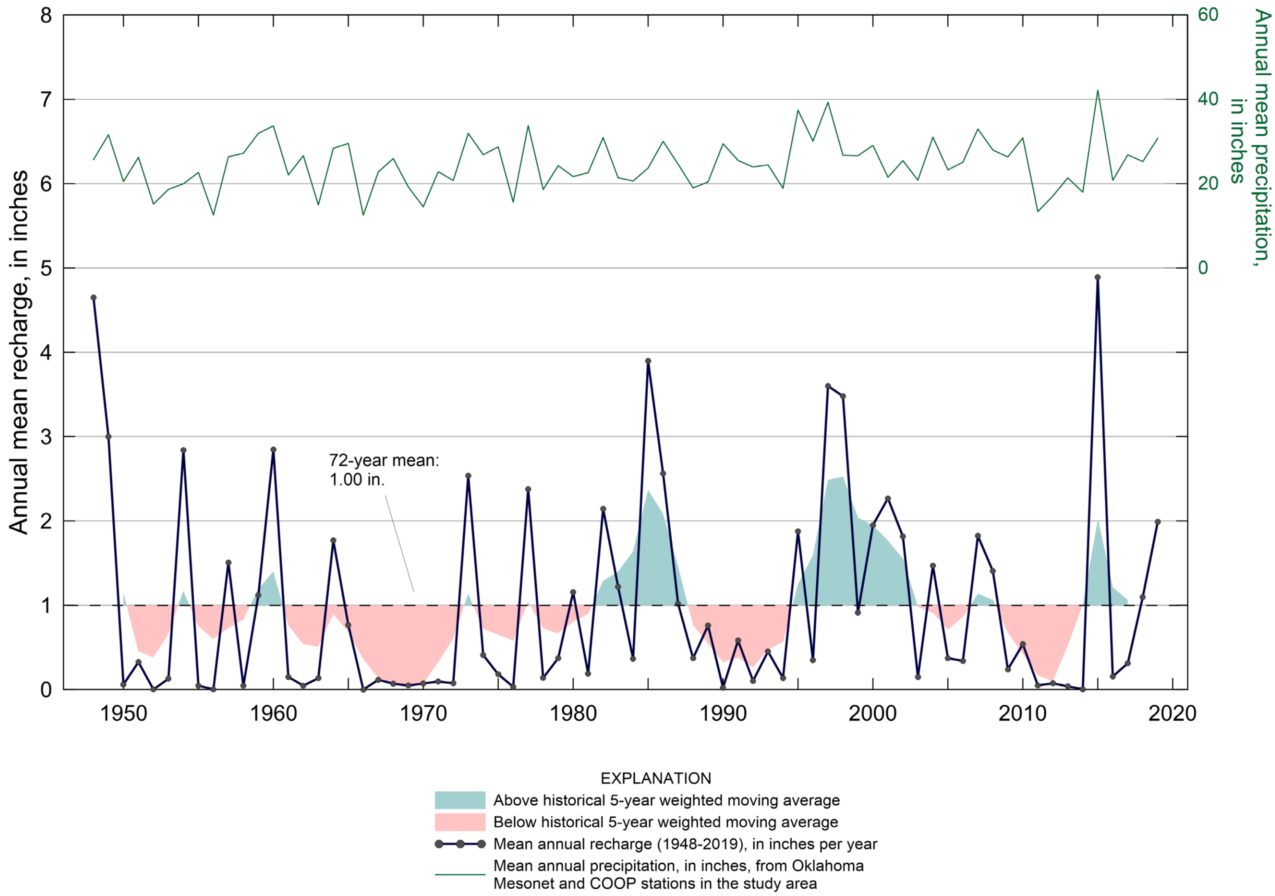


Figure 23. The SWB estimated annual recharge rate, 5-year moving average recharge, and the annual precipitation from Oklahoma Mesonet and COOP stations from 1948-2019.

Table 6. Summary statistics for SWB estimated recharge for 1948-2019, 1948-94, 1995-2008, and 2009-19.

Statistic	Mean annual SWB recharge, in inches			
	1948-2019	1948-1994	1995-2008	2009-2019
Minimum	0	0	0.15	0
Maximum	4.89	4.65	3.60	4.89
Mean	1.00	0.87	1.56	0.85
Median	0.37	0.33	1.64	0.24

Recharge Method Discussion

The SWB-estimated recharge in 2017 was 0.31 inches (1.16% of precipitation), which is substantially lower than the WTF-estimated recharge of 10.1 inches (37.4% of precipitation) at OWRB 141810. The WTF method is likely over-estimating recharge due to the estimated recharge being near or greater than 100% of precipitation following several precipitation events. The SWB estimate is similar to recharge estimates from previous studies. A groundwater flow model estimated recharge in the Ogallala aquifer to the north of the Canadian River to be from 0.06 inches/year to 0.90 inches/year (Luckey and Becker, 1999). Recharge was also previously estimated to be 0.90 inches/year for the Ogallala aquifer in Roger Mills County based on soil types and high infiltration rates (Belden and Osborn, 2002). Therefore, the SWB-estimated recharge is expected to provide a better estimate for recharge.

Hydraulic Properties

Characteristics of an aquifer that affect groundwater flow and storage are referred to as hydraulic properties. The principle hydraulic properties estimated in this study to describe the Ogallala aquifer in Roger Mills County were hydraulic conductivity (K), transmissivity (T), and storativity. Hydraulic conductivity of the aquifer is defined as the rate of flow through a unit cross-sectional area under a unit hydraulic gradient (Ferris and others, 1962). Units for hydraulic conductivity are expressed in units of feet per day for this report. Transmissivity is the rate that water flows through a unit width of aquifer thickness under a unit hydraulic gradient

