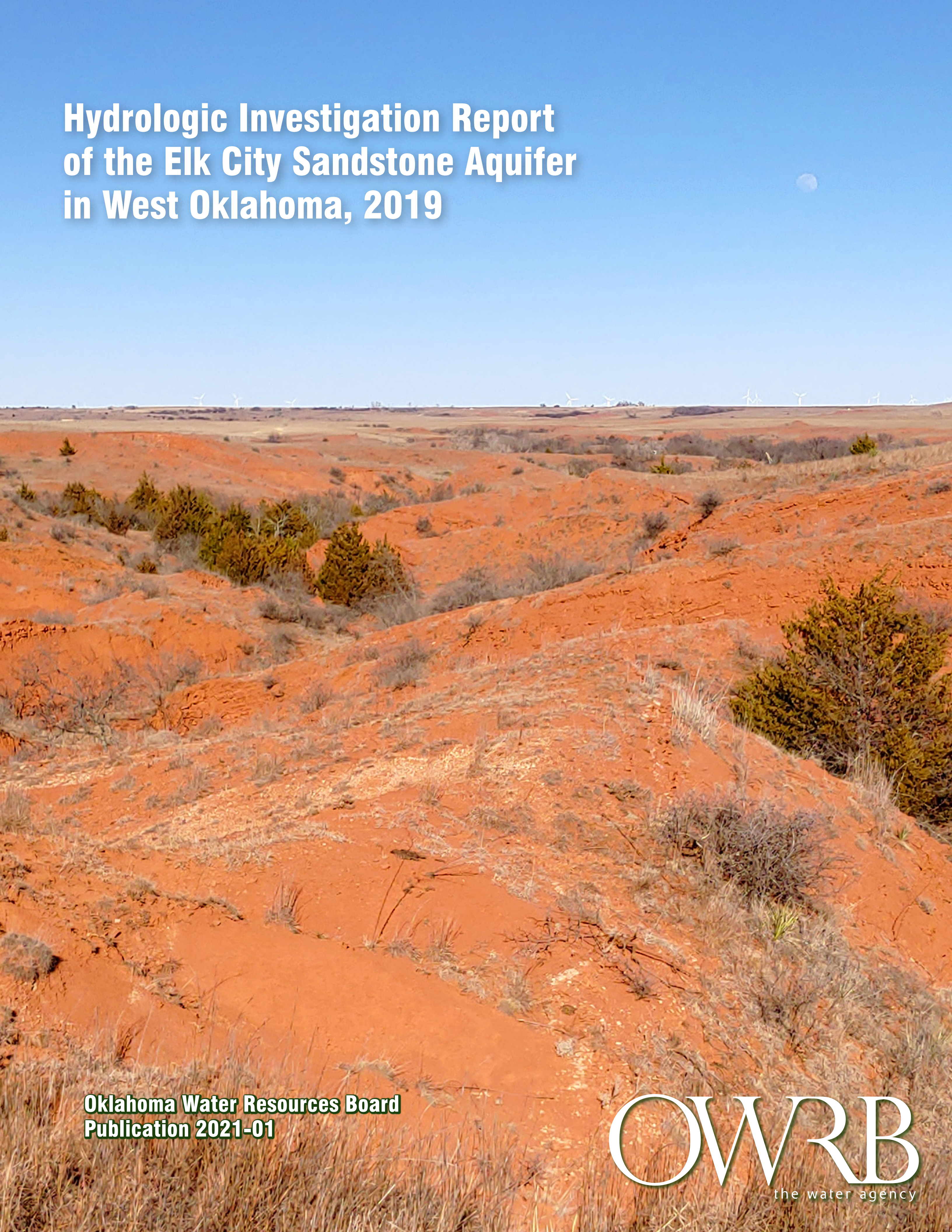
Hydrologic Investigation Report of the Elk City Sandstone Aquifer in West Oklahoma, 2019



Oklahoma Water Resources Board
Publication 2021-01

OWRB
the water agency

Cover. Near Berlin, Oklahoma. Photograph by Derrick Wagner, Oklahoma Water Resources Board, February 24, 2021

Hydrologic Investigation Report of the Elk City Sandstone Aquifer in West Oklahoma, 2019

By Derrick L. Wagner, Jon E. Sanford, Sean P. Hussey, Kyle W. Spears, and Eric G. Fiorentino

Oklahoma Water Resources Board
Publication 2021-01

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

Published December 21, 2021

Acknowledgments

The authors would like to thank landowners, municipalities, and rural water districts that allowed groundwater well access to measure water levels, install water-level recorders, perform slug tests, and conduct a multi-well aquifer pump test. Doug Wallin at Beckham County Rural Water District #3 allowed OWRB staff access to an observation well near one of their pumping wells in order to conduct a multi-well aquifer pump test. Staff from the cities of Canute and Dill City helped take OWRB staff to visit their groundwater wells and staff from the Oklahoma Air & Space Port in Burns Flat have accommodated the OWRB in allowing groundwater monitoring on their fenced property.

This investigation would not have been possible without the hard work of everyone who assisted on it. OWRB Water Quality Streams Monitoring staff Alex Schoppa and Lance Phillips installed and maintained the Buffalo, Little Elk, and Trail Creek streamflow gauging stations. We also extend thanks to OWRB Water Rights Administration Division staff who helped with data collection, maintenance, and technical support including R. Jacob Hernandez, P. Byron Waltman, Alan LePera III, Charles O'Malley, Jessica Correll, and Christopher Neel. Christopher Neel also provided internal technical review, and S. Jerrod Smith at the U.S. Geological Survey Oklahoma Water Science Center provided an external technical review. Darla Whitley, Kylee Wilson, and Tracy Scopel provided internal editorial reviews.

Contents

Figures

Tables

Hydrologic Investigation Report of the Elk City Sandstone Aquifer in West Oklahoma, 2019

By Derrick L. Wagner, Jon E. Sanford, Sean P. Hussey, Kyle W. Spears, and Eric G. Fiorentino

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 findings of the Elk City Sandstone hydrologic investigation and provides information to allow the OWRB to make groundwater management decisions.

The Elk City groundwater basin is a major aquifer in west Oklahoma underlying portions of Beckham, Custer, Roger Mills, and Washita Counties. The boundary of the Elk City groundwater basin was determined by the OWRB for a Maximum Annual Yield (MAY) report in 1982 with an area of 302 square miles and is referred to in this report as the Elk City groundwater basin. The extent of the Elk City groundwater basin was expanded for this investigation to include portions of the Elk City Sandstone that are part of the same groundwater-flow system and is referred to in this report as the Elk City Sandstone aquifer, with an area of 519 square miles. Surficial sands and gravels not part of the Ogallala Formation that overlie portions of the Elk City Sandstone are also included as part of the aquifer. The study area for this report has the same extent as the Elk City Sandstone aquifer.

The Permian-age Elk City Sandstone is the major water-bearing unit in the aquifer, along with some overlying Quaternary sands and gravels. It is composed of reddish-brown, fine-grained sandstone with minor amounts of silt and clay. The unit outcrops throughout the study area, except in the northwest portion where it is overlain by the Ogallala Formation, which is classified by the OWRB as the Ogallala-Roger Mills aquifer. In this area, landowners utilize both aquifers.

Mean precipitation in the Elk City Sandstone aquifer for 1924-2019 was 25.2 inches. The region experienced an extended dry period from 1924-55 when mean precipitation was almost three inches lower than the overall mean, and almost six inches lower than the wettest period, 1986-2018. There was a four-year period of drought from 2010-14, the longest such period in the study area since a seven-year period of below mean precipitation ending in 1955. In 2015, immediately following the 2010-14 drought, one of the wettest years on record occurred and precipitation continued to trend near or above mean values through 2018. Water-level data from the 2010-14 drought inversely relate to precipitation, with steady declines followed by recovery beginning after 2015.

Ten continuous recorders were installed in wells throughout the aquifer during the investigation and most of the wells showed seasonal water-level changes related to precipitation, with generally higher seasonal water-levels in the spring and early summer. The seasonal declines in water levels were typically observed in the late summer. The largest increases in water levels occurred in 2015 in response to high amounts of precipitation in the late spring and summer, especially in May, the wettest month during the period of record from 1924-2019.

OWRB staff measured water levels in 155 wells in February 2016, which were used to create a water table surface map that shows groundwater flowing predominantly from the northwest to the southeast. The contours of the water table surface map bow in a "V" upstream in areas of gaining streams, which were measured in a surface water synoptic measurement of the aquifer that measured 21 streams and determined that seven were gaining streams where the aquifer discharges as base flow to the streams. Using the water table surface map and the base of the aquifer map created using well logs submitted to the OWRB by licensed water well drillers, the saturated thickness of the Elk City Sandstone aquifer was estimated to range from zero feet along the aquifer boundary to 199 feet in the central portion of the aquifer west of Elk City, Oklahoma. The mean saturated thickness was 56 feet. The axis of the Anadarko Basin crosses the Elk City Sandstone aquifer and was observed in the structure of the base of the aquifer, which is highest in elevation in the northwest portion of the study area and regionally dips to the east/southeast.

Reported annual groundwater use data from 184 groundwater permits in the Elk City Sandstone aquifer were analyzed from 1967-2018 with a mean annual water use of 2,314 acre-feet. The largest water use type was public water supply at 48.13% followed by irrigation at 41.5%. The highest groundwater use reported for a single year was

5,031 acre-feet, in 1971, during a period of below mean precipitation for the area. The lowest groundwater use reported for a single year was 900 acre-feet in 1981, in a year with above mean precipitation.

Hydraulic properties for the Elk City Sandstone aquifer were estimated using multiple methods. Hydraulic conductivity of the aquifer was estimated using slug tests at 38 sites, 46 single-well drawdown tests of six hours or more, and a percent coarse analysis of 1,639 driller well logs. Mean values of horizontal hydraulic conductivity were 2.6 feet per day for the slug tests, 2.7 feet per day for the single-well drawdown tests, and 2.8 feet per day for the percent coarse analysis with values ranging from 0.2-9.8 feet per day for the slug tests, 0.4-15.3 feet per day for the single-well drawdown tests, and <0.01-98.9 feet per day for the percent coarse analysis. Specific yield was estimated using a regional method, percent coarse analysis, and a multi-well pumping test. The regional method consisted of monitoring spatially distributed water-level changes each month to estimate the change in aquifer volume in three subsurface watersheds: Buffalo Creek; Little Elk Creek; and Trail Creek, along with regular streamflow gauge data that measured the volume of water draining from the aquifer under base flow conditions. The volume of the aquifer drained could be compared to the volume of base flow to estimate specific yield, which was estimated to range between 0.07 and 0.09 in the three basins. The percent coarse analysis resulted in a mean specific yield of 0.08 and the multi-well pumping test also had a value of 0.08.

Analysis of the 43.9 square mile contact between the overlying Ogallala Formation and the Elk City Sandstone in the northwest portion of the aquifer using a water budget from estimated recharge, water levels, water use, and base flows indicated that there is little water flux from the overlying Ogallala Formation into the Elk City Sandstone. The Elk City Sandstone is less permeable and acts as a type of aquitard, with only 4.9 acre feet of water infiltrating per day into the unit over the overlapping areas.

Recharge was estimated using the Soil-Water Balance (SWB) code as well as the Water-Table Fluctuation (WTF) method. Using land use types and precipitation data from 10 Cooperative Observer (COOP) Network and four Mesonet weather stations, recharge from the SWB code was estimated to be 0.64 inches per year for the period of 1948-2018. The WTF method was used at three sites with continuous water-level recorders taking depth to water measurements every hour and recharge was estimated to range from 3.5-10.5 inches per year for the years 2015-2019.

Water quality samples were collected from 15 wells in the aquifer by OWRB staff. The sampled groundwater had a mean TDS of 361 milligrams per liter, ranging between 254-478 milligrams per liter, and is considered to be good drinking water. The groundwater was plotted on a Piper and Stiff diagrams and all were found to be bicarbonate type. None of the 15 samples contained nitrate or arsenic with concentrations above EPA maximum contaminant levels, but groundwater samples collected by the Oklahoma Department of Environmental Quality from Canute, Dill City, and the New Cordell Utility Authority indicated that water collected in some wells tested above the EPA maximum contaminant level of 10 milligrams per liter.

Introduction

The Elk City groundwater basin of west Oklahoma is located in Beckham, Custer, Roger Mills, and Washita counties and includes the communities of Burns Flat, Canute, Dill City, and Elk City, among others (**Figure 1**). The 302 square-mile extent was set by the OWRB in 1982 upon completion of a hydrologic investigation (Kent and others, 1982). The aquifer extent for this hydrologic investigation (2021) was expanded, primarily to the west and northwest of the original extent based on recent geologic maps published by the Oklahoma Geological Survey (OGS) that indicate the Elk City Sandstone outcrops almost to Sweetwater, Oklahoma (Johnson and others, 2003; Fay, 2010). These areas are hydrologically connected to the previously mapped areas identified as Elk City Sandstone where well yields have exceeded 50 gallons per minute, which by definition allows the classification of "major groundwater basin" by the OWRB (Oklahoma Statutes Title 82 Section 1020.1, 2011). Portions of the Elk City Sandstone that underlie the Ogallala Formation in Roger Mills County were also included in areas where wells are completed in and drawing from the Elk City Sandstone. This report will refer to the expanded area used in this study as the Elk City Sandstone aquifer and the boundary set in 1982 as the Elk City groundwater basin. The area of the updated (2021) aquifer extent used in this report is 519 square miles, a 72 percent increase. Groundwater in the Elk City Sandstone aquifer is predominantly used for public water supply and irrigation purposes, with other uses including commercial, mining, recreation, fish and wildlife, and agricultural (non-irrigation). Public water suppliers that use groundwater from the aquifer include the towns of Burns Flat, Canute, Clinton, Cordell, and Dill City, and Beckham County Rural Water District (RWD) #3. Most of the largest irrigators are located atop the eastern portion of the aquifer east of Elk City in Beckham and Custer counties.

The Elk City Sandstone aquifer area (Figure 1) includes parts of the Western Red-Bed Plains, High Plains, and Western Sand-Dune Belts geomorphic provinces (Curtis and others, 2008). The area is characterized as having areas of gently rolling hills of flat-lying red sandstones and shales with areas of hummocky fields of grass-covered sand dunes. The northwestern portion of the area is described as having relatively featureless flat uplands with dissected streams (Curtis and others, 2008).

Groundwater is discharged as base flow from the Elk City Sandstone aquifer into streams that flow either northward to the Washita River, or southward to the North Fork Red

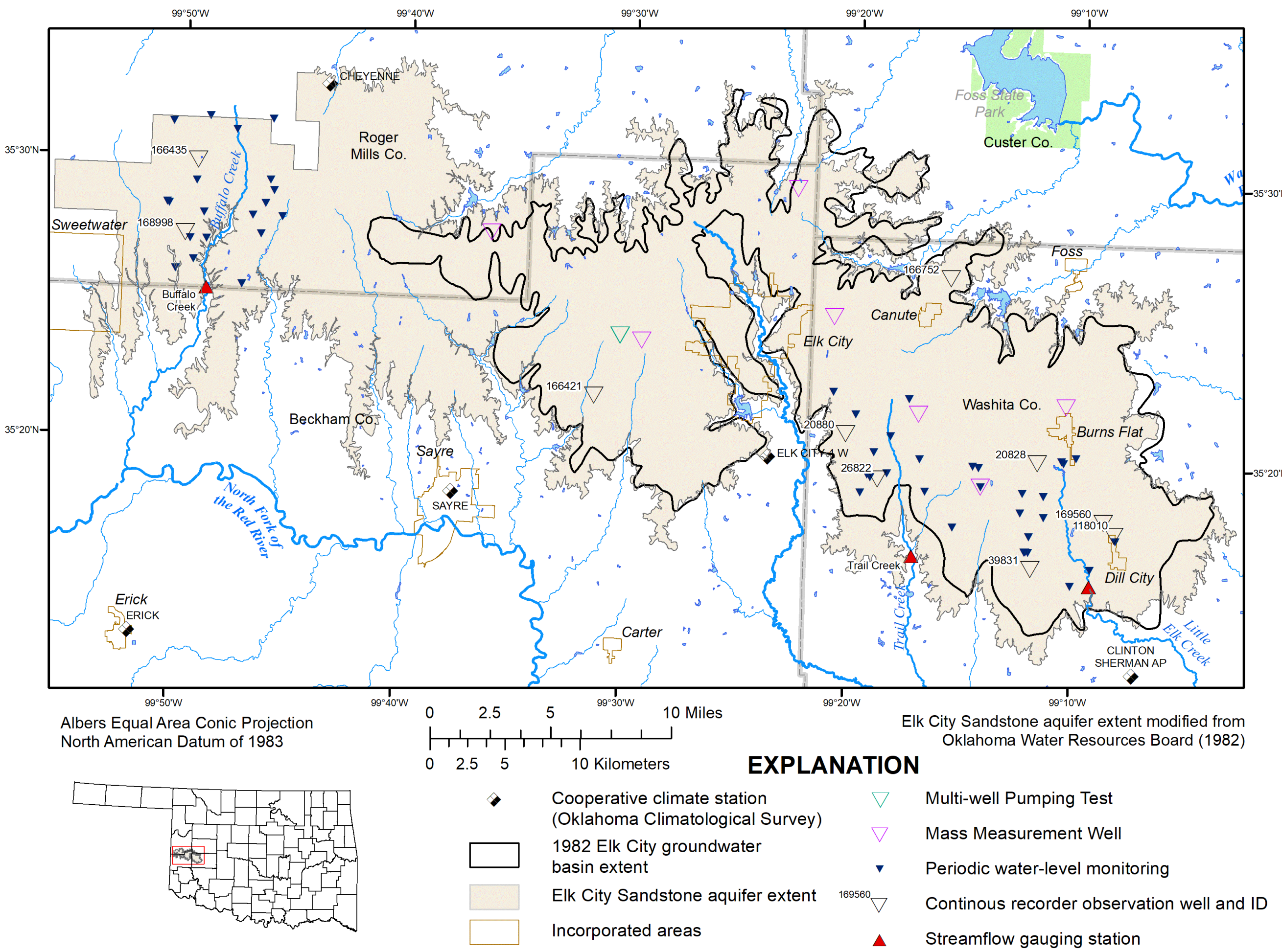


Figure 1. Elk City Sandstone aquifer location, cities, counties, streamflow gauging stations, continuous-recorder wells, periodic water-level wells, slug and drawdown test locations, and climate stations.

River. Streams emanating from the aquifer include Elk Creek, Little Elk Creek, Trail Creek, Long Creek, and Buffalo Creek discharging to the North Fork of the Red River; and Turkey Creek, Oak Creek, and Sandstone Creek discharging to the Washita River. Those streams are mostly increasing in flow as they flow over the aquifer, with some sections of decreasing flow in a few streams.