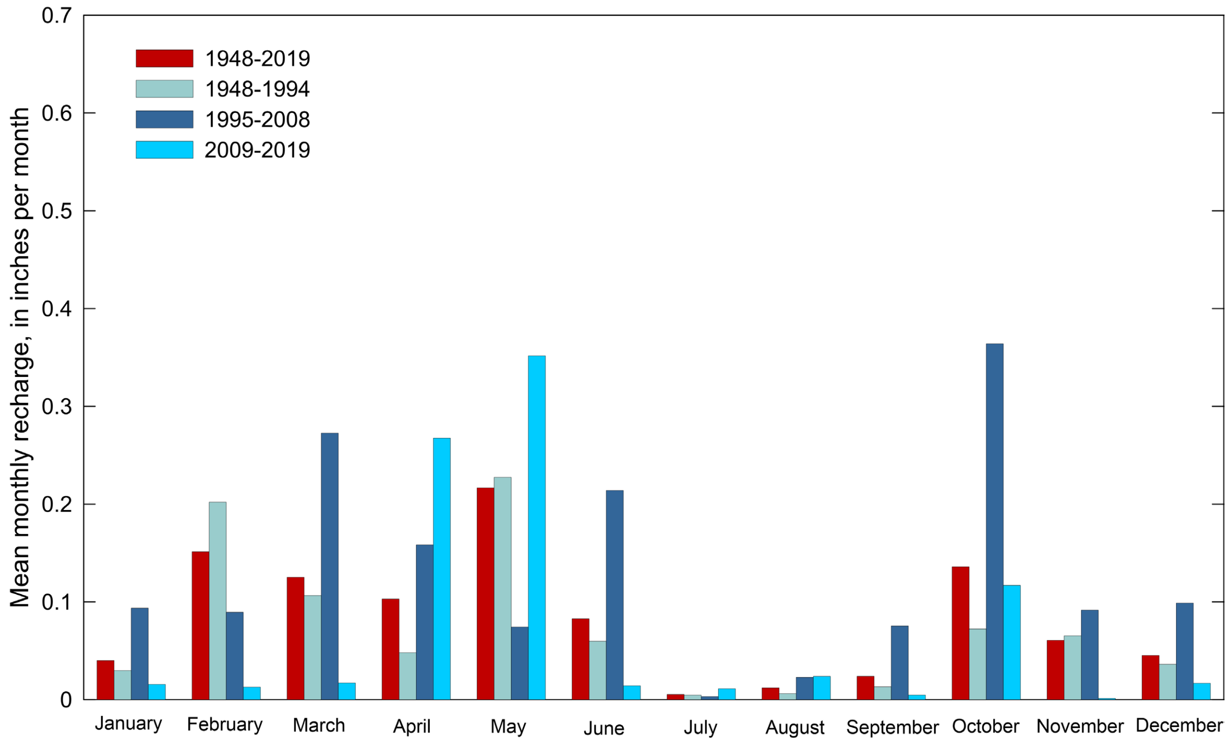


Figure 24. Mean monthly SWB estimated recharge for 1948-2019, 1948-94, 1995-2008, and 2009-19.

in square feet per day (Ferris and others, 1962). Storativity is a dimensionless volume of water released from or taken into storage per unit aquifer surface area per unit change in head (Ferris and others, 1962). Storativity in the Ogallala aquifer in Roger Mills County is released under unconfined conditions as water drains from pore spaces. This is defined as specific yield and is also sometimes referred to as effective porosity.

Hydraulic properties of the aquifer were estimated using several methods (Figure 25). Hydraulic conductivity and transmissivity were estimated using well-drawdown data, slug tests, single well aquifer tests, and percent-coarse analysis. Specific yield was estimated by conducting single well aquifer tests, percent-coarse analysis, and a regional method involving water-level measurements and data from streamflow measurements.

Slug Tests and Well Drawdown Data

Slug tests are a useful method of aquifer testing to determine the hydraulic conductivity of the aquifer near the well and the connectivity of the well to the aquifer. The slug tests were completed by initiating an instantaneous change in water level in the well by introducing a solid PVC cylinder into the well to displace the water and observing the water-level response. Two to four slug tests were completed at each well for a total of 74 slug tests at 21 wells throughout the aquifer (Figure 25). Slug tests were analyzed using the AQTESOLV software package (Duffield, 2007). The Bouwer-Rice unconfined model provided the best match to the data and was used for slug test analysis (Bouwer and Rice, 1976). Hydraulic conductivity estimates ranged from 0.52 feet per day to 207 feet per day with a mean of 21.3 feet per day and a median of 11.2 feet per day (Figure 26). Transmissivity estimates ranged from 14.6 square feet per day to 8,152 square feet per day with a mean of 1,107 square feet per day and a median of 720 square feet per day.

Drawdown tests, also known as specific capacity tests, are performed by well drillers during the time of drilling with the data submitted on well completion reports to the OWRB (Oklahoma Water Resources Board, 2018). These data include pumping rate, pumping duration, well diameter, and drawdown depth to water. Data from 12 wells were utilized in which saturated thickness could be determined and the test had a pumping duration of at least 6 hours to ensure maximum drawdown. Transmissivity at each location was estimated using an equation based on the Cooper and Jacob (1946) solution (Duffield, 2018). The Cooper and Jacob equation is:

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

where

Q is discharge rate the well was pumped in cubic feet per day

Sw is the total length of equilibrated drawdown in feet

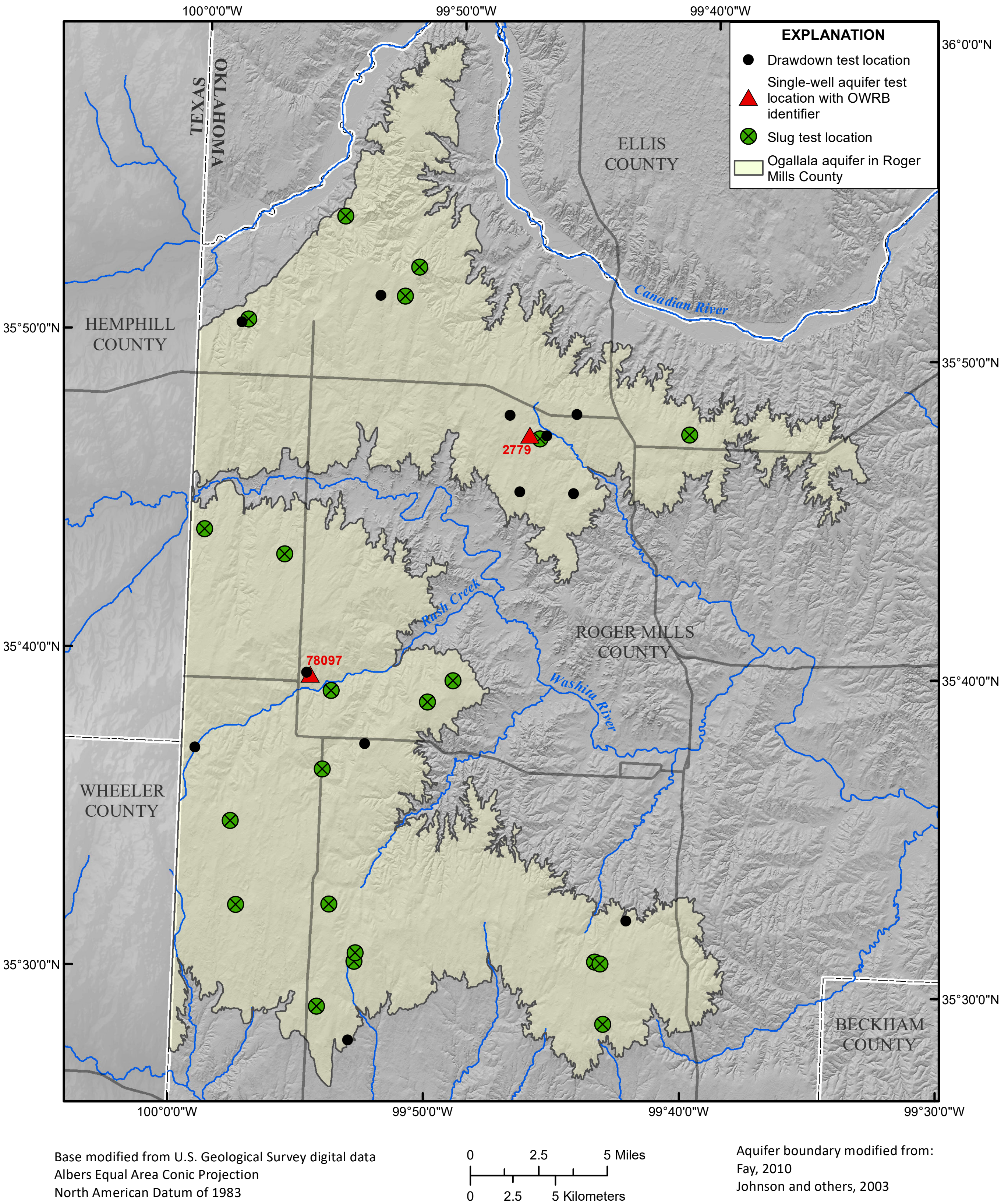


Figure 25. Spatial distribution of single-well aquifer tests, drawdown tests, and slug tests in the Ogallala aquifer in Roger Mills County as part of this study.