Land cover over the aquifer is mostly grass/pasture and crops, which account for 40.9 and 29.6 percent of land cover, respectively (Fry and others, 2011; Multi-Resolution Land Characteristics Consortium, 2011; Figure 2). Shrubland is the only other major land cover type over the aquifer with 22.3% coverage and 5.8% of the land overlying the aquifer is classified as developed. Grass/pasture is the predominant cover in the western part of the aquifer, and crops are the predominant cover in the eastern part of the aquifer. Winter wheat (57.0 percent) and cotton (17.6 percent) together accounted for nearly 75 percent of crop cover over the aquifer (**Figure 2**). Winter wheat is present throughout cropland areas over the aquifer while cotton is mostly present in cropland areas in the eastern portion.

The 2012 Oklahoma Comprehensive Water Plan (OCWP) (Oklahoma Water Resources Board, 2011) placed the Elk City Sandstone aquifer in the Southwest (Planning Basins 34 and 37) and West Central (Planning basins 19 and 20) watershed planning regions. Planning Basin 37 in the Southwest watershed planning region and Planning Basin 20 in the West Central watershed planning region were identified as having potential bedrock groundwater quantity limitations with localized storage depletions, and a historical and future increase in reliance on aquifers was noted for all basins (Oklahoma Water Resources Board, 2011).

Purpose and Scope

The purpose of this report is to describe a hydrologic investigation of the Elk City Sandstone aquifer that includes

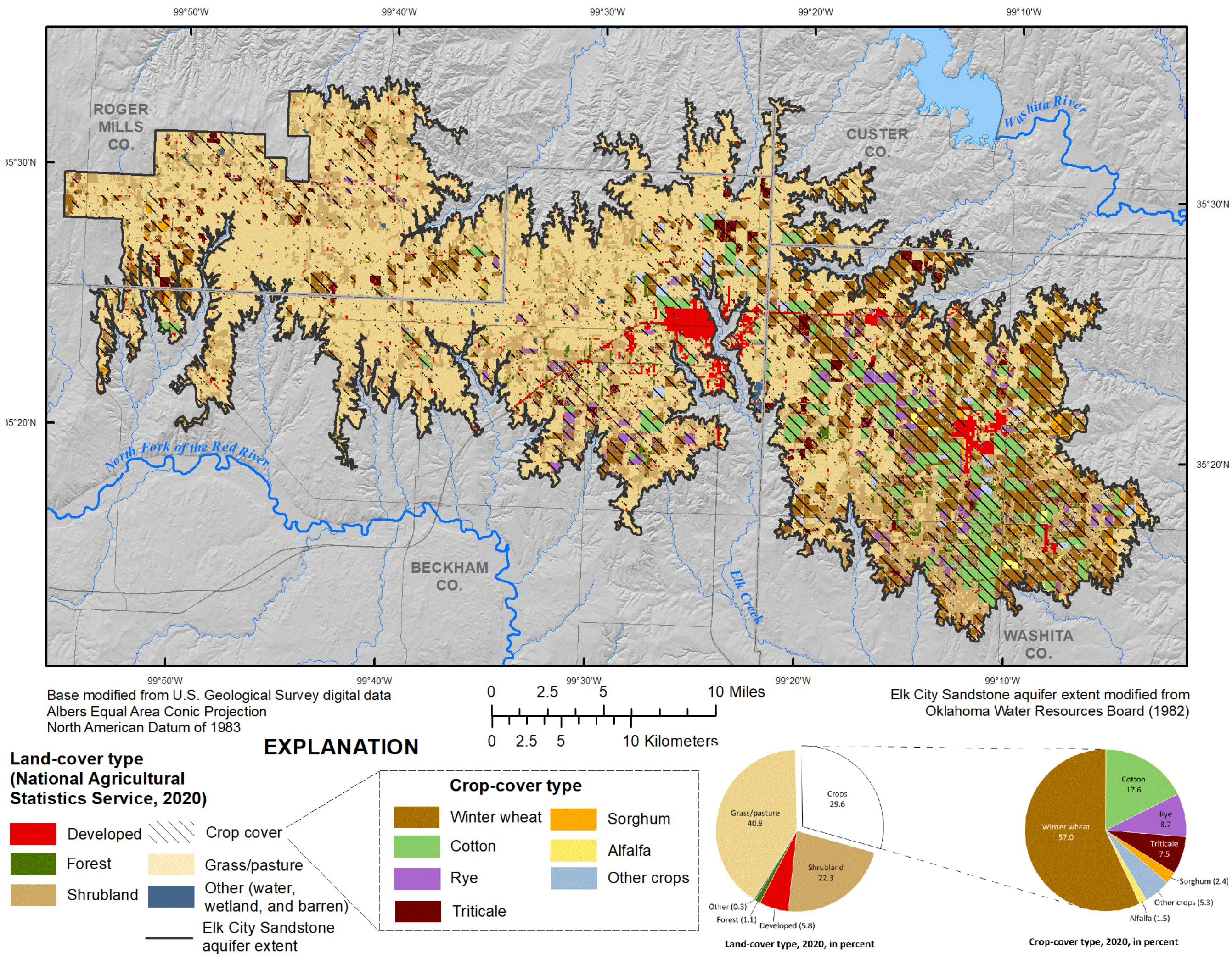


Figure 2. Land and crop cover over the Elk City Sandstone aquifer, west Oklahoma, 2020.

an updated summary of recharge to the aquifer, report of water use in the aquifer, and aquifer hydrogeologic characteristics. The results of this report may be used by the OWRB to reevaluate the MAY for the amount of groundwater in the aquifer. Oklahoma groundwater law requires the OWRB to conduct hydrologic surveys and investigations (herein referred to as hydrologic investigations) of the State's aquifers to determine the MAY and equal proportionate share (EPS) for each aquifer. The MAY is defined as the total amount of fresh groundwater that can be produced from the aquifer allowing for a minimum 20-year life of the basin. Life of the basin is defined as period during which 50 percent of the total overlying land of the basin will retain a saturated thickness of 15 feet for bedrock aquifers. The EPS is defined as the portion of the MAY allocated to each acre of land (Oklahoma Water Resources Board, 2017). The objective of the Elk City Sandstone aquifer hydrologic investigation is to perform a study focused on the hydrogeology of the aquifer that will supply the OWRB information needed to update the existing MAY report on the Elk City hydrologic basin, which was completed in 1982 (Kent and others, 1982) and included a groundwater model. In November 1982, the OWRB issued a final order that set the MAY for the Elk City groundwater basin at 157,440 acre-feet per year and the EPS to 1.0 acre-feet per acre per year. After issuance of a final order determining the MAY of a basin, the OWRB is required by Oklahoma statues to review and update the hydrologic survey at least every 20 years (Oklahoma Water Resources Board, 2017).

Description of Study Area

The geographic scope of the hydrologic investigation is the Permian-age Elk City Sandstone geologic unit and hydrologically connected alluvium and terrace deposits overlying the Elk City Sandstone, as well as characterizing the underlying Permian-age Doxey Shale. These geologic units are located in parts of Beckham, Custer, Roger Mills, and Washita counties. An important part of understanding the groundwater in an aquifer is understanding the geology and boundaries of the basin. In the time since the boundary for the Elk City hydrologic basin was defined (Kent and others, 1982), the Oklahoma Geological Survey (OGS) has updated geologic maps over much of Oklahoma, including the entirety of the study area. These new geologic maps (Johnson and others, 2003; Fay, 2010) indicate the extent of the Elk City Sandstone is larger than previously mapped. For this report, the Elk City Sandstone aquifer includes the area previously defined as the aquifer boundary (Kent and others, 1982), as well as the updated geology, including some additional areas in the northwest portion of the aquifer where well log analysis determined the Elk City Sandstone was being utilized as an aquifer underneath the Ogallala Roger Mills aquifer. The boundary of the Elk City Sandstone aquifer in this report is defined as the mapped geologic contact between the Elk City Sandstone and the underlying Doxey Shale in the Johnson and others (2003) and Fay (2010) maps in most areas. For a detailed description of the boundary, see Appendix A.

Until such time as the OWRB officially updates the boundary to reflect the new mapping, the official Elk City groundwater basin boundary is the boundary defined by Kent and others (1982) and adopted by the OWRB.

Climate

The Elk City Sandstone aquifer lies within the Central Great Plains ecoregion (U.S. Environmental Protection Agency, 2013), which is classified as Cfa, or humid subtropical, in the Köppen-Geiger Climate Classification, but is near the mapped boundary with Bsk, a cold semi-arid climate, and may show similarities to both classifications (Köppen-Geiger, 2018). This area of western Oklahoma lies within the Central Great Plains ecoregion.

Climate data were acquired to analyze long-term precipitation and temperature trends of the study area. Data were queried through the Oklahoma Climatological Survey from the National Weather Service's Cooperative Observer Program (COOP) (Oklahoma Climatological Survey, 2019a), which is a network of volunteers who manage the collection of daily hydrometeorological data at weather stations across the state (National Weather Service, 2014). These data include daily maximum, minimum and mean temperature, as well as 24-hour accumulated precipitation. Seven stations were utilized in this study: Clinton Sherman AP, Cordell, Elk City 4 W, Sayre, Erick, Retrop, and Cheyenne, (**Figure 1**). The period of record varied from station to station but the compiled data spanned 96 years (1924-2019) across the eight stations (**Table 1**). Years with fewer than ten months of recorded data and months with less than 25 days of recorded data were omitted from the analysis. Stations with less than half of period's applicable yearly climate data were also excluded. In addition for trends analysis stations with less than half of the data available to identify a trend were also excluded.

Mean monthly air temperature across the study area is 60.3 degrees Fahrenheit and ranges from 91.0 degrees Fahrenheit in July to 24.4 degrees Fahrenheit in January (Oklahoma Climatological Survey, 2019b). Record highs and lows were both observed at the ERICK cooperative climate station (**Figure 1**) where the highest temperature recorded was 115 degrees Fahrenheit in June 1953 and the lowest temperature recorded was -13 degrees Fahrenheit in January 1942.

Mean annual precipitation of the study area for the period of 1924-2019 was determined to be 25.20 inches (**Figure 3**). This was calculated by querying daily precipitation data from the 7 COOP stations in the study area, omitting years and months that did not meet established standards, adding the values in Microsoft Excel, and dividing the sum by the total valid years provided by each station. Precipitation trends for the 96-year period of record were identified by observing the relationship between each year's total precipitation and the overall mean annual precipitation. The 5-year weighted moving average annual

Table 1. Data collection periods of precipitation at the Cooperative Observer Stations used in the Elk City Sandstone aquifer study.

Station name	Period of record	Number of years	Mean annual precipitation, in inches	1924-1955 mean precipitation, in inches	1956-1985 mean precipitation, in inches	1986-2019 mean precipitation, in inches
Cordell	1937-2008	71	27.64	23.66	27.28	31.22
Erick	1930-2019	87	24.70	22.35	23.91	26.98
Sayre	1937-2018	80	24.14	21.51	23.35	26.35
Elk City 4W	1927-2019	78	25.39	21.12	24.81	30.52
Retrop	1981-2017	35	27.89	* NA (0 records)	*NA (5 records)	28.06
Clinton Sherman AP	1959-1969, 1999-2019	32	23.99	* NA (0 records)	*NA (11 records)	22.02
Cheyenne	1924-1994, 2004-2016	67	23.49	23.49	24.66	*NA (14 records)
Overall	**1924-2019**	**95**	**25.20**	**22.42**	**24.81**	**27.57**

*Stations with fewer than half of the annual precipitation records per period were excluded

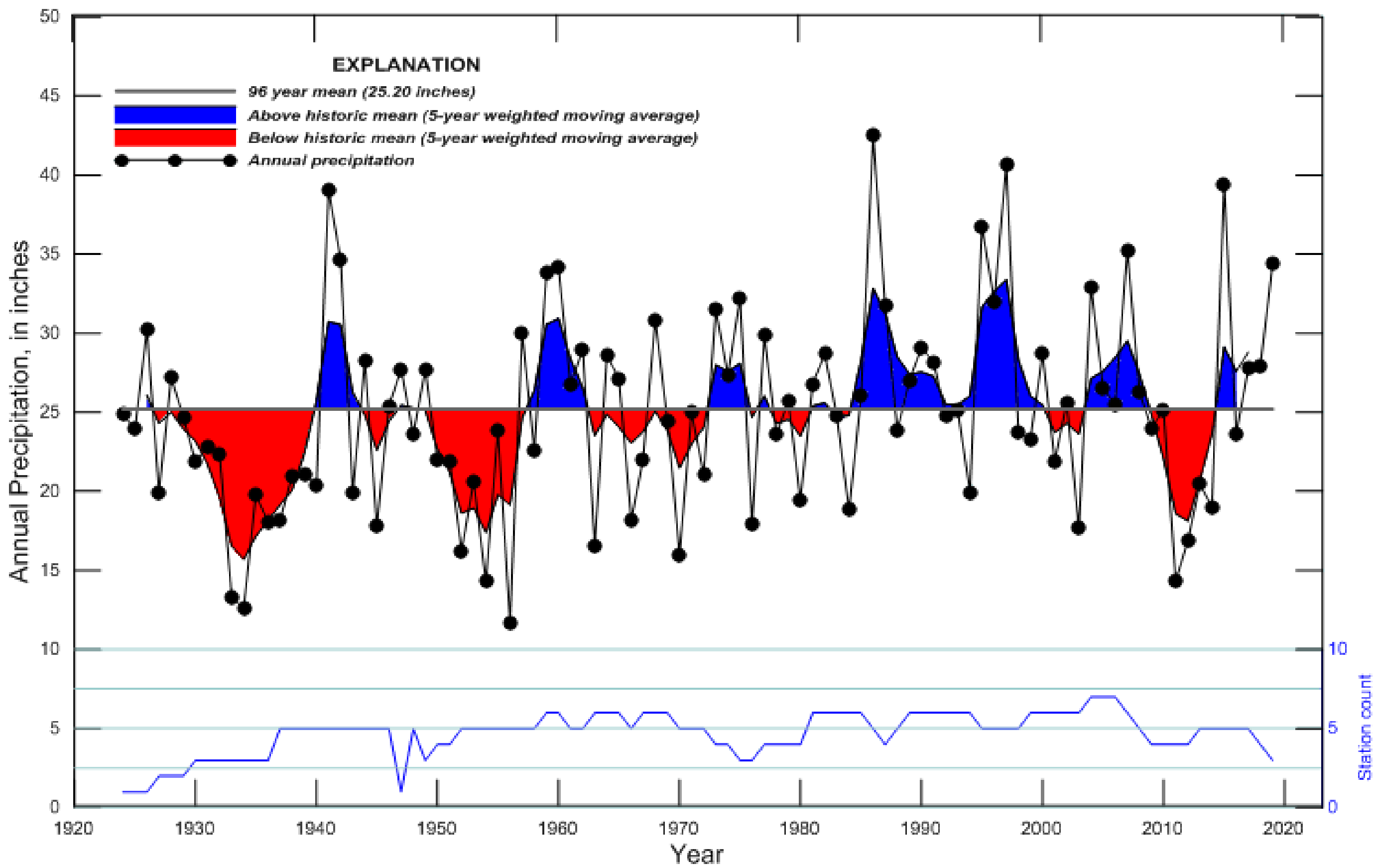


Figure 3. Annual precipitation and 5-year weighted average from 1924-2019 from 13 COOP stations.

precipitation was less than the 96 year mean for most of the interval during 1924-55 with a mean annual of 22.42 inches. The period 1956-85 experienced near mean precipitation with an annual mean of 25.09 inches. An above mean precipitation period occurred during 1986-2019 with an annual average of 27.10 inches.

Precipitation data show that from 1924-55, the mean monthly precipitation was 1.90 inches. Maximum mean monthly precipitation was 4.21 inches in May, and minimum mean monthly precipitation was 0.87 inches in December (**Figure 4**). Mean monthly precipitation data from 1986-2019 was 2.32 inches. Maximum mean monthly precipitation was 4.10 inches in May and minimum mean monthly precipitation was 0.89 inches in January (**Figure 4**). The 1986-2019 timeframe had an increase of 0.42 inches of precipitation per month from 1924-55. Precipitation increased every month but May during the above mean precipitation period of 1986-2019 (Figure 4). The increase in monthly precipitation between the two periods was greatest during August, with a difference of 1.30 inches. Precipitation data from the 7 weather stations indicates that mean precipitation values increased substantially from the 1924-55 to the 1986-2019 period.

The study area experienced drought during 2011-14, when the mean annual precipitation was 17.9 inches per year. Mean monthly precipitation during the same period is 1.49 inches, with a maximum mean precipitation occurring in June with 2.34 inches, and a minimum mean precipitation of 0.47 inches in January.

Geology

The Elk City Sandstone aquifer consists of Permian Elk City Sandstone, as well as minor deposits of Cretaceous, and Quaternary-aged sediments. (**Figure 5**). Stratigraphically below the Elk City Sandstone is the Permian-age Doxey Shale (**Table 2**). In the northwest portion of the aquifer, the Ogallala Formation unconformably overlies the Elk City Sandstone.

Geologic History and Depositional Environments

The Elk City Sandstone aquifer is situated along the axis of the northwest trending, Permian-age Anadarko Basin (Johnson, 1989), a thick accumulation of sediment that developed as the result of subsidence and tectonically controlled faults. During the Cambrian Period, the structural setting along the southwestern boundary of the Anadarko Basin was characterized by features associated with extensional forces causing rifting with linear troughs extending from the

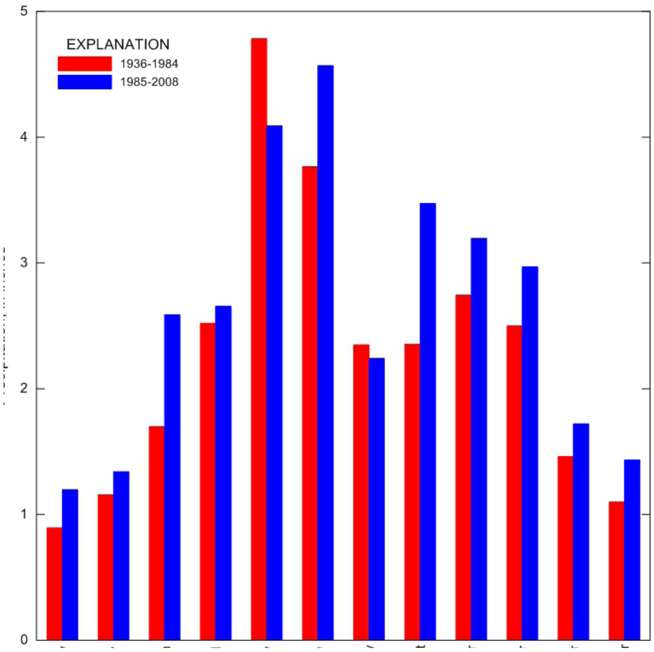


Figure 4. Mean monthly precipitation in the Elk City Sandstone aquifer from 1924-2019, split into four timeframes.

Table 2. Stratigraphic column of geologic and hydrologic units in the Elk City Sandstone aquifer.

Era	Period	Geologic Unit	Description	Thickness, in feet	Hydrogeologic Unit
Cenozoic	Quaternary	Quaternary Units	Undifferentiated stream-laid and wind-blown clay, silt, sand, gravel, and volcanic ash [1,2,3]	10 - 65 [3]	
Cenozoic	Neogene	Ogallala Formation	Late Tertiary-age rocks composed of grey to light-brown, fine- to medium-grained sand, calcite cement, and interbedded with clay, silt, gravel, volcanic ash, and caliche beds [1,4]	0 - 335 [5]	Ogallala - Roger Mills Aquifer
Mesozoic	Cretaceous	Dakota Group/ Kiowa Formation	Grey to brown coarse-grained sandstone/conglomerate and dark-grey shale with thin beds of fossiliferous limestone [1,6]	3 - 20 [6]	Elk City Sandstone Aquifer
Paleozoic	Permian	Elk City Sandstone	Late Permian-age reddish, fine-grained sandstone with minor amounts of silt and clay; sand grains are very friable, sub-rounded, well sorted, display vuggy porosity and are weakly cemented by iron oxide, calcite, clay, and gypsum [2,3,7]	0 - 260 [3,7,8,9]	
Paleozoic	Permian	Doxey Shale	Blocky, reddish-brown, well laminated, silty shales and siltstone, with small-scale ripple marks and cross-bedding, interbedded with thin beds of sandstone [1,3,8,10]	160 - 195 [3,7,8,11]	Confining

[1]Carr and Berggman, 1976
[2]Zabawa, 1976
[3]Kent and others, 1982
[4]Fay, 1962
[5]Sanford and others, 2018
[6]Johnson and others, 2003
[7]Johnson, 1978
[8]Lyons, 1978
[9]Martell and others, 1992
[10]Al-Shaieb, 1976
[11]Ham and others, 1957

inner craton out through the continental margin at high angles (Perry, 1989) (Zabawa, 1976). During the mid-Cambrian Period, this area was dominated by carbonate deposition along with other sediments and igneous material associated with rifting, which resulted in subsidence prior to basin development (Nuccio and others, 2001).

Paleogeographic and paleoclimatic reconstruction (Ziegler, 1990; Breit, 1998) indicates that western Oklahoma was at or near the equator during the Permian Period, when the Elk City Sandstone was deposited. Climatic conditions during the early Permian Period alternated between wet and dry climates. In the late Permian Period, climatic conditions shifted to consistently dry conditions. Much of present-day western Oklahoma and the Texas Panhandle was covered by an equatorial epeiric sea through the early Permian Period. The late Permian-age rocks of the study area were deposited under a combination of fluvial, deltaic, and marginal marine environments (Breit, 1998), which resulted in the deposition of red shale and sand as well as thin dolomite and gypsum beds (Al-Shaieb and others, 1976; Lyons, 1978).

Much of the study area underwent an erosional period during the Triassic and Jurassic periods, caused by the region being situated above sea level (Johnson, 1989). This period of erosion ended in the Tertiary Period when piedmont sediments were transported from the west as a result of the Laramide Orogeny, depositing the Ogallala Formation (Lyons, 1978). About 500 to 1,000 feet of subsequent erosion and redeposition during the Quaternary Period formed alluvial and terrace deposits of western Oklahoma (Johnson, 1989).

Permian-Age Geologic Units

The Permian-age geologic units of western Oklahoma are composed of thick packages of evaporite deposits, red-bed shales, and sandstones. Within the study area, these geologic units are nearly horizontal and erode to form gently rolling hills. The area was influenced by Quaternary-age small-scale faulting and folding, which are expressed in the form of gently-plunging synclines (Zabawa, 1976; Lyons, 1978).

Quartermaster Formation

The Quartermaster Formation was first described as reddish silty shales and friable sandstones (Gould 1902), and includes both the Elk City Sandstone and Doxey Shale. The Quartermaster Formation is the youngest portion of the Permian-age red-bed sequence in Oklahoma, Kansas, and the Texas Panhandle. Some early interpretations of the Quartermaster and Cloud Chief formations classified them as possibly Triassic-age because of a lack of paleontological evidence (Zabawa, 1976). However, the consensus is that the Elk City Sandstone and Doxey Shale are of Permian-age based on the absence of an unconformity below the Cloud Chief

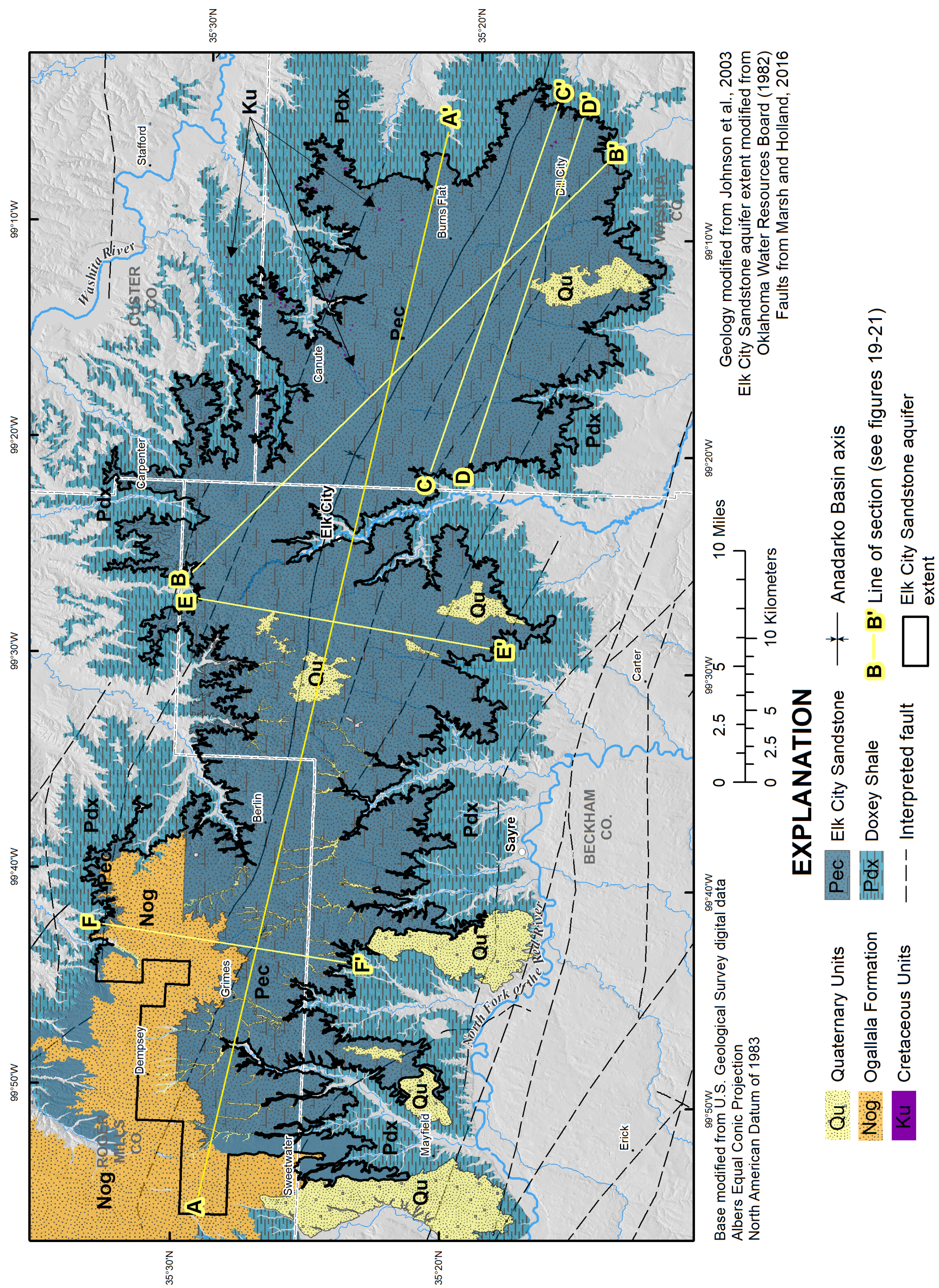


Figure 5. Surficial geologic units in the extent of the Elk City Sandstone aquifer.

Formation that would have indicated the end of the Paleozoic era (Zabawa, 1976). More recently, the Quartermaster Formation terminology has been less favored as the Doxey Shale and Elk City Sandstone are significantly different lithologic units deposited under different systems (Fay and Hart, 1978).

Doxey Shale

The late Permian-age Doxey Shale is stratigraphically above the Cloud Chief Formation and underneath the Elk City Sandstone (Johnson, 1978). The Doxey Shale consists of blocky reddish-brown silty shales and siltstone and serves as a lower confining unit for the Elk City Sandstone aquifer (Lyons, 1978; Carr and Berman, 1976). The formation is interbedded with thin layers of siltstone and sandstone. (Kent and others, 1982). Individual beds of reddish-brown colored shales have a thickness of a foot or less and are well laminated. The Doxey Shale was deposited at a time when the area was dominated by near-shore marine facies as indicated by siltstones containing sharp bases, small-scale cross-bedding, ripple marks, and a lenticular shape in cross-section (Al-Shaieb and others, 1976). The texture of the shale beds has been described as “greasy” and resembling the texture of talc or kaolin (Roth and others, 1941). Within the very well laminated shale beds are dark greenish-brown clay minerals. These layers have been interpreted as being deposited as water-laid volcanic ash; shales of this color do not occur below the Doxey Shale, except in the Marlow Formation where they are associated with Relay Creek Dolomites (Roth and others, 1941). Within the study area, the thickness of the Doxey Shale ranges from 160 to 200 feet thick (Lyons, 1978; Kent and others, 1982; Ham and others, 1957; Johnson, 1978) and may be truncated near the western extent of the Anadarko Basin (Johnson, 1978). In outcrops, the resistant siltstone beds form an undulating topography (Lyons, 1978). The contact between the Doxey Shale and the underlying Cloud Chief Formation is gradational with sediment fining upwards across the contact and selenite veins marking the gradational contact between the units (Green, 1936). This contact can be observed where surface relief is high but difficult to observe in low relief areas where slumping has occurred caused by the dissolution of evaporates in the Cloud Chief Formation (Roth and others, 1941).

Elk City Sandstone

The youngest Permian-age unit within the study area is the Elk City Sandstone, which is the primary water-bearing unit in the Elk City Sandstone aquifer. The geographic extent of the Elk City Sandstone spans a total surface area of 460 square miles (Kent and others, 1982). The depositional environment has been interpreted as being of tidal flat and deltaic in origin (Al-Shaieb and others, 1976) but also an alluvial plain environment as indicated by a lack of bioturbation and bimodal crossbedding (Lyons, 1978).

The Elk City Sandstone is composed of reddish-brown, fine-grained sandstone with minor amounts of silt and clay (Kent and others, 1982). The sandstone grains are very friable, sub-rounded, well sorted, and cemented by gypsum, calcite, clay, and iron oxide, which gives the formation its distinct red color. The friable nature of the formation causes it to be susceptible to erosion with very few outcrops preserved across the study area. The sandstone units show medium-scale crossbedding, ripple and scour marks, and contain interbedded reddish-brown lenses of siltstones and mudstones and interbeds of gypsum and dolomite (Zabawa, 1976; Johnson, 1978). The dominant detrital grains present are quartz, with traces of garnet, mica, rutile, tourmaline, zircon, and magnetite (Lyons, 1978). Sections of the Elk City Sandstone basal unit include coarse sand and cobble-sized clay intraformational clasts, considered to be clay rip-up clasts re-worked from the top of the Doxey Shale (Lyons, 1978). The contact between the Elk City Sandstone and Doxey Shale is easily identified by the juxtaposition of fine laminations of the Doxey Shale with the blockier, friable Elk City Sandstone. In some portions, the Elk City Sandstone has filled in cut channels within the Doxey Shale. The Elk City Sandstone outcrops along the borders of the study area at the Doxey Shale contact, and has a maximum thickness of 260 feet in the interior portion of the unit (Lyons, 1978; Kent and others, 1982; Johnson, 1978; Martell and others, 1992).

Structural and deformation features present throughout the Elk City Sandstone include folds; clastic dikes; dissolution features; fractures; and some small-scale normal, thrust, and reverse faults. The structural environment of the Elk City Sandstone is dominated by a set of northwest-trending subsurface faults that run parallel to the Wichita megashear fault system (Harlton, 1963). A doctoral study in the area mapped 64 faults spanning Roger Mills, Beckham, Washita, and Custer counties and suggested that fault patterns may be a reflection of deformational trends associated with the formation of the Southern Oklahoma Aulacogen (Zabawa, 1976). Fifty-nine of the faults were high angle normal faults with a dip of about 75 degrees, four were reverse faults with dips greater than 35 degrees, and one was a thrust fault with a dip less than 35 degrees. Surface deformation features are likely related to major northwest-trending subsurface faults and not exclusively solution collapse (Zabawa, 1976). There is good evidence for Pleistocene Epoch and older Tertiary Period faulting based on down-dropped blocks of Pliocene-age material and fractures filled with early Pleistocene-age material and there is also some evidence of Cretaceous Period faulting based on fractures filled with possible lower Cretaceous Period material and Permian faulting due to fractures filled with Cloud Chief Formation material (Zabawa, 1976). A majority of the clastic dikes are located within a mile of fault traces and are composed of calcareous sandstone, quartz pebbles, quartzite sandstone, red sandstone, and gypsum (Zabawa, 1976). These structural and depositional features are likely sources of secondary porosity and permeability.

Cretaceous-Age Geologic Deposits

The Cretaceous-age undivided sediment is described as a "chaotic mixture of large blocks of Dakota and Cheyenne Sandstones, interbedded with Kiowa Shale, preserved due to subsurface salt dissolution and collapse into older formations." (Johnson and others, 2003). The Cretaceous-age units only outcrop as exposed cap rock in the eastern portion of the study area. These deposits are very minor in the Elk City Sandstone aquifer and are no more than 20 feet thick. They are considered hydrologically connected to the Elk City Sandstone but were not identified as being water bearing within the aquifer.

Tertiary- and Quaternary-Age Geologic Deposits

Ogallala Formation

The Ogallala Formation composes most of what is known as the High Plains Aquifer, which covers over 174,000 square miles in North America and is one of the largest known freshwater aquifers in the world (Guru and Horne, 2001). A portion of the late-Tertiary-age Ogallala Formation overlies the Elk City Sandstone in the northwest section of the study area and represents piedmont alluvial sediments that were sourced from the Laramide Orogeny (Rocky Mountains) to the west (Lyons, 1978).

The Ogallala Formation consists of grey to light-brown, fine- to medium-grained sand interbedded with clay, silt, gravel, limestone, volcanic ash, and caliche beds locally cemented with calcium carbonate (Carr and Bergman, 1976; Fay, 2010). Well logs submitted to the Oklahoma Water Resources Board indicate a maximum thickness for the Ogallala Formation of 155 feet within the study area, thinning toward the southern boundary.

Quaternary Deposits

Quaternary-age terrace deposits, sand dunes stabilized by vegetation, and alluvium lie unconformably on top of the Elk City Sandstone and Ogallala Formation. The terrace deposits are undifferentiated, reworked, stream-laid material consisting of multicolored clay, silt, sand, gravel, and volcanic ash (Richardson 1970, Carr and Bergman, 1976; Zabawa, 1976; Kent and others, 1982) with a typical thickness of 10 to 15 feet (Kent and others, 1982). In the central portion of the study area, there is a remnant of buried channel deposits trending south-southeast and consisting of coarse alluvium (gravel, sand, and silt) with a maximum thickness of 65 feet (Kent and others, 1982).

Hydrologic Characteristics of the Elk City Sandstone Aquifer

Streamflow

The Elk City Sandstone aquifer underlies a dendritic network of both perennial and intermittent streams that flow into the Washita River to the north of the aquifer and the North Fork Red River to the south. Perennial streams originating in the Elk City Sandstone aquifer include Buffalo, Elk, Little Elk, Trail, and Turkey creeks; intermittent streams include Coffee Bean, Starvation, and Timber creeks. Groundwater discharging from the aquifer maintains base flow to the perennial streams. Unlike in the nearby Rush Springs aquifer, no large rivers flow over the Elk City Sandstone aquifer. The Washita River and North Fork Red River are downgradient from and fed by tributaries with headwaters in the Elk City Sandstone aquifer. A groundwater and surface water divide runs through the Elk City aquifer resulting in some streams discharging groundwater to the Washita River to the north and other streams discharging groundwater to the North Fork Red River to the south.

No streams within the Elk City Sandstone aquifer had recent long-term streamflow gauging stations maintained by either the U.S. Geological Survey (USGS) or the OWRB. To quantify base flows discharging from the aquifer, the OWRB installed three streamflow gauging stations on Buffalo, Little Elk, and Trail creeks near where each stream exits the aquifer (**Figure 1**). The stations measured stream stage at 15-minute increments, and a daily average streamflow was computed once a stream rating curve was determined. A series of 13 streamflow gauging stations were installed in 1952-53 by the USGS on Sandstone Creek, a tributary of the Washita River in the north central portion of the study area as part of the Sandstone Creek Watershed Project (Weems, 1968). These stations were in place for more than 20 years at most sites, but since they were installed along with 42 flood control dams along Sandstone Creek, streamflow data were not considered adequate for analysis. The largest stream with headwaters in the Elk City Sandstone aquifer is Elk Creek; However, only the first four miles of the stream are over the aquifer and a wastewater disposal facility discharges to the stream. Therefore, a streamflow gauging station was not chosen for Elk Creek.