T is the transmissivity of the aquifer near the well in square feet per day

t is time in days

S is the storativity of the aquifer (dimensionless)

The Cooper and Jacob (1946) equation can also be written to solve for transmissivity which may be used to determine hydraulic conductiviy:

$$T=Kb$$

where

K is the hydraulic conductivity of the aquifer adjacent to the well in feet per day

b is the saturated thickness of the aquifer in feet

Using a storativity value of 0.21, which was derived from the mean value of the percent sand analysis (see Percent-Coarse analysis section of this report) and single-well aquifer tests (see Single-Well Aquifer Tests section of this report) conducted in this study, the hydraulic conductivity was estimated with a range from 0.93 feet per day to 49.8 feet per day with a mean of 14.2 feet per day and a median of 7.3 feet per day (Figure 26). The estimated transmissivity ranged from 93.2 square feet per day to 3.486 square feet per day with a mean of 1,101 square feet per day and a median of 463 square feet per day.

Differences in the estimated hydraulic properties between the drawdown data and the slug tests are most likely caused by the limited spatial coverage and number of wells used for the drawdown data. The wide range of hydraulic conductivity identified in the slug tests and drawdown data illustrate grain-size variations that exist in the Ogallala aquifer in Roger Mills County ranging from fine-grained clay and silt to coarse-grained sand and gravel.

Single-Well Aquifer Tests

Two constant-rate single-well aquifer tests were completed as part of this investigation to determine transmissivity, hydraulic conductivity, and specific yield. The two public water supply wells are located in Reydon, OK (Roger Mills Rural Water, Sewer & Solid Waste Management #3) and 4 miles west of Roll, OK (Red Star Rural Water District) (Figure 25). Each test was performed by measuring water-level responses with a continuous recorder in the pumped well rather than an observation well. Both well sites lacked observation wells close enough to the production wells to capture the effects of pumping on water levels. Each well was turned off prior to the test to allow the water to return to static levels. The aquifer tests were analyzed using the AQTESOLV software package (Duffield, 2007) and

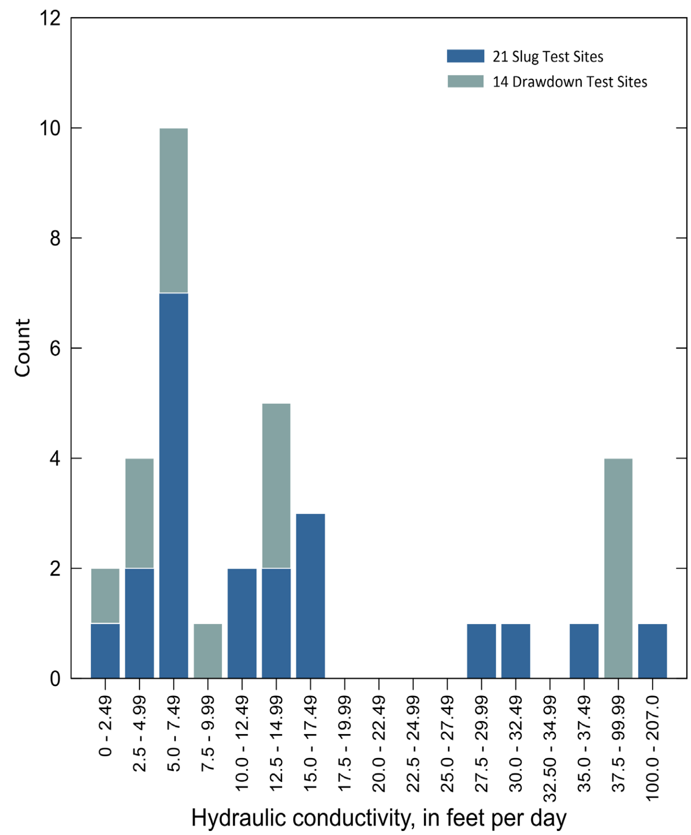


Figure 26. Histogram showing the hydraulic conductivity distribuion of slug tests and drawdown data.

several curve matching solutions were tested for the pumping and recovery periods of each well with the Moench curve matching solution for unconfined aquifers providing the best fit for both pumping tests (Moench, 1997; Table 7).

Roger Mills Rural Water, Sewer & Solid Waste Management #3

The production well (OWRB 78097) was completed to the base of the aquifer at a depth of 94 feet below land surface and sealed to a depth of 20 feet. The eight-inch diameter casing was screened from 54-94 feet below land surface. Pumping began at the well at 11:49 AM on December 13, 2017, and pumped at a rate of approximately 100 gallons per minute for 46 minutes and shut off at 12:35 PM. Water levels were measured at 30-second intervals to document drawdown and recovery from 11:49 AM to 2:27 PM on December 13, 2017. The drawdown period was not analyzed due to possible wellbore storage. During the recovery period, AQTESOLV estimated 700 square feet per day for transmissivity, 0.20 for specific yield, and 13.57 feet per day for hydraulic conductivity (Figure 27).

Red Star Rural Water District

The production well (OWRB 2779) was completed to the base of the aquifer at a depth of 161 feet below land surface

Table 7. AQTESOLV analysis results from single-well aquifer tests.

Site ID	Test Status	Method	Transmissivity, in square feet per day	Specific Yield	Hydraulic Conductivity, in feet per day
78097	Recovery	Moench (1997)	700	0.20	13.57
2779	Pumping	Moench (1997)	633	0.23	8.63
2779	Recovery	Moench (1997)	615	0.25	8.39

and sealed to a depth of 12 feet. The six-inch diameter casing was screened from 143-163 feet below land surface. Pumping began at the well at 10:50 AM on April 4, 2017 and pumped at a rate of approximately 55 gallons per minute for two days and shut off at 11:00 AM on April 6, 2017. Water levels were measured at one-minute intervals to document drawdown and recovery from April 4 through April 10, 2017. During the drawdown period, AQTESOLV estimated 633 square feet per day for transmissivity, 0.23 for specific yield, and 8.63 feet per day for hydraulic conductivity (Figure 28). During the recovery period, AQTESOLV estimated 615 square feet per day for transmissivity, 0.25 for specific yield, and 8.39 feet per day for hydraulic conductivity.