Stream hydrographs of Buffalo, Little Elk, and Trail creeks show regular streamflow that is responsive to precipitation (**Figure 6**). Of the three watersheds where the OWRB installed streamflow gauging stations, Trail Creek is the largest with a surface watershed of 30.3 square miles. Trail Creek also had the largest streamflow values with minimum, median, mean, and maximum streamflows of 1.1, 4.9, 8.4, and 124.6 cubic feet per second, respectively. The Buffalo Creek surface watershed is 29.0 square miles but had the lowest flow of the three streams with minimum, median, mean, and

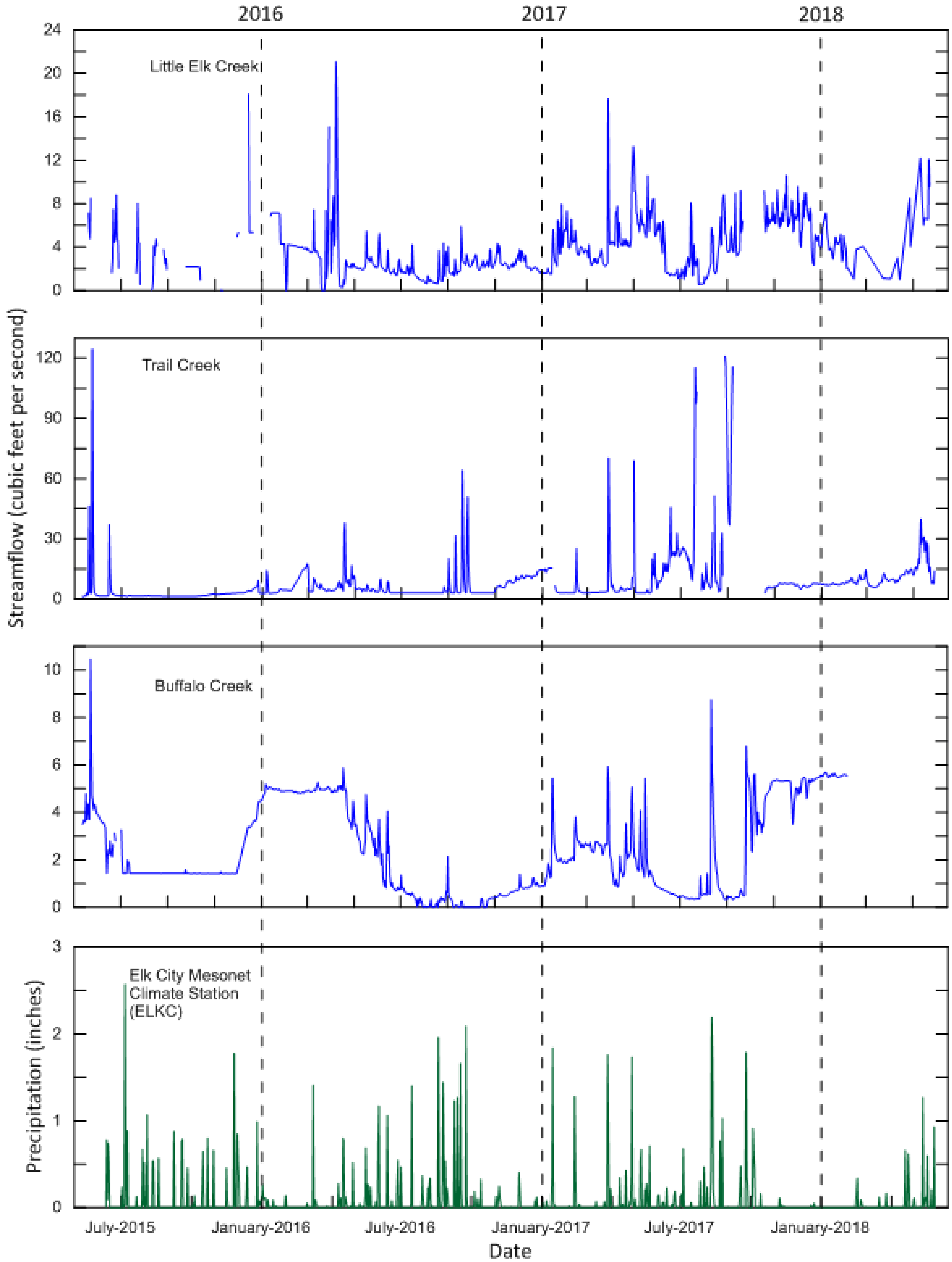


Figure 6. Stream flow measurements recorded by OWRB streamflow gauging stations on Buffalo, Little Elk, and Trail creeks with precipitation totals from the Elk City Mesonet station.

Table 3. Streamflows and base flows at OWRB streamflow gauging stations in the Elk City Sandstone aquifer from 2015-2018.

Station name	Surface watershed area, in square miles	Subsurface watershed area, in square miles	Period of analysis	Mean annual streamflow, in cubic feet per second	Median annual streamflow, in cubic feet per second	Mean annual base flow, in cubic feet per second	Median annual base flow, in cubic feet per second	Baseflow index (%)
Buffalo Creek	29.0	26.2	07/01/2015-01/31/2018	2.4	1.4	2.0	1.4	82
Little Elk Creek	19.7	24.0	06/01/2015-5/10/2018	3.4	2.5	2.6	2.1	76
Trail Creek	30.3	30.5	06/01/2015-04/30/2018	8.4	4.9	4.6	3.4	86

maximum streamflows of 0.0, 1.4, 2.4, and 10.4 cubic feet per second, respectively. The Little Elk Creek watershed is the smallest area of the three watersheds with a streamflow gauging station installed at 19.7 square miles. The minimum, median, mean, and maximum streamflows were 0.0, 2.5, 3.4, and 42.5 cubic feet per second, respectively (**Table 3**).

Base flow

The component of streamflow that is discharged from groundwater is referred to as base flow and is defined for this report as the portion of streamflow that is not runoff. Base flow maintains streamflow in perennial streams within the aquifer. A base-flow separation method (BFI; Wahl and Wahl, 1995) was used to partition the streamflow hydrograph into runoff and base-flow components.

Streamflow data from Buffalo, Little Elk, and Trail creeks were analyzed from mid-2015 when the streamflow gauging stations were installed through early-to-mid 2018 when they were decommissioned. Annual base-flow volumes and mean base-flow index (the ratio of base flow to total streamflow) values were estimated for these sites (Table 3). The mean base flow at the Buffalo Creek streamflow gauging station was 2.0 cubic feet per second (1,449 acre-feet per year) with total annual base-flow volumes of 1,447 acre-feet (2.0 cubic feet per second) in 2016 and 1,241 acre-feet (1.7 cubic feet per second) in 2017. Monthly mean base flow ranged from a low of 0.04 cubic feet per second (2.4 acre-feet per month) in September 2016 to a maximum of 5.5 cubic feet per second (338 acre-feet per month) in January 2018. The mean base-flow index was 82 percent for the period of record at the Buffalo Creek streamflow gauging station. The mean base flow at the Little Elk Creek streamflow gauging station was 2.6 cubic feet per second (1,884 acre-feet per year) between January 2016 and April 2018. The total annual base-flow volumes were 1,458 acre-feet (2.0 cubic feet per second) in 2016 and 2,429 acre-feet (3.4 cubic feet per second) in 2017. Monthly base flow ranged from 0.76 cubic feet per second (46.7 acre-feet per month) in August 2016 to 6.0 cubic feet per second (369 acre-feet per month) in October 2017. The mean base-flow index was 76 percent for the period of record at the Little Elk Creek streamflow gauging station. The Trail Creek streamflow gauging station had full monthly measurements from June 2015 to June 2017 and October 2017 to April 2018 with the station not recording full months in July-September 2017. Over the period of record, the mean annual base flow in Trail Creek was 4.6 cubic feet per second (3,333 acre-feet per year). The total annual base-flow volume in 2016, the only year with a full 12-month record, was 3,122 acre-feet. The mean monthly base flow ranged from 1.3 cubic feet per second (77.4 acre-feet per month) in September 2015 to 12.4 cubic feet per second (738 acre-feet per month) in June 2017. The mean base-flow index was 86 percent for the period of record at the Trail Creek streamflow gauging station. (**Figures 7-9**).

Synoptic Streamflow Measurements

To characterize base flows discharging from the Elk City Sandstone aquifer, synoptic streamflow measurements of 21 streams originating in the aquifer were measured from February 22, 2017, to February 24, 2017 (**Figure 10**). Late February was chosen as the period to measure streamflow because the December-February period is historically the lowest period of precipitation, as mentioned in the Climate section of this report, and any streams flowing at this time should be under base-flow conditions. Prior to the surface-water synoptic measurement, no significant precipitation had been recorded in the study area since February 14, 2017, with 0.49 inches of precipitation recorded at the Elk City 4 W Cooperative Observer Station. As such, all discharge measurements recorded in this synoptic are assumed to be base-flow measurements. Over the 21 streams visited, 69 sites were investigated, and 44 base-flow measurements were collected for the synoptic measurement. Base-flow measurements were collected along each stream from the headwaters to just outside the study area boundary. The procedure for taking measurements involved selecting a site where stream flow was as well distributed across the channel as possible. Velocity measurements were then taken at equal intervals measured by a tag line perpendicular to direction of flow. The USGS midsection method (**Figure 11**) was used to calculate streamflow by dividing the stream into a sufficient number of sub-sections to capture the irregular geometry of the streambed. Typically, natural streams require 20-30 sub-sections to adequately characterize the irregular geometry of stream beds. Average velocity in feet per second was measured at each

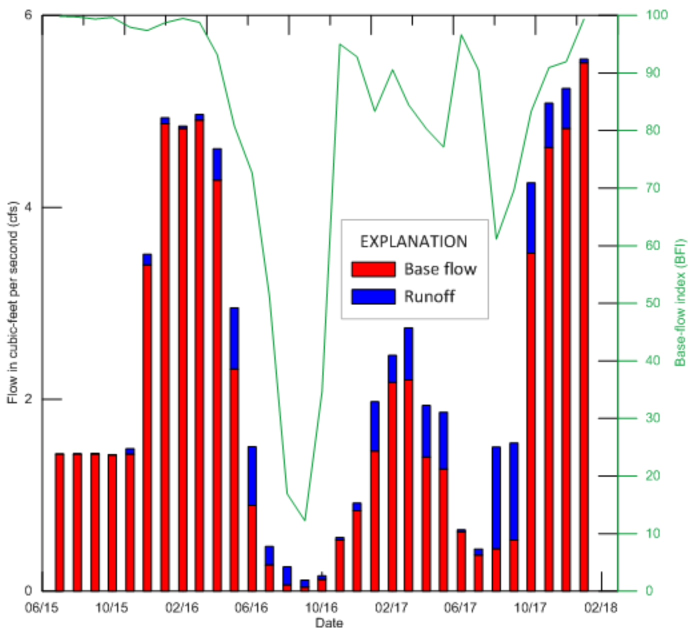


Figure 7. Monthly mean base flow, runoff, and base-flow index for the Buffalo Creek streamflow gauging station, June 2015-January 2018.

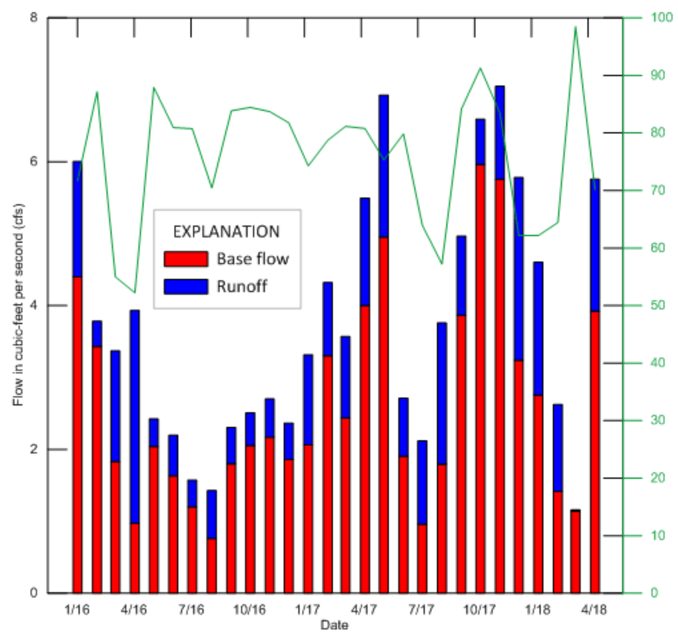


Figure 8. Monthly mean base flow, runoff, and base-flow index for the Little Elk Creek streamflow gauging station, January 2016-April 2018.

sub-section and applied to an area that extended halfway to the preceding and following measurement points. The area of the sub-section was determined by multiplying the width of the sub-section and the measured depth. The total discharge of the stream was calculated by summing the products of sub-section area and velocity measurements recorded across the stream.

Streams that increase in base flow downstream indicate a gaining stream where the water table intersects the streambed surface and groundwater seeps into the stream as base flow; streams that decrease in base flow downstream indicate a losing stream where the water table is below the streambed and surface water seeps into the underlying bedrock. The purpose of the synoptic streamflow measurements was to gain insight into how streams were interacting with the Elk City Sandstone aquifer. Of the 21 streams investigated during the synoptic streamflow measurements, seven had increasing base flow between stations at the time of measurement: Little Elk, Trail, Buffalo, George, Oak, Sergeant Major, and Long creeks (Figure 10). Streams with the most base flow were Trail Creek and Little Elk Creeks which typically had flat slabs of red siltstone forming their streambeds. The flow in these streams was consistently high enough to prevent the settling of finer material. In general, streams with lower flow rates tended to have streambeds consisting of predominantly silt and clay sized material. As seen in the Cross Sections section of this report, Trail and Little Elk creeks were gaining streams where the northern section shows the water table to be nearly equal to the stream beds in elevation and the southern section shows the water table to be above the

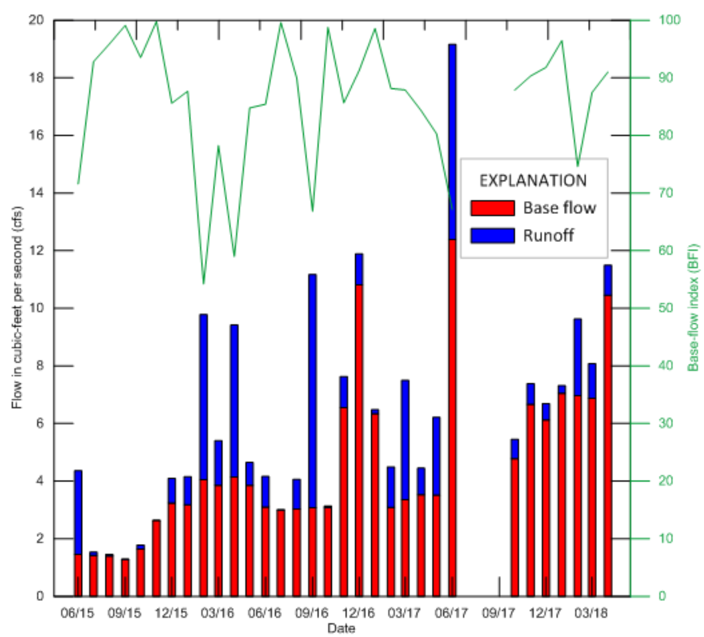


Figure 9. Monthly mean base flow, runoff, and base-flow index for the Trail Creek streamflow gauging station, June 2015-April 2018.

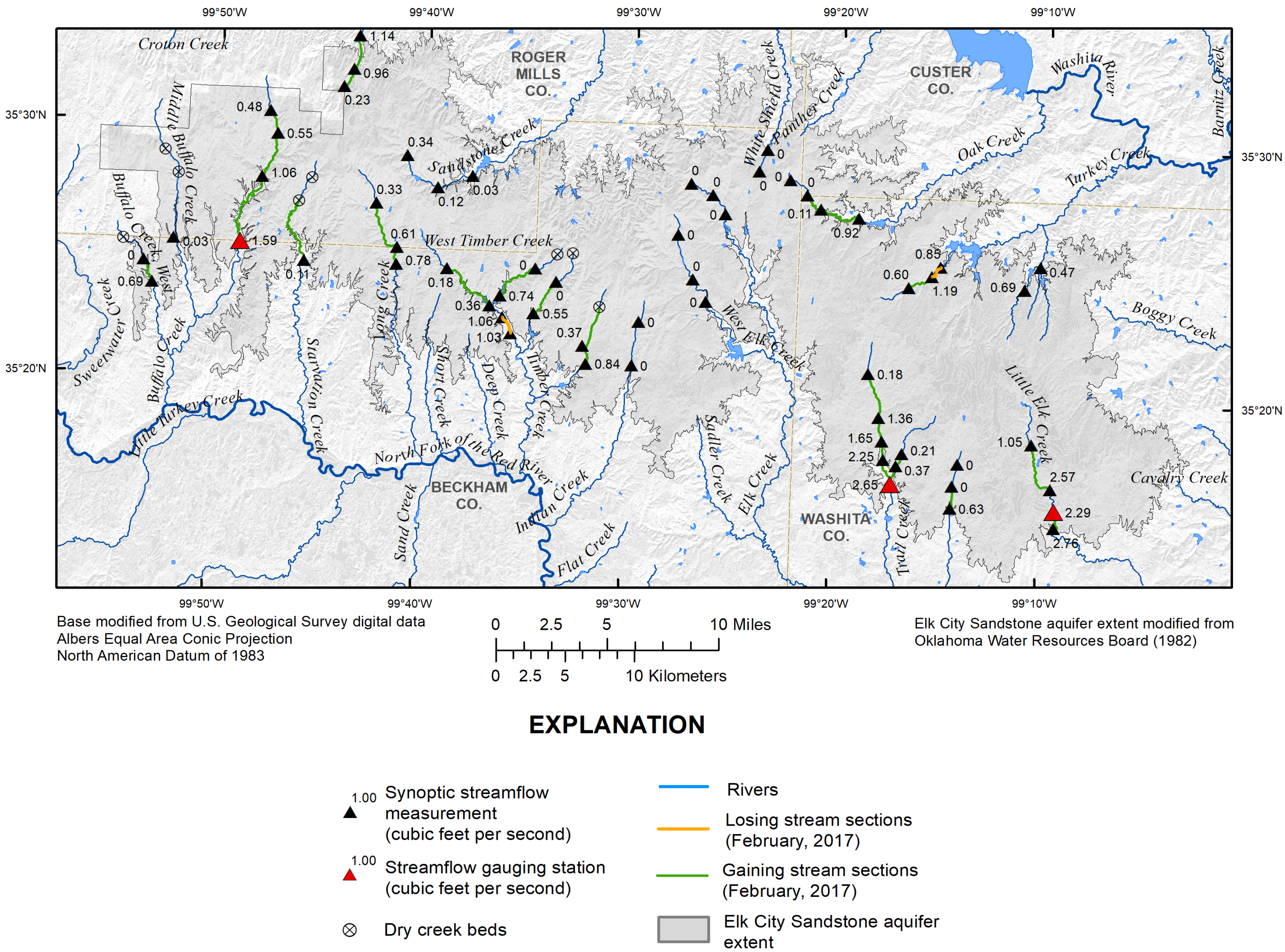


Figure 10. Stream flow measurements collected by OWRB staff in February 2017 as part of a surface-water flow synoptic. Sixty-nine sites were visited over the course of the synoptic and 44 base-flow measurements were recorded.

stream beds in elevation meaning groundwater will discharge to the streams.

Only one stream appeared to be decreasing in flow. Sandstone Creek was flowing at 0.34 cubic feet per second near its headwaters and decreased to 0.12 cubic feet per second near the boundary and was trickling at 0.03 cubic feet per second just past the study area boundary. However, as Sandstone Creek and its tributaries have 42 flood control dams which are part of a stream flood prevention project in the 1940s and early 1950s, it impossible to assess whether the stream is actually losing surface water to the aquifer or if the water is being impounded.

Elk, Indian, West Elk, and White Shield Creeks held standing water, possibly from precipitation that had fallen about a week and half earlier; however, there was no flow at any point over the aquifer in these four streams. Typically, the sections of the investigated streams had significant amounts of vegetation growing in and around the streambeds and did not appear to hold water year round. The remainder of the investigated streams did not have measurable flow until they exited the Elk City Sandstone aquifer. This may be the result of seepage from the contact of the aquifer with the underlying Doxey. These streams, which include Coffee Bean, East Timber, Middle Buffalo, Spring, Starvation, Timber, West Timber, and West Buffalo creeks, are likely intermittent streams that only flow when there has been recent precipitation. Turkey Creek was the only stream that did not have a consistent trend in base flow from the headwaters to the study area boundary; base flow initially increased from 0.60 cubic feet per second to 1.19 cubic feet per second and then decreased to 0.85 cubic feet per second at the aquifer boundary. The section of Turkey Creek with decreasing base flow was observed by staff to have some small dams rerouting flow, which may have caused the reduction in measured base flow. This could be the result of land use practices, construction of dams, rerouting of the stream channel, or nearby groundwater pumping that could override the natural flow conditions of the stream.

Groundwater-level Fluctuations

Historic

Long-term annual groundwater-level measurements have been collected across the state by the OWRB since the 1950s. Observations of historical groundwater levels can be useful for characterizing the response of aquifers to varying stresses. Groundwater levels may display seasonal and annual variations as well as evidence of groundwater pumping and recovery. Groundwater-level responses to precipitation can also provide insight into the recharge and hydraulic properties of an aquifer. Annual groundwater-level measurements for eight wells screened in the Elk City Sandstone aquifer were inspected for trends. **Figure 12** shows groundwater-level fluctuations from 2010-2019. One well (OWRB 20880) had 31 years of measurements from 1989 to 2019 (**Figure 13**).

During the 1989-2019 period, groundwater levels generally followed precipitation trends. For example, a wetter than average period occurred from 1989 through 2000 causing an increase in water levels during that time. Below mean precipitation in 1994 caused a decline in groundwater levels. A trend of overall declining groundwater levels occurred from 2000-14, which corresponds to decreased precipitation. The lowest groundwater levels observed during the period of record (1989-2019) occurred in 2014 through early 2015 following multiple years of drought conditions.

Increased groundwater pumping during dry periods could also contribute to declines in groundwater levels. A sharp rebound in groundwater levels occurred in 2015 when the study area received above-mean precipitation. An increase in groundwater levels beginning in late 2018 was also observed in all but two wells.

Continuous

Continuous groundwater levels were monitored in ten wells screened in the Elk City Sandstone aquifer as part of this study (Table 4). Depth to water was measured hourly by automated data recorders and inspected from January 2015 through December 2019 (**Figure 14**). Seven wells (OWRB 39831, 20828, 20880, 26822, 118010, 166752, and 169560) were in the eastern portion of the aquifer. Depth-to-water measurements in those wells ranged from 5 to 24 feet below land surface. OWRB 169560 showed a recurring pumping signature from late 2015 through June 2016 and occasionally during 2017 because of its proximity to a municipal well for the City of Dill City, Oklahoma. OWRB 166421 was in the central portion of the aquifer and had depths to water ranging from 2 to 10 feet below land surface. Two wells (OWRB 166435 and 168998) were in the western portion of the aquifer with depths to water ranging from 23 to 27 feet (OWRB

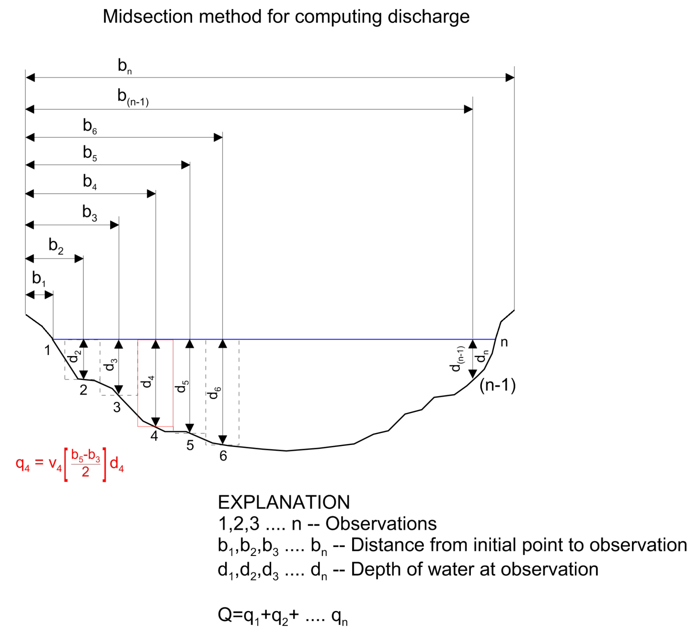


Figure 11. Cross-sectional diagram of USGS Midsection method for measuring streamflow velocity.

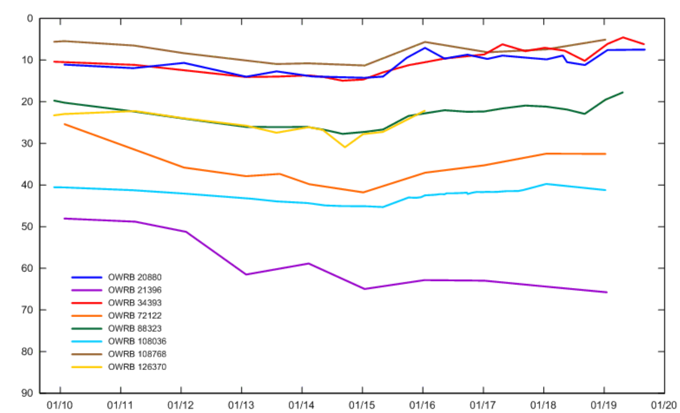


Figure 12. Depth-to-water measurements from Elk City Sandstone wells measured by the OWRB, 2010-19.

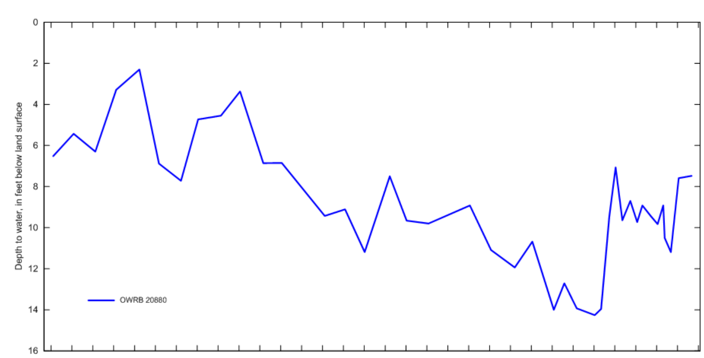


Figure 13. Depth-to-water measurements from OWRB 20880 from February 1989 to September 2019.

Table 4. Groundwater well sites with continuous groundwater-level recorders in the Elk City Sandstone aquifer.

OWRB Well ID	Latitude	Longitude	Total well depth, in feet below land surface	Period of analysis
20828	35.33515	-99.19369	136	1/30/2015 - 12/31/2019*
20880	35.34924	-99.33623	122	1/1/2015 - 12/31/2019*
26822	35.32299	-99.31172	82	6/10/2015 - 12/31/2019*
39831	35.27207	-99.19662	120	4/21/2015 - 1/24/2018
118010	35.29348	-99.13539	120	6/10/2015 - 12/31/2019*
166421	35.36674	-99.52346	90	3/31/2015 - 12/31/2019*
166435	35.49823	-99.82270	100	5/6/2015 - 12/31/2019*
166752	35.44357	-99.26207	40	4/21/2015 - 12/31/2019*
168998	35.45466	-99.83052	140	11/24/2015 - 12/31/2019*
169560	35.30103	-99.14365	211	9/4/2015 - 4/20/2018

*recording at time of publication

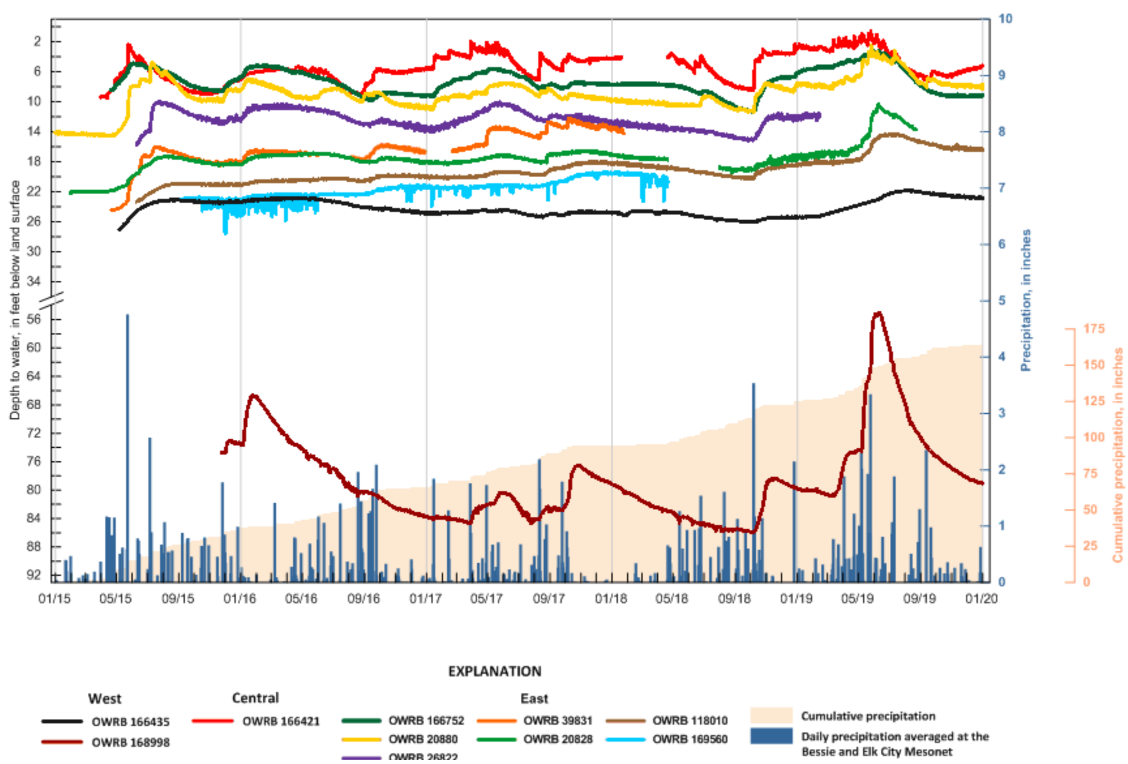


Figure 14. Groundwater levels from OWRB continuous recorder wells from January 2015 through December 2019 showing possible responses from long-term precipitation patterns or nearby groundwater pumping in the Elk City Sandstone aquifer area.

166435) and from 66 to 85 feet (OWRB 168998). Differences in depth to water and groundwater fluctuations at OWRB 168998 compared to the other continuous monitoring wells may be explained by OWRB 168998 being partially screened below the Elk City Sandstone aquifer and its location near the western edge of the aquifer where a greater amount of shale and clay is present as observed in the well driller completion report.

Many of the observed groundwater levels showed seasonal changes related to precipitation with generally higher water levels in the spring and early summer. Groundwater levels generally declined through late summer caused by decreased precipitation and increased pumping and evapotranspiration. Smaller-scale decreases in groundwater levels were observed in many of the wells during the winter months, likely caused by decreased precipitation. The largest increases in observed groundwater levels occurred in 2015 in response to above mean precipitation in the late spring and summer, especially in May. Above mean annual precipitation was recorded each year from 2015-17 and contributed to higher observed mean groundwater levels in 2017 annual measurements compared to 2015.

Groundwater Use

The Elk City Sandstone aquifer provides water for a wide variety of uses including public-water supply, irrigation, commercial, mining, industrial, recreation, agriculture, and domestic. The term "public water supply" is used to describe groundwater use by municipalities, rural water districts, housing additions, trailer parks, churches, and schools. The OWRB issues permits to regulate water use from the aquifer, which is self-reported annually by permit holders, with the exception of domestic use. Domestic use is defined as water use of less than five acre-feet per year for domestic and agricultural purposes or water use for irrigation on land not exceeding three acres. There are 185 long-term, provisional-temporary, and prior right groundwater permits within the aquifer that reported groundwater use within the period of 1967-2018. Groundwater-use data were reviewed for inconsistencies and corrected to ensure accuracy.

Long-term Permitted Groundwater Use

The annual reported groundwater use for the Elk City Sandstone aquifer is shown in **Figure 15** and **Table 5**. Mean annual groundwater use for the period 1967-2018 was 2,314 acre-feet per year, with a median of 2,047 acre-feet per year. The highest annual reported groundwater use (5,031 acre-feet per year) occurred in 1971. The lowest annual reported groundwater use (900 acre-feet per year) occurred in 1981, although this could be due to incomplete or missing records. The next lowest annual reported groundwater use (1,170 acre-feet per year) occurred 2010.

It should be noted that groundwater-use reporting forms supplied to permit holders by the OWRB changed several times over the period of record. Prior to 1980, groundwater use for irrigation was reported by the number of acres irrigated and number of times the crop was irrigated but not by the amount of water applied to the land. As a result, the OWRB developed rules to estimate groundwater use based on assumptions on how many inches were applied for each crop type. According to OWRB rules Title 785, Chapter 30: Taking and Use of Groundwater, prior to 1980, OWRB staff would assume that each of the first six applications of irrigated water was four inches, three inches per application from seven to 10 applications, two inches per application from 11 to 15 applications, and one inch per application for each additional application (Oklahoma Water Resources Board, 2017). Since 1980, permit holders have been required to estimate how many inches were applied during each application. As a result, water use may have been overestimated prior to 1980.

Five periods were identified based on trends in the reported groundwater use data. These periods include 1967-85, 1986-96, 1997-2002, 2003-10, and 2011-18 (**Table 5**). The first period, 1967-1985, had the highest mean annual reported groundwater use (3,325 acre-feet per year). Periods of lower mean annual reported groundwater use occurred in 1986-96 (1,536 acre-feet per year) and 2003-10 (1,518 acre-feet per year). Periods with higher amounts of reported groundwater use occurred from 1997-2002 (2,083 acre-feet per year) and 2011-18 (1,951 acre-feet per year) which both correspond with below mean precipitation during those periods. Groundwater use began to increase in 2011 as the study area entered drought conditions (Oklahoma Climatological Survey, 2013).

Public water supply and irrigation accounted for the majority of annual groundwater use in the Elk City Sandstone aquifer in 1967-2018 (**Table 6**). Municipalities and rural water districts such as the cities of Dill City, Oklahoma, Burns Flat, Oklahoma, Canute, Oklahoma, Cordell and Oklahoma, and Beckham County RWD #3, receive public-water supply from the aquifer. The city of Elk City, Oklahoma, receives public-water supply from the North Fork of the Red River alluvial and terrace aquifer. In 1967-2018, public-water supply accounted for 48.1 percent, irrigation accounted for 41.5 percent, and commercial use accounted for 8.4 percent of reported groundwater use. Mining, industrial, agriculture, recreation, fish, and wildlife use types combined accounted for 2.0 percent of reported groundwater use. All other use types accounted for 0.1 percent of reported groundwater use.

Provisional-temporary Groundwater Permits

Provisional-temporary groundwater permits are nonrenewable permits that have been issued by the OWRB since 1977 for temporary groundwater use, however records

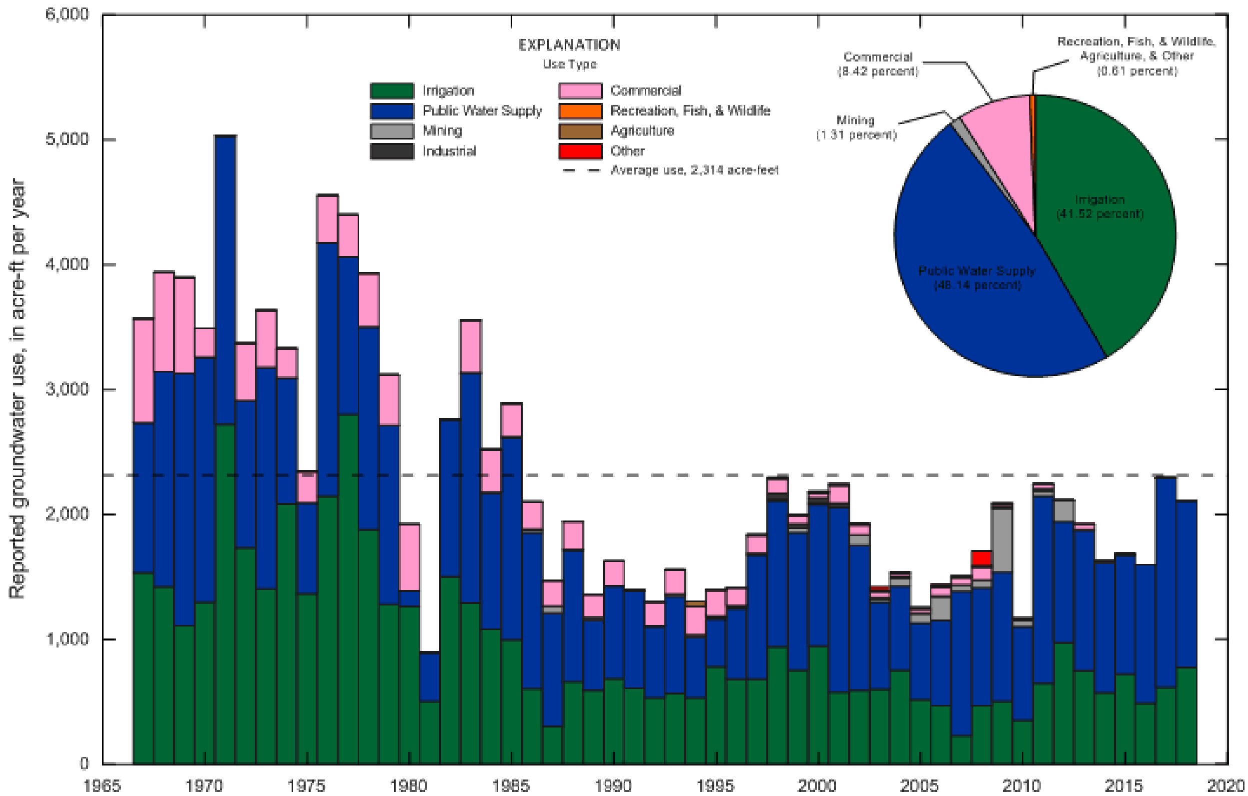


Figure 15. Annual reported groundwater use, by type, for the Elk City Sandstone aquifer from 1967-2018.