Percent-Coarse Analysis

Percent-coarse analysis was used to determine the theoretical horizontal hydraulic conductivity of the aquifer, which uses lithologic descriptions. This method has given reasonable estimates of hydraulic conductivity and storage for other bedrock and unconsolidated aquifers in Oklahoma (Mashburn and others, 2013; Ellis and others, 2017). Lithologic descriptions were determined from 647 groundwater water well logs submitted to the OWRB by groundwater well drillers with depths ranging from 4-335 feet, a mean depth of 115 feet, and a median depth of 105 feet (Oklahoma Water Resources Board, 2018). To simplify and standardize lithologic descriptions, the descriptions were reclassified into six categories: sandstone, gravel, coarse sand, sand, fine sand, and clay. Hydraulic conductivity and specific yield values were assigned to each lithologic interval based on previously published values (Heath, 1983) for each type of material as well as slug and single-well pump tests performed in the aquifer. The assigned values were then used to calculate hydraulic conductivity and specific yield for each well weighted by the thickness of each lithologic interval. The estimated hydraulic conductivity value ranged from 1.7-42.9 feet per day, with a mean of 12.4 feet per day and median of ten feet per day (Figure 29). Transmissivity values were estimated using saturated thickness values derived from this study. The estimated transmissivity ranged from 5.8-4,326 square feet per day, with a mean of 698.7 square feet per day and a median of 550.6 square feet per day. The estimated specific yield values ranged from 0.05-0.23, with a mean of 0.18 and median of 0.19.

Regional Method to Determine Storage Coefficient

A regional method was used to analyze hydrologic data at a sub basin-wide scale. The method uses streamflow and groundwater-level measurements to estimate the specific yield of the aquifer. It assumes that in the absence of recharge to the aquifer and any significant water use, the specific yield is equal to the ratio of the volume of groundwater discharged to the volume of the aquifer drained (Christenson and others, 2011). A limitation of this method is that it estimates the storage for only the portion of the aquifer that was drained. The equation can be written as follows:

$$Sy = Qb/\Delta DTW$$

where

S_y is the specific yield (dimensionless)

Q_b is the amount of base flow during a set period of time

ΔDTW is the change in the depth to water over a set period of time

Base flow and groundwater levels were measured weekly from December 15, 2017 to April 18, 2018, to estimate storage in the Rush Creek watershed within the aquifer (Figure 30). This method was used during the winter and early spring when vegetation was dormant and groundwater use was minimal. The period also had little precipitation, with 0.80 inches reported at the Cheyenne Mesonet from December 15, 2017 to April 18, 2018. One groundwater well was equipped with a continuous water-level recorder and groundwater levels did not increase indicating no recharge. A 60.4 square mile portion of the Rush Creek basin used for this method and stretches from about 0.7 miles east of the Oklahoma-Texas border to about 3.5 miles northeast of Reydon, Oklahoma. Streamflow was measured weekly under base-flow conditions on Rush Creek at N1760 Rd. to estimate the amount of water that was discharging from the aquifer. Groundwater levels were measured at three wells within the Rush Creek watershed. Discharge from Rush Creek ranged from 2.8-4.8 cubic feet per second with a mean of 4.0 cubic

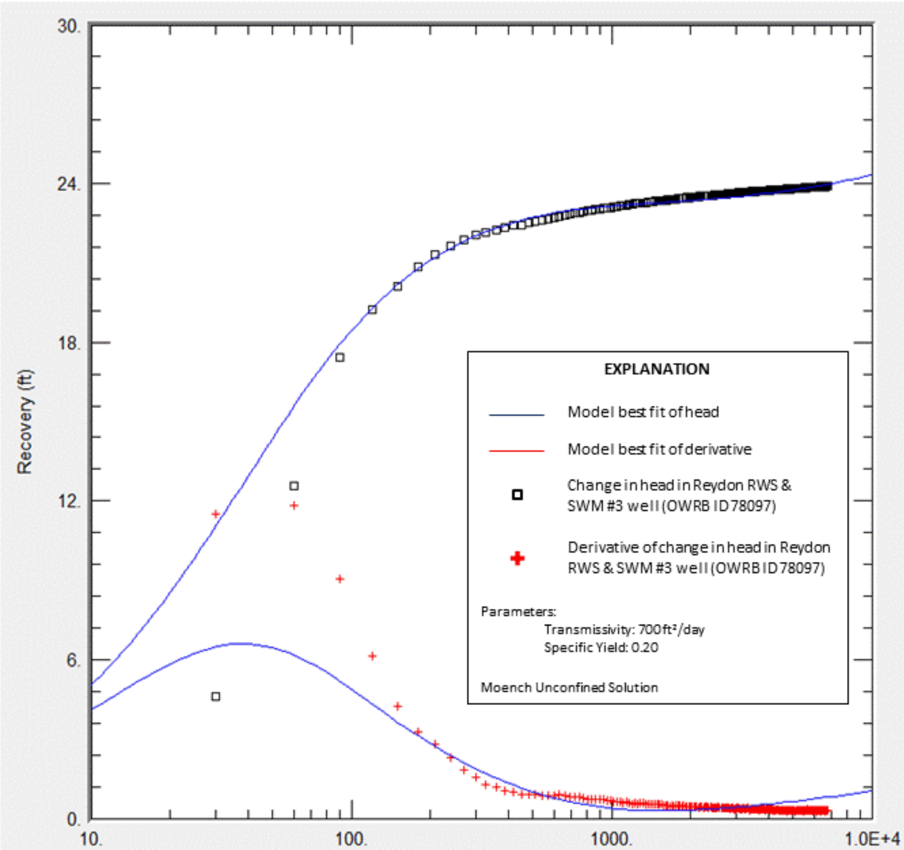


Figure 27. Recovery draw-down curve and derivative with best-fit Moench method for the Roger Mills Rural Water, Sewer & Solid Waste Management #3 single-well aquifer test at site 78097.

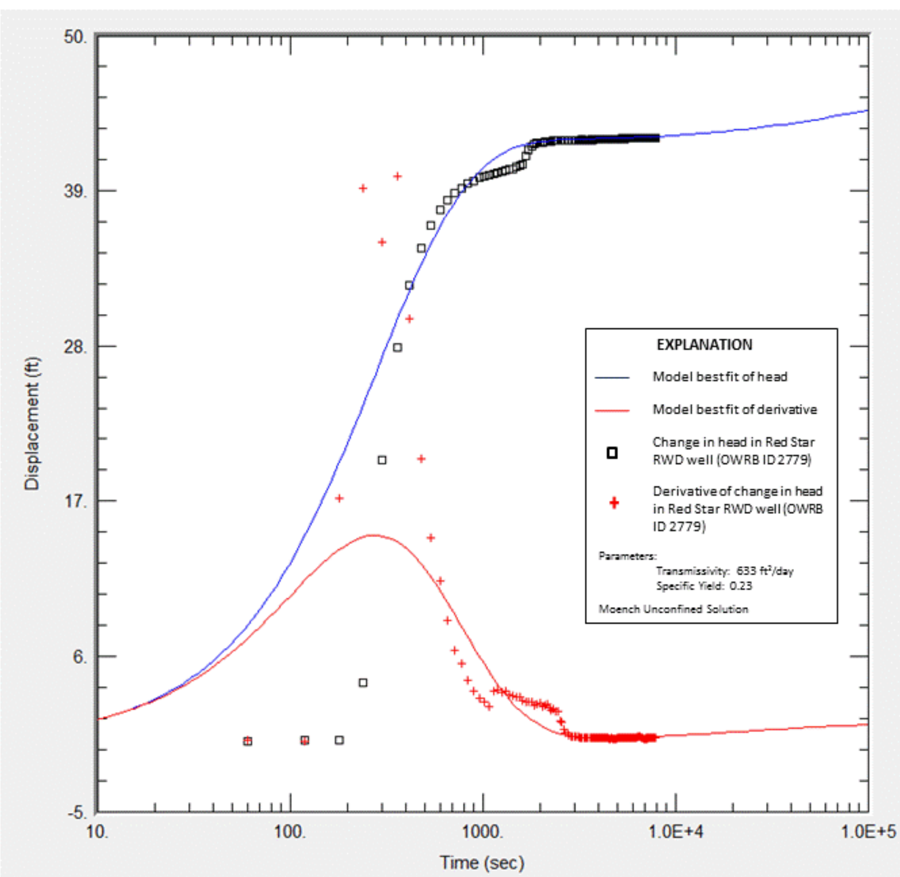


Figure 28. Drawdown curve and derivative with best-fit Moench method for the Red Star Rural Water District single-well aquifer test at site 2779.

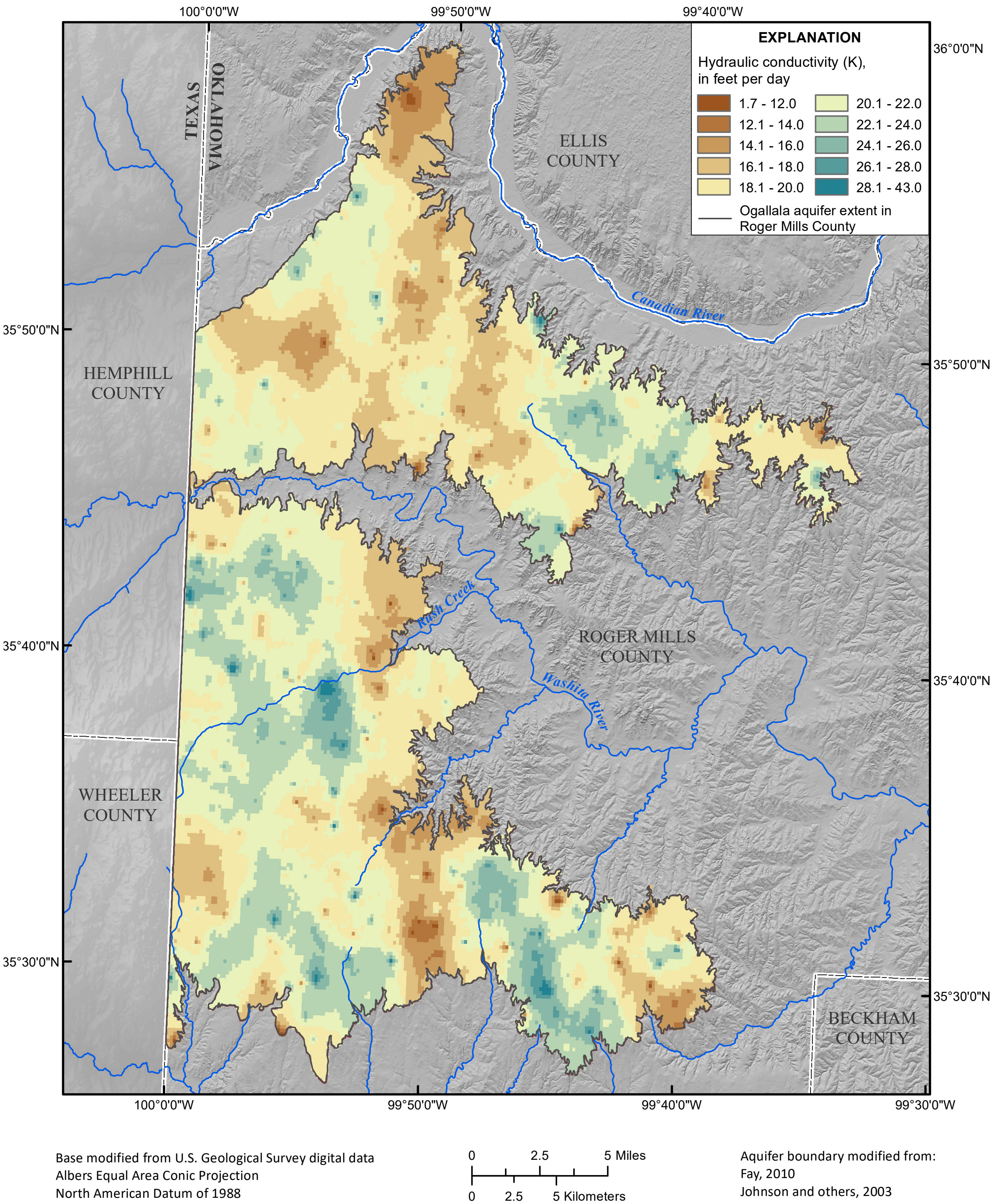


Figure 29. Estimated horizontal hydraulic conductivity using percent-coarse analysis.