Table 5. Summary statistics of annual reported groundwater use in the Elk City Sandstone aquifer from 1967-2018.

Statistic	Reported annual water use (acre-feet per year)					
	1967-2018	1967-1985	1986-1996	1997-2002	2003-2010	2011-2018
Average	2,314	3,325	1,536	2,083	1,518	1,951
Median	2,047	3,490	1,418	2,094	1,476	2,020
Minimum	900	900	1,302	1,840	1,170	1,599
Maximum	5,031	5,031	2,103	2,297	2,092	2,296

Table 6. Mean annual reported groundwater use by type in the Elk City Sandstone aquifer from 1967-2018.

Time span	Mean annual reported water use (acre-feet per year)							
	Irrigation	PWS*	Mining	Industrial	Commercial	Recreation	Agriculture	Other	Total
1967-1985	1,549	1,398	1	0	376	1	0	0	3,325
1986-1996	596	734	15	4	179	3	5	0	1,536
1997-2002	750	1,172	24	29	96	7	6	0	2,083
2003-2010	488	819	127	7	45	8	6	18	1,518
2011-2018	695	1,212	30	4	9	0	0	1	1,951
1967-2018	961	1,114	30	6	195	3	3	3	2,314

*(PWS) Public Water Supply

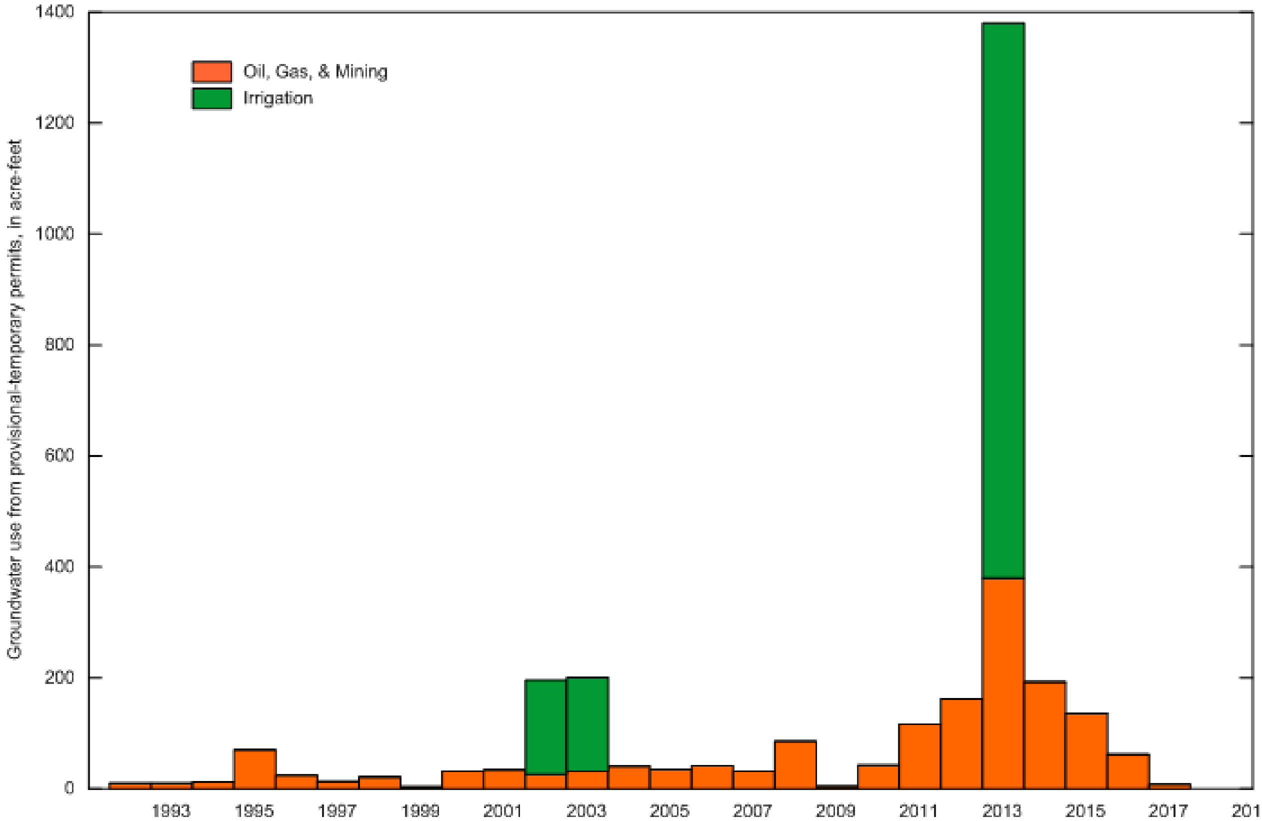


Figure 16. Annual groundwater use by provisional-temporary permits in the Elk City Sandstone aquifer from 1992-2018.

Table 7. Summary statistics from provisional-temporary permits in the Elk City Sandstone aquifer from 1992-2018.

Statistic	Reported annual water use (acre-feet per year)		
	Irrigation	Oil, Gas, & Mining	Total
Mean	50	61	111
Median	0	32	35
Minimum	0	3	3
Maximum	1,000	380	1,380
Percent of total use	55%	45%	

on provisional-temporary groundwater permits are only available since 1992. These permits expire 90 days after issuance and are typically used to provide a short-term water supply or supplement the groundwater supply of existing permit holders. Unlike long-term permits, annual water use reports from the permit holder are not required for provisional-temporary permits and the volume used by the permit holder is assumed not to exceed the authorized amount. A more detailed description of provisional-temporary permits is available in OWRB Rules Chapter 30: Taking and Use of Groundwater (Oklahoma Water Resources Board, 2017).

Between 1992 and 2018, a total of 263 provisional-temporary permits were issued in the Elk City Sandstone aquifer (**Figure 16**). Mining, typically referring to oil & gas activity, accounted for 55 percent of groundwater use from 260 permits; irrigation accounted for 45 percent of the groundwater use from 3 permits (**Table 7**). The highest volume authorized was 1,380 acre-feet in 2013 from 1 irrigation and 20 mining permits. The irrigation permit for 2013 was for 1,000 acre-feet, much larger than any other provisional-temporary permit. The lowest annual volume authorized was 3 acre-feet for mining in 1999. The mean authorized use for the entire period was 111 acre-feet per year.

Hydrogeology

The primary water-bearing geologic unit of the Elk City Sandstone aquifer is the late-Permian-age Elk City Sandstone. The aquifer is unconformably overlain to the northwest by the late-Tertiary Ogallala Formation and overlies relatively impermeable shales and mudstones of the Late-Permian Doxey Shale. Some Quaternary-age alluvium and terrace deposits lie unconformably on top of the Elk City Sandstone and, because of their hydrologic connection with the Elk City Sandstone, are considered to be part of the Elk City Sandstone aquifer.

Regional Groundwater Flow

Groundwater in the Elk City Sandstone aquifer is under mostly unconfined conditions. The northwest portion of the aquifer where the Ogallala Formation overlies the Elk City Sandstone was assumed to be somewhat confining. Groundwater flows toward streams that incise the bedrock to form perennial streams. Regional groundwater flow is split between a northward flow toward the north edge of the aquifer (Washita River basin) and south-southeastward flow to the south boundary of the aquifer (North Fork of the Red River basin) with an east-west groundwater divide between the upper one-third and lower two-thirds of the aquifer.

A potentiometric surface map was constructed for the Elk City Sandstone aquifer from well measurements collected in July 1973 (Kent and others, 1982; Lyons, 1978). The July 1973 potentiometric surface generally followed the topography and ranged in elevation from about 2,125 feet to 1,725 feet with a contour interval of 25 feet (Kent and others, 1982; Lyons, 1978). However, the July 1973 potentiometric surface map was limited in extent to the central and eastern portions of the aquifer.

February 2016 Potentiometric Surface

The potentiometric surface of an aquifer is the altitude to which the water level would rise in a tightly cased well. In unconfined areas of an aquifer, the potentiometric surface is usually equal to the water-table surface. Where the aquifer is confined, the water level may rise above the top of the aquifer due to hydrostatic pressure pushing the water upward in a well. The Elk City Sandstone aquifer is considered to have both confined and unconfined portions, but the term potentiometric surface is used for the entire area for consistency. To create a potentiometric surface map for the Elk City Sandstone aquifer, depths to water were measured in 134 wells in February 17-19, 2016, as part of this study. Those depths to water ranged from 1.8 to 85.9 feet below land surface with a median of 16.8 feet below land surface. The elevation of the potentiometric surface (**Figure 17**) was estimated by subtracting the depth-to-water measurements from the land-surface altitude at each well location. The land-surface altitude was determined by using a differentially corrected Global Positioning System receiver with a horizontal accuracy of 10 centimeters (3.9 inches) and a vertical accuracy of 15-50 centimeters (5.9-19.7 inches) and referenced to the North American Vertical Datum of 1988 (NAVD 88). February 2016 potentiometric contours were generated with a 50-foot contour interval in a geographic information system (GIS) by using the potentiometric surface altitude determined at wells. A potentiometric surface raster map was used to estimate the proper location of contours in areas with sparse well coverage. Contours were also adjusted to account for inconsistencies, especially near streams in the western portion of the aquifer.

Regional groundwater flow is generally to the southeast across the aquifer. Locally, groundwater flows toward headwater streams of the North Fork of the Red River and Washita River drainage basins. Potentiometric contours bend upstream along several streams, especially Buffalo, Elk, Little Elk, Sandstone, and Trail Creeks, indicating local groundwater flow toward these streams. The February 2016 potentiometric surface contours and flow directions (perpendicular to the potentiometric surface contours) are similar to the July 1973 potentiometric surface (Kent and others, 1982; Lyons, 1978) in the eastern and central sections of the aquifer. The main difference in the 1973 potentiometric surface map occurs where contour bending is less pronounced around some of the streams.

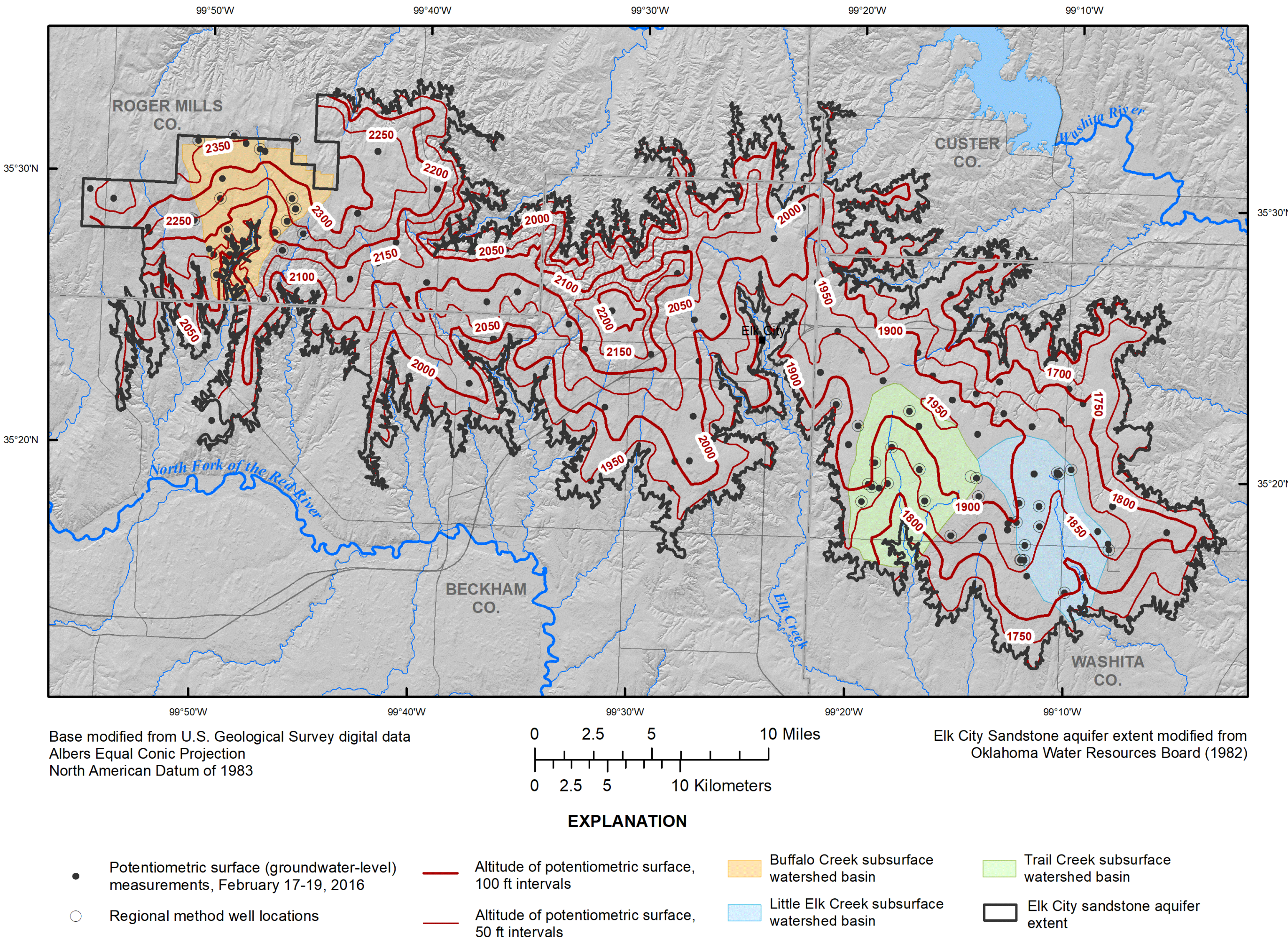


Figure 17. Potentiometric surface map of the Elk City Sandstone aquifer, February 17-19, 2016.

Base of the Elk City Sandstone

The base of the Elk City Sandstone aquifer was previously analyzed and mapped by Kent and others (1982) using lithologic logs provided by the OWRB. The Kent and others (1982) map included only the central and eastern portions of the aquifer with base elevations decreasing from northwest to southeast from about 2,175 to 1,650 feet above NAVD 88. Since that map was published (1982), new sources of surface and subsurface data, including hundreds of new lithologic logs submitted by well drillers to the OWRB (Oklahoma Water Resources Board, 2018), and new geologic maps have been published by the Oklahoma Geological Survey (Johnson and others, 2003; Fay, 2010). Therefore, the base of the aquifer was reanalyzed and mapped as part of this study; the aquifer was determined to extend further west than the area previously mapped by Kent and others (1982).

About 780 lithologic logs were used to determine the base of the Elk City Sandstone aquifer. The contact between the Elk City Sandstone and the underlying Doxey Shale, which marks the base of the Elk City Sandstone aquifer, can generally be determined in lithologic logs. Well drillers rarely name the Elk City Sandstone or Doxey Shale, but the two geologic units have distinctive lithologies that can be easily discerned in lithologic logs. For wells that were assumed to fully penetrate the aquifer, the last lithologic description in lithologic logs of is often described as “red bed” or “red shale/clay”. This description often denotes a change in the grain size of drill cuttings from fine- to medium-grained sands of the Elk City Sandstone to silts and clays of the Doxey Shale. Most wells that had only sandstone in their lithologic logs were assumed to only partially penetrate the aquifer and were not used in determining the altitude of the aquifer-base. The altitude of the base of the Elk City Sandstone at selected wells was determined by subtracting the depth to the aquifer base from the land surface altitude provided by a 10-meter Digital

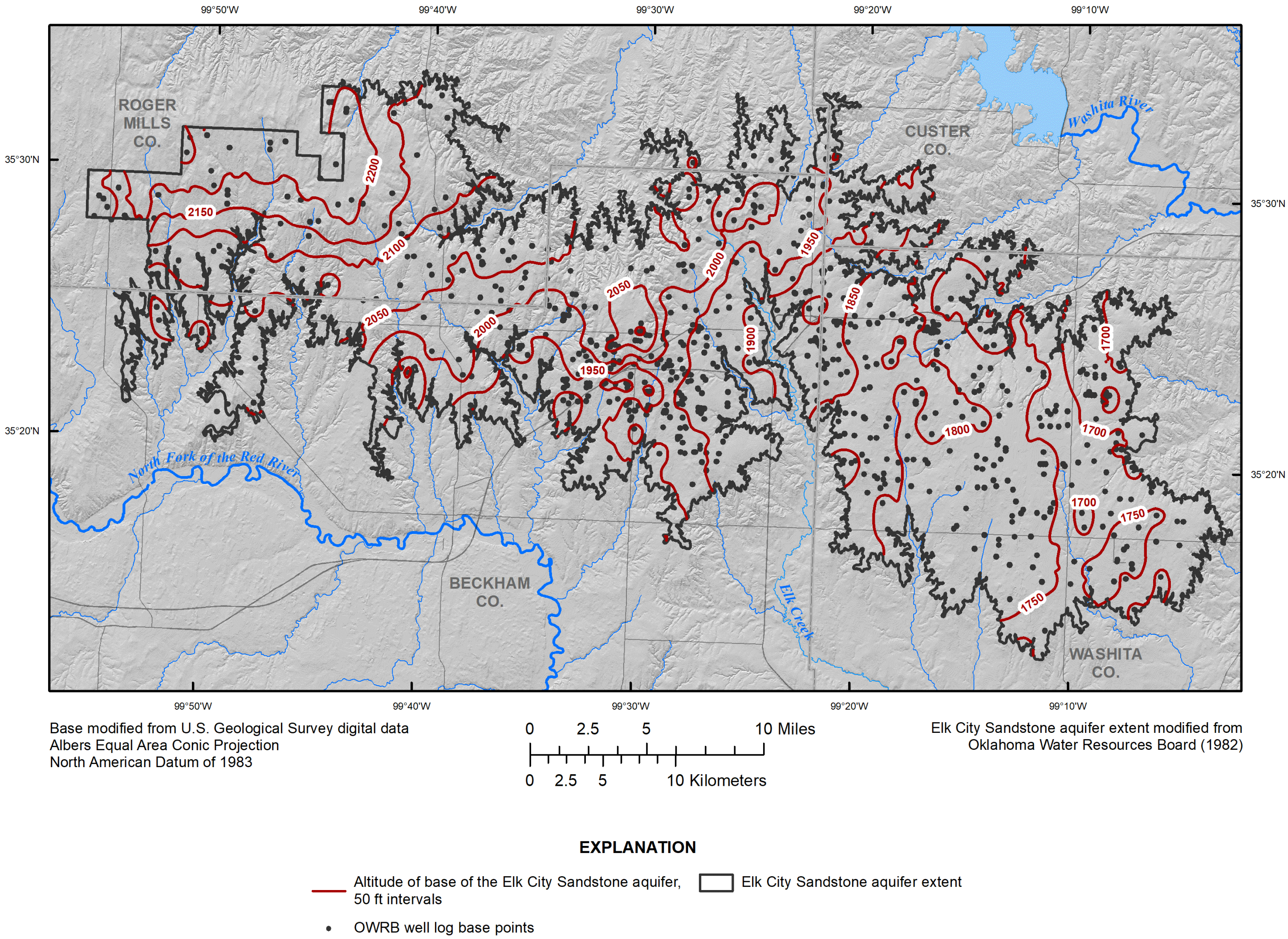


Figure 18. Altitude of the base of the Elk City Sandstone aquifer derived using lithologic logs submitted to the OWRB.