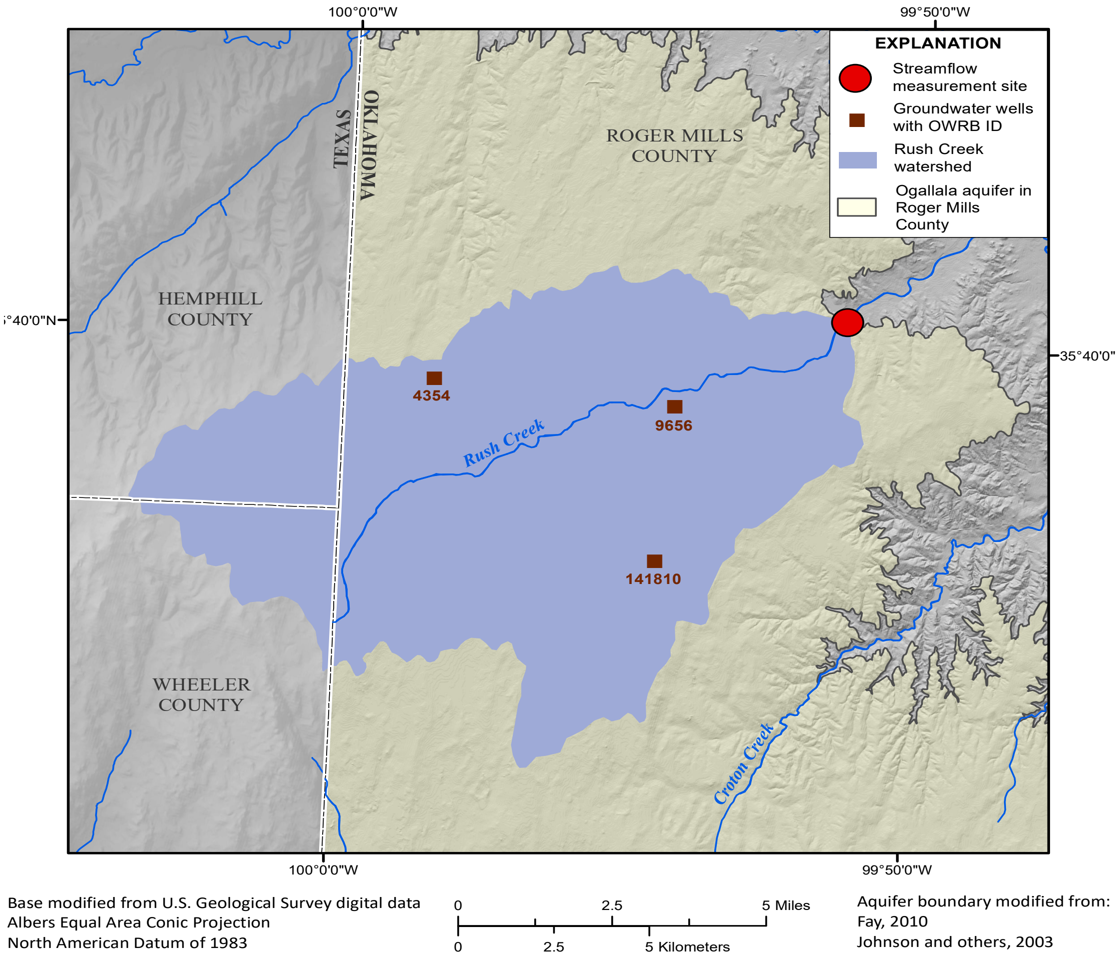


Figure 30. Groundwater wells and streamflow measurement sites in the Rush Creek watershed used for the regional method to determine specific yield.

feet per second and groundwater levels decreased a mean of 0.14 feet over this time period. To estimate the specific yield, the mean decline in water levels was multiplied by the area of the basin and divided by the estimated amount of baseflow discharging from the aquifer during this period. Using this method, specific yield of the aquifer was estimated to be 0.09.

Hydraulic Properties Discussion

Hydraulic properties were estimated using various methods. Table 8 shows the hydraulic conductivity statistics as a part of this study from slug tests, single-well pumping tests, drawdown, and percent-coarse analysis. Mean hydraulic conductivity values ranged from 11.0 feet per day in single-well aquifer tests to 21.3 feet per day in slug tests. These values are within the lower range of hydraulic conductivity estimated in previous studies by Luckey and Becker (1999) and similar to the estimate by Havens and Christenson (1984). Luckey and Becker (1999) used a regional groundwater flow model which estimated hydraulic conductivity to be 10-122 feet per day with a mean of 33 feet per day and a mean specific yield of 0.16 for the Oklahoma High Plains aquifer north of the Canadian River. A regional groundwater flow model by Havens and Christenson (1984) in the eastern portion of the Oklahoma High Plains aquifer estimated hydraulic conductivity to be 19.3 feet per day with a specific yield of 0.15. Gutentag and others (1984) estimated hydraulic conductivities of 25-100 feet per day and specific yields from 0.10-0.30 based on lithology descriptions.

Table 9 summarizes the hydraulic properties of the Ogallala aquifer in Roger Mills County estimated with each method during this investigation. Mean transmissivity values ranged from 649-1,107 square feet per day and mean specific yield ranged from 0.09-0.23. The specific yield values from the single well pumping test and the percent-coarse analysis are similar to values from previous studies. The specific yield estimated with the regional method is slightly lower than previous estimates and could be a result of differences in the extent that each method measures hydraulic properties of the aquifer.

Table 8. Summary statistics for hydraulic conductivity, in feet per day, derived from slug tests, single-well pumping tests, drawdown, and percent-coarse analysis.analysis.

Horizontal Hydraulic Conductivity, feet per day	Slug Tests	Single-well aquifer tests	Drawdown	Percent-Coarse
Minimum	0.5	8.4	0.9	1.7
Maximum	207	13.6	49.8	42.9
Average	21.3	11.0	14.2	12.4
Median	11.2	11.1	7.3	10.0
Count	21	2	12	637

Table 9. Summary of estimated hydraulic properties from different methods used in this study.

Method	Mean Transmissivity, square feet per day	Mean Specific Yield	Mean Hydraulic Conductivity, square feet per day	Median Hydraulic Conductivity, square feet per day
Single Well Aquifer Tests	649	0.23	10.2	8.6
Percent Coarse	699	0.18	12.4	10.0
Slug Tests	1,107	-	21.3	11.2
Drawdown Tests	1,101	-	14.2	7.3
Regional Method	-	0.09	-	-

Groundwater Quality

Groundwater quality in the Ogallala aquifer in Roger Mills County is considered to be very good for drinking with the exception of localized areas of high nitrate and total dissolved solids (TDS) concentrations (Oklahoma Water Resources Board, 2012b). Groundwater samples were collected and analyzed in 2013 in 19 wells completed in the aquifer (Oklahoma Water Resources Board, 2017b). Samples were analyzed for physical properties and for concentrations of major ions, trace metals, and nutrients (Table 10).

Water types in the aquifer are typically calcium carbonate to sodium bicarbonate. A Piper (1944) plot (Figure 31) and Stiff (1951) diagrams (Figure 32) were used to summarize the relative concentrations in milliequivalents per liter of dissolved cation and anion concentrations. The dominant cation is calcium, with concentrations ranging from 53.5-114 milligrams per liter with a mean of 76.6 milligrams per liter. The dominant anion is carbonate/bicarbonate, with concentrations ranging from 173-336 milligrams per liter with a mean of 260 milligrams per liter. Calcium carbonate is derived from the solution of calcium carbonate cement in the Ogallala Formation as well as layers of caliche. Mean sodium concentration was 40.8 milligrams per liter, ranging from 15.2-128 milligrams per liter with a median of 28.7 milligrams per liter. Mean sulfate content was 24.3 milligrams per liter, ranging from 11.8-82.6 milligrams per liter with a median of 16.0 milligrams per liter. The low median sodium and sulfate concentrations compared to the mean indicate that