Elevation Model (DEM) (U.S. Geological Survey, 2019). A map of the altitude of the base of the Elk City Sandstone (**Figure 18**) was generated based on the base elevation at each suitable well log site using the Kriging method in ArcGIS. The altitude of the base of the Elk City Sandstone aquifer gradually decreases from over 2,200 feet above NAVD 88 in the northwest to about 1,650 feet above NAVD 88 in the east. The thickness of the Elk City Sandstone and overlying Quaternary deposits exceeds 220 feet in the central and eastern portions of the aquifer.

Elk City Sandstone Aquifer Saturated Thickness

The 2016 saturated thickness of the Elk City Sandstone aquifer (**Figure 19**) was estimated by subtracting the base of the aquifer from the 2016 potentiometric surface. The mean saturated thickness for the Elk City Sandstone aquifer was 56 feet. The saturated thickness was greatest in areas along and near the axis of the Anadarko Basin. The thickest saturated portions were 151-199 feet and were located in three areas: northeast of Sweetwater, Oklahoma; six miles west of Elk City, Oklahoma; and between Dill City, Oklahoma, and Burns Flat, Oklahoma, to 5.5 miles southwest of Burns Flat, Oklahoma. The thinnest saturated portions of the aquifer are located near streams and along the edges of the aquifer as a result of erosion.

Cross Sections

Six cross-sections were created to show the top and base of the Elk City Sandstone as well as the 2016 potentiometric surface in the Elk City Sandstone aquifer (**Figure 20-Figure 22**). The dendritic network of streams incising the surface creates the hummocky land surface apparent in all of the cross-sections. Groundwater discharges to streams that

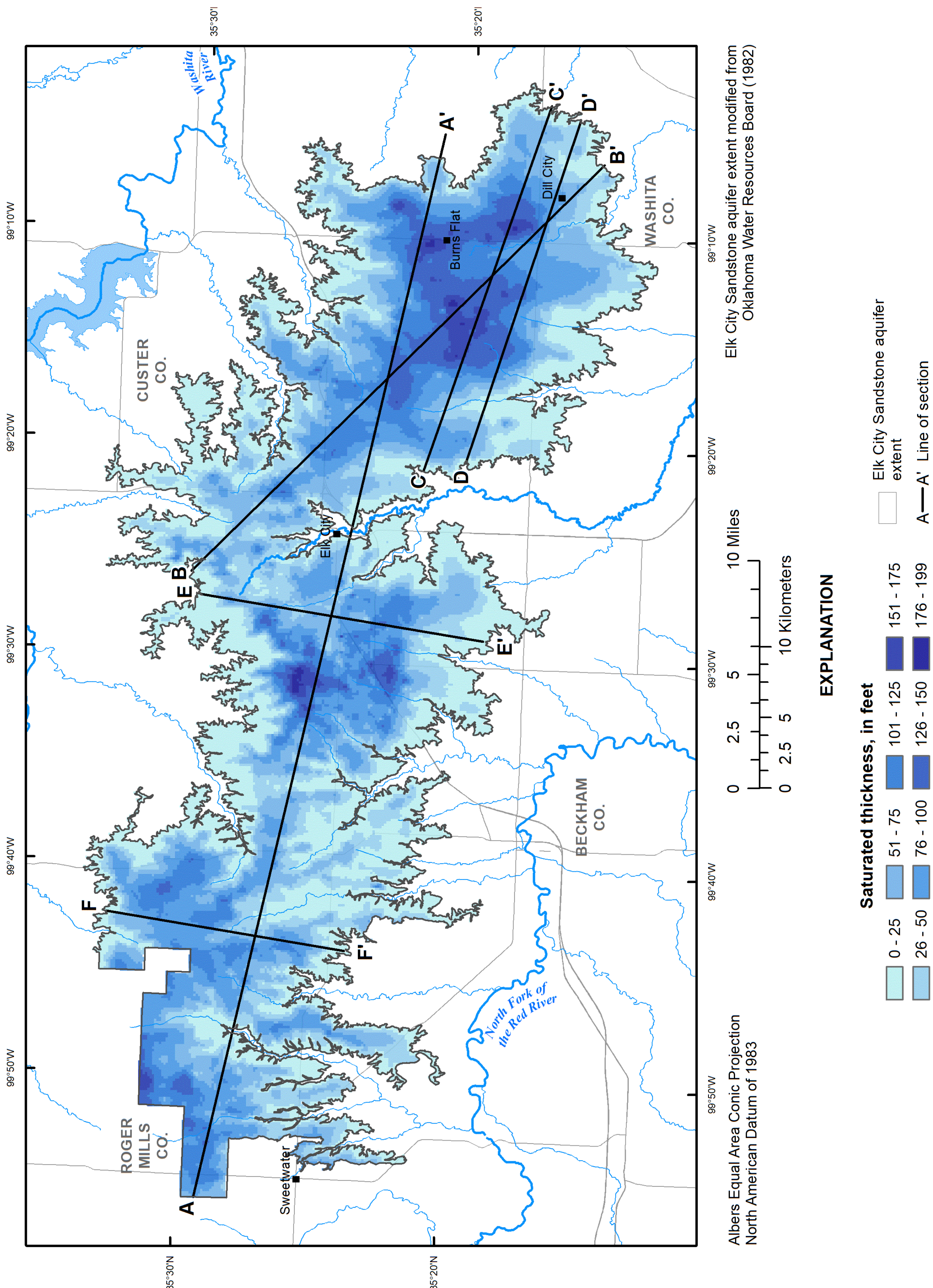


Figure 19. Saturated thickness (2016) of the Elk City Sandstone aquifer with cross-section lines shown.

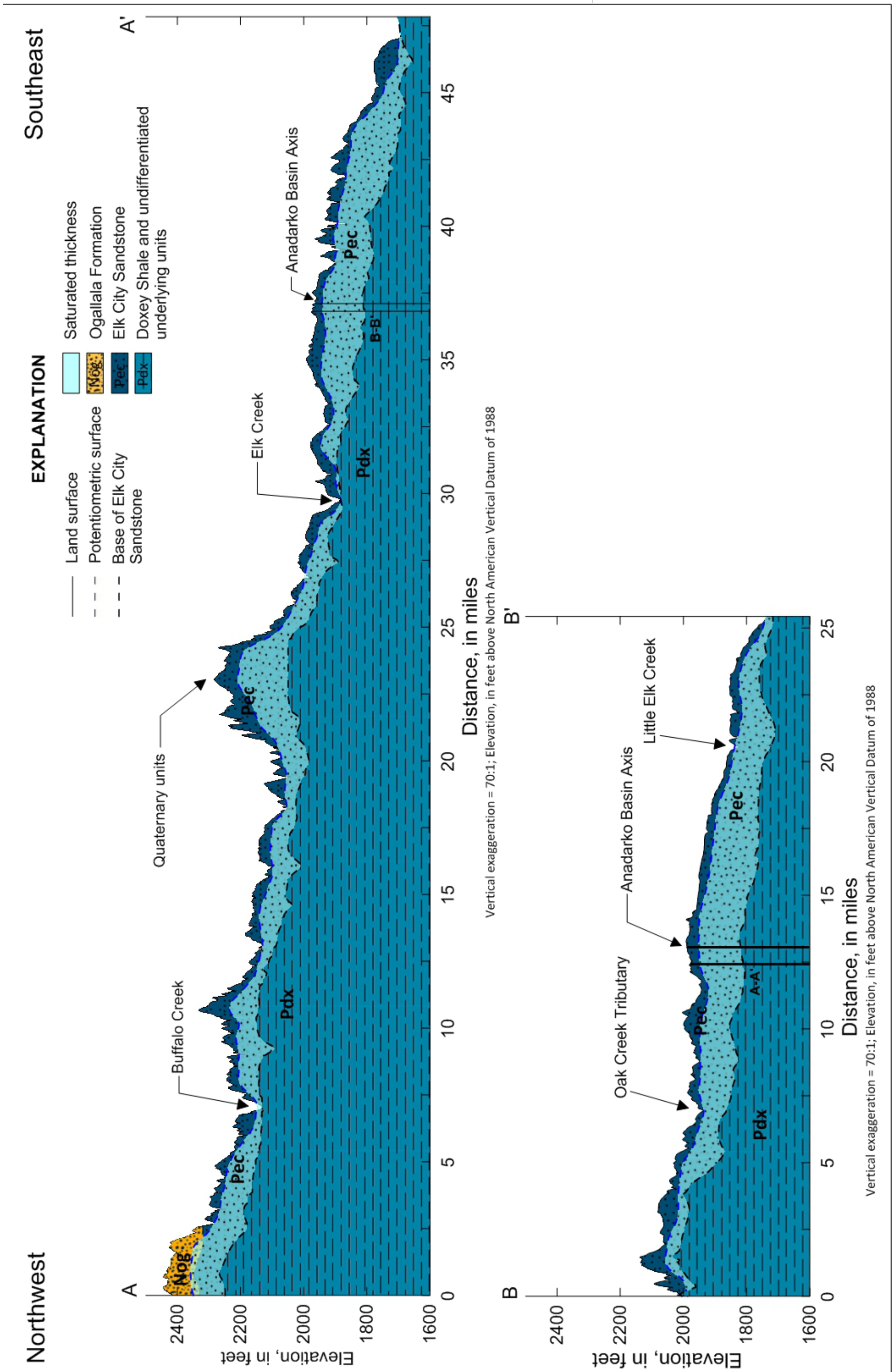


Figure 20. Cross sections A-A' and B-B' from the northwest to southeast showing geologic units, 2016 potentiometric surface, and saturated thickness.

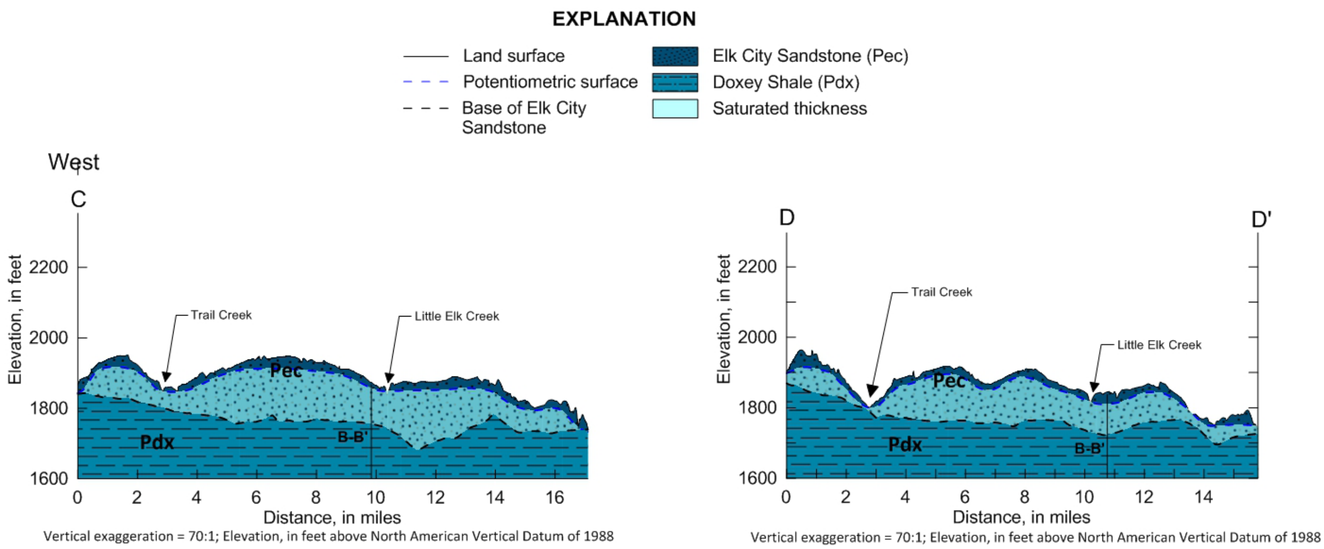


Figure 21. Cross sections C-C' and D-D' from the northwest to southeast portion of the eastern lobe of the Elk City Sandstone showing geologic units, 2016 water table, and saturated thickness.

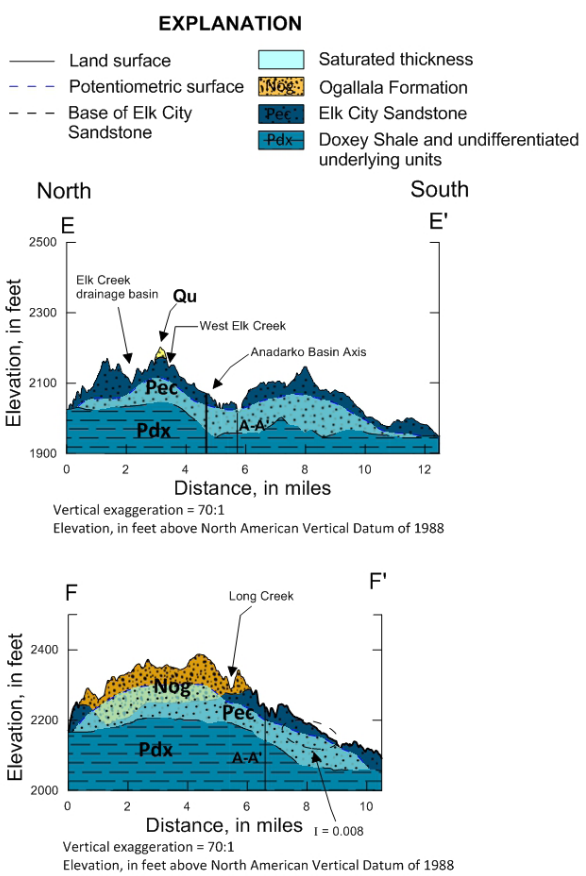


Figure 22. Cross sections E-E' and F-F' from the north to the south showing geological units, 2016 water table, and saturated thickness.

intersect the water table. Many intermittent streams contain base flows from groundwater only when the water table is relatively high and recharge is greater than the sum of evapotranspiration, base-flow discharge, and groundwater pumping. Precipitation from Spring 2015 through Summer 2016 was above average, and many intermittent streams that were dry prior to 2015 as observed by OWRB staff, were observed to contain base flow in 2015-16.

Cross-section A-A' (**Figure 20**) extends 47.8 miles northwest to southeast across the aquifer and is nearly parallel to the Anadarko Basin axis. The western 2.5 miles of cross section A-A' show the Ogallala Formation overlying the Elk City Sandstone to be about 100 feet thick. The base of the Ogallala Formation in this area was derived from lithologic descriptions in water well logs submitted to the OWRB. A small area of Quaternary cover sand and terrace approximately two miles wide near the middle of the cross section corresponds with a local topographic high. Buffalo Creek is the only perennial stream intersected by this cross-section. The interpolated 2016 potentiometric surface intersects the land surface at the Buffalo Creek stream bed indicating that groundwater is discharging to this stream. Elk Creek has incised through the Elk City Sandstone into the Doxey Shale, and the water table lies below the stream bed, suggesting there is little or no groundwater contribution to this stream within the aquifer boundary. Saturated thickness and aquifer thickness on this cross section are greatest in the southeastern part of the aquifer near Burns Flat.

Cross-section B-B' (**Figure 20**) extends 25.4 miles from northwest to southeast through the eastern portion of the aquifer. This cross-section dissects some of the thickest parts of the aquifer and intersects the axis of the

Anadarko Basin near mile 13. The 2016 potentiometric surface was above the streambed elevation for Little Elk Creek indicating groundwater discharged to this stream, which was confirmed by streamflow gauging station data collected as part of this study as well as field observations by OWRB staff. The 2016 potentiometric surface also was above the streambed elevation for an Oak Creek tributary. Field observations and streamflow measurements collected by OWRB staff confirmed that this stream is intermittent and only flows when the potentiometric surface is relatively high following long periods of above average precipitation and increased recharge. In general, cross-sections A-A' and B-B' show the base of the Elk City Sandstone to be sloping toward the southeast.