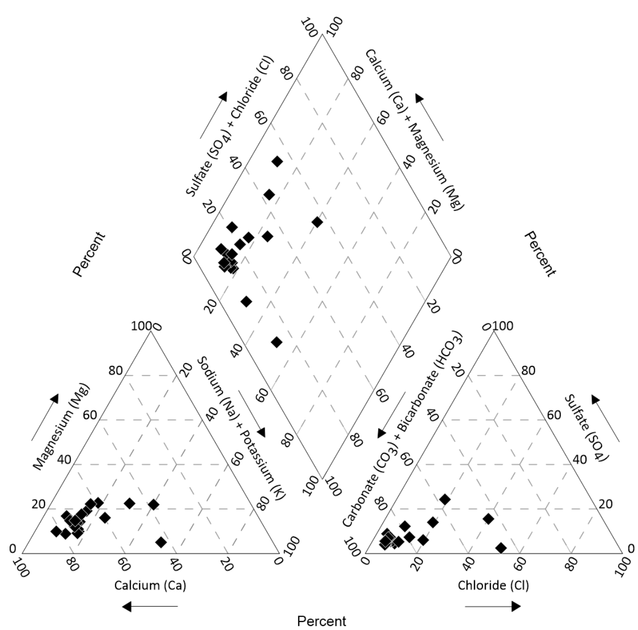


Figure 31. Piper plot from groundwater samples collected in the Ogallala aquifer in Roger Mills County, 2013.

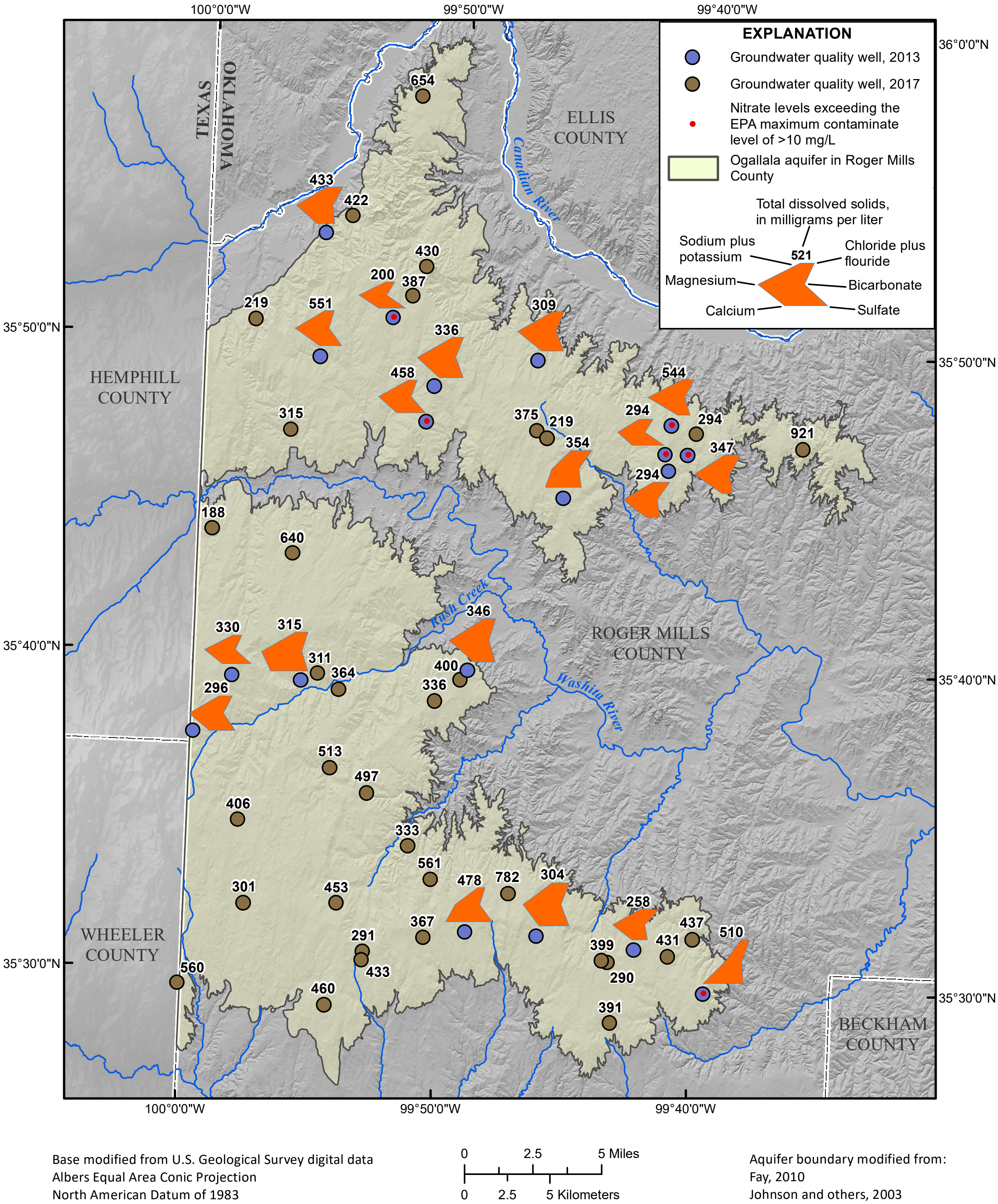


Figure 32. Groundwater quality stations in the Ogallala aquifer in Roger Mills County, 2013 and 2017.

Table 10. Summary statistics of constituent concentrations in groundwater samples collected in the Ogallala aquifer in Roger Mills County, 2013 and 2017.

Constituent	Samples analyzed	Mean Detected	Minimum	Maximum	Samples below detection limit (detection limit)	Percentile of Detected		
						25	50	75
Specific conductance^	54	685.5	314.0	1,535.0	0 (-)	512.9	666.0	820.8
Temperature(°C)^	52	19.0	16.0	28.5	0 (-)	17.3	18.1	20.8
pH	19	7.1	6.8	7.3	0 (-)	7.0	7.1	7.2
Total dissolved solids*^	54	411.3	188.0	921.0	0 (10)	307.8	399.6	492.5
Hardness*	19	228.0	150.0	336.0	0 (-)	193.0	221.0	252.0
Calcium*	19	76.6	53.5	114.0	0 (5)	58.3	72.4	90.3
Magnesium*	19	10.3	5.2	15.9	2 (5)	7.3	9.0	13.9
Sodium*	19	40.8	15.2	128.0	0 (5)	21.8	28.7	37.8
Potassium*	19	1.8	0.8	2.6	0 (0.5)	1.5	1.7	2.1
Bicarbonate*	18	260.4	173.0	336.0	0 (12)	238.3	259.0	287.8
Sulfate*	19	24.3	11.8	82.6	4 (10)	13.4	16.0	25.9
Chloride*	19	41.4	13.8	134	9 (10)	17.0	32.8	49.4
Fluoride*	19	0.3	0.2	0.4	8 (0.2)	0.2	0.3	0.3
Bromide**	19	272.8	123.0	1,770.0	0 (100)	194.0	257.0	334.0
Silica*	19	26.3	20.1	31.6	0 (50)	24.9	26.0	27.4
Nitrate as N*	19	9.0	0.9	24.8	0 (0.05)	4.1	6.7	12.5
Phosphorous**	19	0.02	0.01	0.09	12 (0.005)	0.01	0.02	0.02
Aluminum**	19	++	++	++	19 (100)	++	++	++
Arsenic**	19	++	++	++	19 (10)	++	++	++
Barium**	19	389.4	65.8	656.0	0 (10)	277.0	375.0	520.0
Boron**	19	67.6	58.3	83.5	15 (50)	58.6	64.2	79.9
Cadmium**	19	++	++	++	19 (5)	++	++	++
Chromium**	19	++	++	++	19 (5)	++	++	++
Copper**	19	16.1	6.3	44.6	14 (5)	7.7	9.6	27.8
Iron**	19	++	++	++	19 (50)	++	++	++
Lead**	19	++	++	++	19 (10)	++	++	++
Manganese**	19	++	++	++	19 (50)	++	++	++
Molybdenum**	19	++	++	++	19 (10)	++	++	++
Uranium**	19	1.9	1.0	4.0	2 (1)	1.3	1.7	2.4
Vanadium**	19	14.6	10.6	19.5	1 (10)	12.2	14.8	17.2
Zinc**	19	49.7	10.7	77.6	6 (10)	26.5	60.2	67.4

++ analyses were below analytical detection limit or statistics could not be estimated
* presented in milligrams per liter
** presented in micrograms per liter
^ includes analysis of samples from 2013 and 2017
specific conductance is in microseimens per centimeter at 25° C

a majority of the samples had lower sodium and sulfate concentrations and that a small distribution of samples had higher sodium and sulfate content.

Some of the water samples from 2013 exceeded the U.S. Environmental Protection Agency's (EPA) maximum contaminant levels and secondary drinking water standards (US Environmental Protection Agency, 2018). Maximum contaminant levels are established for contaminants which may pose a risk to humans at excessive levels in drinking water (US Environmental Protection Agency, 2018). Secondary standards are guidelines regarding the aesthetic and cosmetic effects of drinking water without posing a health risk (US Environmental Protection Agency, 2018). Six wells located in the northern and eastern part of the aquifer had samples which exceeded the ten milligrams per liter maximum contaminant level for nitrate, which could be the result of runoff from agricultural activity (Figure 32). Ten wells exceeded secondary drinking water guidelines for total dissolved solids with concentrations greater than 500 milligrams per liter (Figure 32). Possible sources for high concentrations of total dissolved solids include upward movement of saline water from lower geologic units and contamination from nearby oil and gas activity. Dissolution of gypsum and halite deposits in the underlying Permian formations are the source for saline water, which can move upward as the result of pumping (Belden and Osborn, 2002).

TDS concentrations were measured utilizing a handheld meter at 35 wells in the aquifer in 2017 as a part of this investigation (Figure 32). In 2017, TDS values ranged from 188-921 milligrams per liter with a mean of 429 milligrams per liter and a median of 406 milligrams per liter. In the 19 samples analyzed in 2013, TDS values ranged from 255-551 with a mean of 379 milligrams per liter and a median of 346 milligrams per liter (Table 10).

Summary

The Ogallala aquifer in Roger Mills County consists of the Neogene-age Ogallala Formation, which is composed primarily of fine- to medium-grained sand with smaller amounts of sandstone, clay, silt, and caliche. The aquifer covers 385 square miles of west-central Oklahoma and is regionally part of the High Plains aquifer system that underlies parts of eight states in central United States. This investigation includes all areas of Roger Mills County where the Ogallala Formation is present. The aquifer boundary was modified from the 2002 OWRB report based on updated OGS geologic maps and field observations. Water from the aquifer is used for public, irrigation, agricultural, commercial, and domestic supply purposes.

Water levels were measured in 79 wells as part of this study in January 2017. The 2017 water levels, in feet below land surface, ranged from 4.9-169.8 feet, with a median of 60.7 feet. Annual water-level measurements collected by the OWRB since 1980 were analyzed for long-term trends, which tend to fluctuate with climate trends.

The base of the aquifer was estimated from groundwater well lithologic descriptions and the base is generally distinguished by a change in color from white or tan Ogallala sediments to red Permian-age sediments. The thickness of the Ogallala Formation ranges from 0-250 feet. Mean saturated thickness of the aquifer, based on 2017 well measurements, was 45 feet with a maximum of 166 feet.

Aquifer hydraulic properties were estimated from slug tests, drawdown analysis, single-well aquifer tests, and a percent-coarse analysis from lithologic logs. Hydraulic conductivities estimated from slug tests ranged from 0.5-207 feet per day, with a mean of 21.3 feet per day and median of 11.2 feet per day. Mean estimated transmissivity from slug tests was 1,106.9 square feet per day. Hydraulic conductivity estimates from drawdown analysis at 12 sites ranged from 0.9-49.8 feet per day, with a mean of 14.2 feet per day and a mean transmissivity estimate of 1,101 square feet per day. Single-well aquifer test data from two sites showed a mean hydraulic conductivity estimate of 10.2 feet per day, a mean transmissivity estimate of 649 square feet per day, and a mean specific yield estimate of 0.23. Lithologic logs from 637 groundwater wells were used for the percent-coarse analysis and estimated a mean hydraulic conductivity of 12.4 feet per day, with a median of 10.0 feet per day. The regional method was used to estimate a specific yield of 0.09 for the Rush Creek subsurface watershed using base flow discharge and groundwater-level measurements.

Mean precipitation in the study area was 24.5 inches per year from 1924-2019 and is the primary source of recharge to the aquifer. Recharge was estimated using code-based water-balance technique called the Soil-Water Balance (SWB) code and the hydrograph-based Water Table Fluctuation (WTF) method. Estimates using the SWB code for the period 1948-2019 ranged from zero inches in 1966 to 5.4 inches in 2015, with a mean annual recharge of 1.0 inches. The WTF method was used at one well with a shallow water table to estimate localized recharge in 2017 and 2018 resulting in a mean estimated recharge of 9.2 inches. Since the WTF method is likely overestimating recharge, the SWB code provides a more accurate estimate for recharge.

Mean annual reported groundwater use from 1967-2018 was 668 acre-feet, with a median of 599 acre-feet. During this period, 62.4 percent of reported groundwater use in the aquifer was used for irrigation, 35.3 percent was for public water supply, and 2.3 percent was for other purposes. Water-use trends generally correspond to changes in precipitation since the majority of groundwater from the aquifer is used for irrigation.

Groundwater quality was analyzed at 19 wells in the aquifer in 2013 and total dissolved solid concentrations were analyzed at 35 wells in 2017. Total dissolved solid concentrations ranged from 188 to 921 milligrams per liter, with a mean of 411 milligrams per liter and a median of 400 milligrams per liter. Ten wells exceeded the EPA secondary drinking water guideline for total dissolved solids with concentrations greater than 500 milligrams per liter. Concentrations of major ions, trace metals, and nutrients were analyzed at 19 locations. Six wells had samples which exceeded the ten milligrams per liter maximum contaminant level for nitrate. Water types in the aquifer are typically calcium carbonate to sodium bicarbonate. The dominant cation of the samples is calcium and the dominant anion is carbonate/bicarbonate.

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