Cross-sections C-C' and D-D' (**Figure 21**) extend from west to east across the eastern portion of the aquifer. These two cross-sections intersect two perennial streams, Trail Creek and Little Elk Creek. In cross-section C-C', which is parallel to and 1.5 miles north of cross-section D-D', the 2016 potentiometric surface was near the streambeds of Trail Creek and Little Elk Creek, whereas in cross-section D-D', the potentiometric surface was above the streambeds. This may suggest that these streams increase in base flow from north to south, although the resolution of the potentiometric surface in this area based on the density of wells measured may not be accurate enough to state that definitively. Surface-water measurements from the 2017 synoptic streamflow event also indicated that these streams gained in flow at that time. These two cross-sections also show that Trail Creek and Little Elk Creek have incised further into the formation from north to south as indicated by elevation data where the surface elevation for each creek

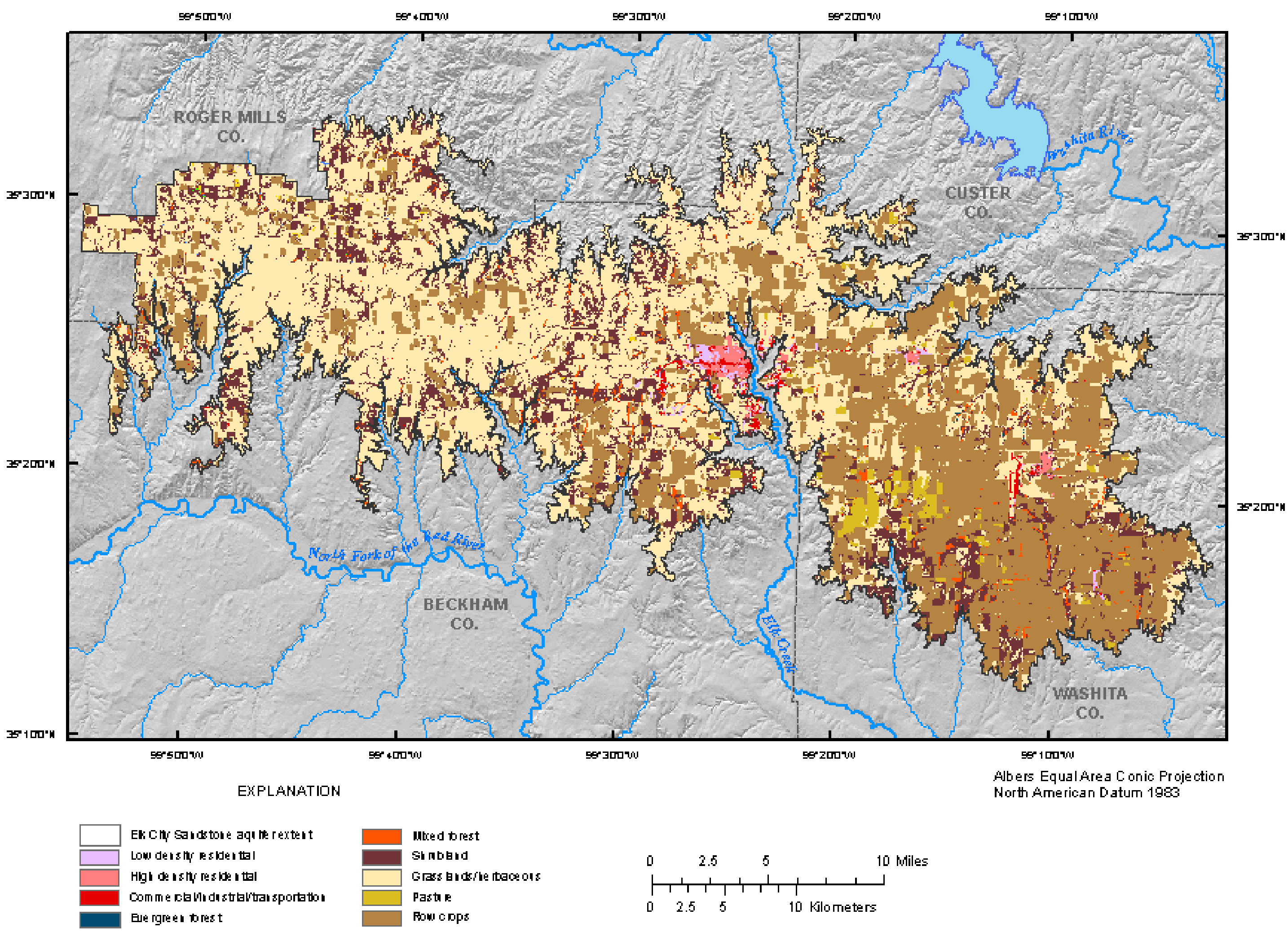


Figure 23. Land use types within the Elk City Sandstone aquifer extent (Multi-Resolution Land Characteristics Consortium, 2000).

is about 20-30 feet lower in cross-section D-D' compared to C-C'. The Trail Creek basin is also more incised in cross-section D-D' than in cross-section C-C' with steeper slopes toward the creek. The southern cross-section, D-D', shows the stream bed elevations below the 2016 potentiometric surface correlating to stream-flow measurements taken by OWRB staff, which showed that stream-flows, that were assumed to be equal to base flow increased from north to south. Stream-flow in Trail Creek was measured at 0.18 cubic feet per second at cross-section C-C' and 1.36 cubic feet per second at cross-section D-D'. Streamflow in Little Elk Creek was measured at 1.05 cubic feet per second at cross-section C-C' and 2.57 cubic feet per second just south of cross-section D-D'.

Further to the west, cross-section E-E' (**Figure 22**) extends 12.5 miles from north to south across the central portion of the aquifer. Elk Creek can be seen above the water table, suggesting this stream does not have base flow contribution.

Cross-section F-F' (**Figure 22**) is in the western portion of the aquifer and shows the Ogallala Formation overlying the Elk City Sandstone. The Ogallala Formation is over 100 feet thick in some places along this cross-section. Thickness of the Elk City Sandstone is as little as 10 feet underlying the Ogallala Formation. The Elk City Sandstone is very thin from 1 to 2 ½ miles along cross section F-F', likely due to the presence of a subsurface channel that was subsequently filled with sediments of the Ogallala Formation.

Recharge

For this investigation, groundwater recharge is defined as the process by which precipitation enters the groundwater flow system. Recharge is the predominant means of inflow to the Elk City Sandstone aquifer. The rate of recharge is controlled by various factors, such as the precipitation rate, 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. Recharge to the Elk City Sandstone aquifer was estimated using a soil-water-balance (SWB) code and the water-table-fluctuation (WTF) method. The SWB code is a method that uses precipitation rates and landscape characteristics to estimate recharge across the entire aquifer. The WTF method uses a groundwater hydrograph to estimate recharge and was used on groundwater-level data acquired at two well locations.

Soil-Water Balance Code

The soil-water-balance code provides a spatial and temporal estimation of groundwater recharge at a local scale using a modified Thornthwaite-Mather soil-water-balance approach in conjunction with landscape characteristics, land use, and climatological data (Westenbroek and others, 2010). Thornthwaite and Mather (1957) derived a non-linear relationship between soil moisture and water deficit. Soils lose more water to evapotranspiration (ET) in the first few days of a water deficit and subsequently less as the deficit grows. The SWB code uses this relationship to calculate 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 them 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, either growing or dormant. The Hargreaves-Samani method (Hargreaves and Samani, 1985) was used for this investigation because this method utilizes climate data from multiple climate stations as spatially-gridded datasets and estimates ET using the minimum and maximum air temperature in addition to daily precipitation. The potential ET represents the maximum amount of ET possible given no limitation to soil moisture. Soil moisture is determined from several variables including precipitation minus potential ET, accumulated potential water loss, actual ET, soil-moisture surplus, and soil-moisture deficit (Westenbroek and others, 2010). 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 and the grid cell is considered saturated, the excess is converted to recharge (Westenbroek and others, 2010). Any 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 5 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)

Table 8. Period of record for National Weather Service COOP and Oklahoma Mesonet stations used for the SWB code in the Elk City Sandstone aquifer study area.

Climate station name	Station ID	Period of record
NOAA COOP[a]		
Arnett 3NE	332	1945-2004
Canadian, TX	USC00411412	1945-2001
Cheyenne 11NW	1744	2012-2016
Clinton	1909	1945-2004
Clinton-Sherman	1906	1958-2019
Cordell	2125	1945-2008
Elk City 4 W	2849	1945-2019
Hammon 3SSW	3871	1945-2005
Reydon 2SSE	7579	1945-2006
Sayre	7952	1945-1975
Oklahoma Mesonet[b]		
Arnett	ARNE	1997-2019
Cheyenne	CHEY	1994-2019
Elk City	ELKC	2015-2019
Retrop	RETR	2009-2014

[a]Oklahoma Climatological Survey, 2019a

[b]Oklahoma Mesonet, 2017

Table 9. Summary statistics for recharge calculated using the SWB code for four timeframes: 1948-2019, 1948-84, 1985-98, and 1999-2019.

Statistic	Annual SWB recharge, in inches per year			
	1948-2019	1948-1983	1984-2001	2002-2019
Minimum	0.00	0.00	0.04	0.00
Maximum	2.66	1.97	2.66	1.87
Mean	0.61	0.42	1.12	0.47
Median	0.31	0.16	0.98	0.18

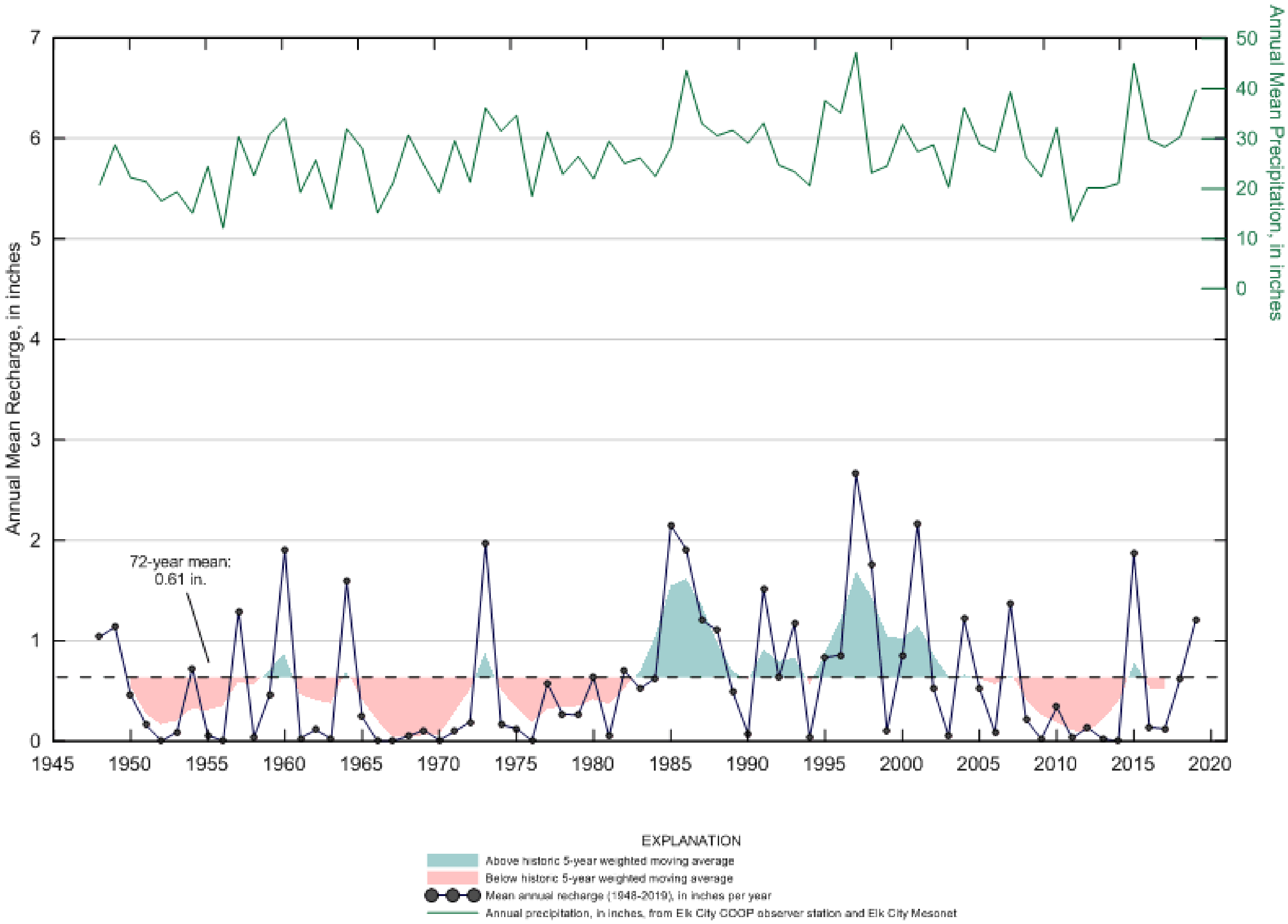


Figure 24. Mean annual recharge to the Elk City Sandstone aquifer, calculated using the SWB code, with historic 5-year moving average, 1948-2019.

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.

The code requires seven datasets, which include available soil-water capacity, land cover class, hydrologic soil groups, flow-direction, daily precipitation, and daily minimum and maximum temperatures (Westenbroek and others, 2010). Soils are represented by four hydrologic soil groups (A-D) (U.S. Department of Agriculture, 2009), with 'A' soils having the highest infiltration capacity and 'D' soils having the lowest infiltration capacity (Westenbroek and others, 2010). Available soil-water capacity must be assigned for each soil type and was derived from the Grided Soil Survey Geographic (gSSURGO) (Natural Resources Conservation Service, 2014). The values for available soil-water capacity were assigned based on soil texture as outlined by Westenbroek and others (2010, **Table 7**). The available water capacity values 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, 2000) (**Figure 23**). Land-use data, in conjunction with available soil-water capacity, was used to calculate surface runoff and maximum soil-moisture holding capacity (Westenbroek and others, 2010). A flow direction grid is 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 model uses a land-use lookup table containing NRCS 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 depths, maximum soil recharge, interception, and curve numbers are based on averages for each land-use and

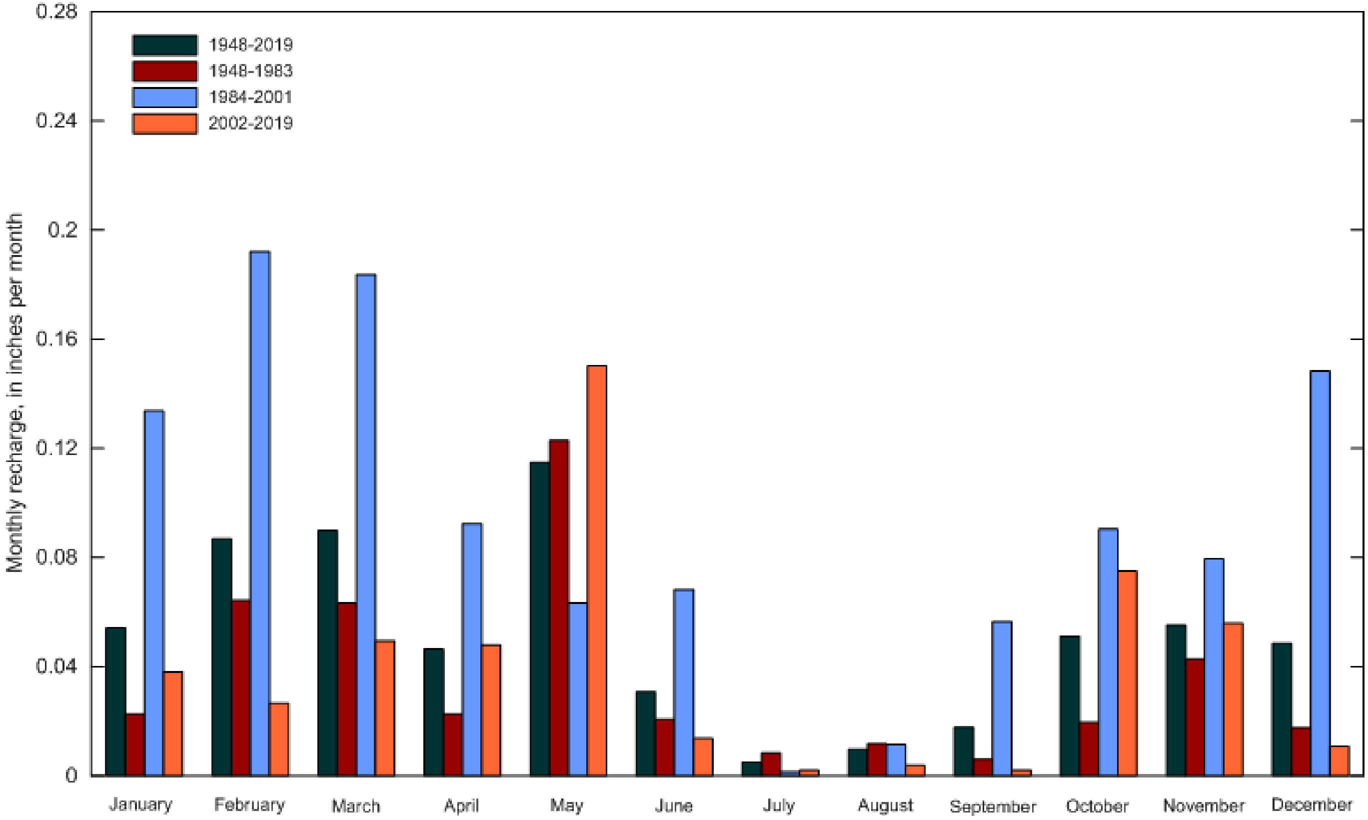


Figure 25. Mean monthly recharge to the Elk City Sandstone aquifer, calculated using the SWB code, 1948-2019.

soil type. Daily minimum/maximum temperatures and precipitation from 10 NOAA cooperative observer (COOP) stations and four Oklahoma Mesonet stations were used in this analysis and were selected based on their period of record and proximity to the study area (**Table 8**).

The SWB code was used to estimate spatially distributed groundwater recharge from 1948 to 2019 over the Elk City Sandstone aquifer. Each dataset was resampled to a 100-meter grid and clipped to the extent of the Elk City Sandstone aquifer. The outputs of the SWB code were monthly and annual recharge grids. Mean annual recharge estimated using the SWB model for the gridded aquifer area was 0.61 inches per year for the 1948-2019 period (**Table 9**) (**Figure 24**). An extended period of below-mean annual recharge occurred from 1948-83 with mean annual recharge of 0.42 inches per year. This was followed by a period of above-mean annual recharge from 1984-2001 with mean annual recharge of 1.12 inches per year. The period of 2002-2019 had below-mean annual recharge of 0.47 inches per year. Mean monthly recharge from 1948-2019 was greatest during May, with recharge of 0.11 inches per month, and was lowest in July, with recharge of less than 0.01 inches per month (**Figure 25**). The 1984-2001 period had higher mean monthly recharge than most other periods, consistent with increased mean precipitation over those years. However, during the 1984-2001 period, mean monthly recharge in May was less than that for eight other months. The 1948-83 and 2002-2019 periods each had below-mean monthly recharge for nine months and eight months respectively, compared to the period of record, 1948-2019.

Mean annual recharge for 1948-2019 was greatest in the eastern half of the aquifer (**Figure 26**). This is possibly caused by smaller grain sizes (siltstone) in the western half of the aquifer with coarser grains (sandstone) in the eastern half. Recharge also was higher in the northwestern portion, likely caused by the greater infiltration rates in the mostly unconsolidated sand and gravel deposits of the Ogallala Formation and not the Elk City Sandstone. Differences in land use between the eastern and western portions of the aquifer could also cause spatial differences in recharge. Root-zone depths are based on land use types and are an important parameter in determining recharge (Westenbroek and others, 2010). The land use of the western half of the aquifer is predominately grasslands with deeper root-zone depths, while the eastern half of the aquifer is predominately shallow rooted agriculture (**Figure 23**). Small areas of higher recharge rates in the central and northwest portions of the aquifer also correspond to land-use types with shallower root-zone depths. The highest annual recharge during the period of record (2.66 inches)

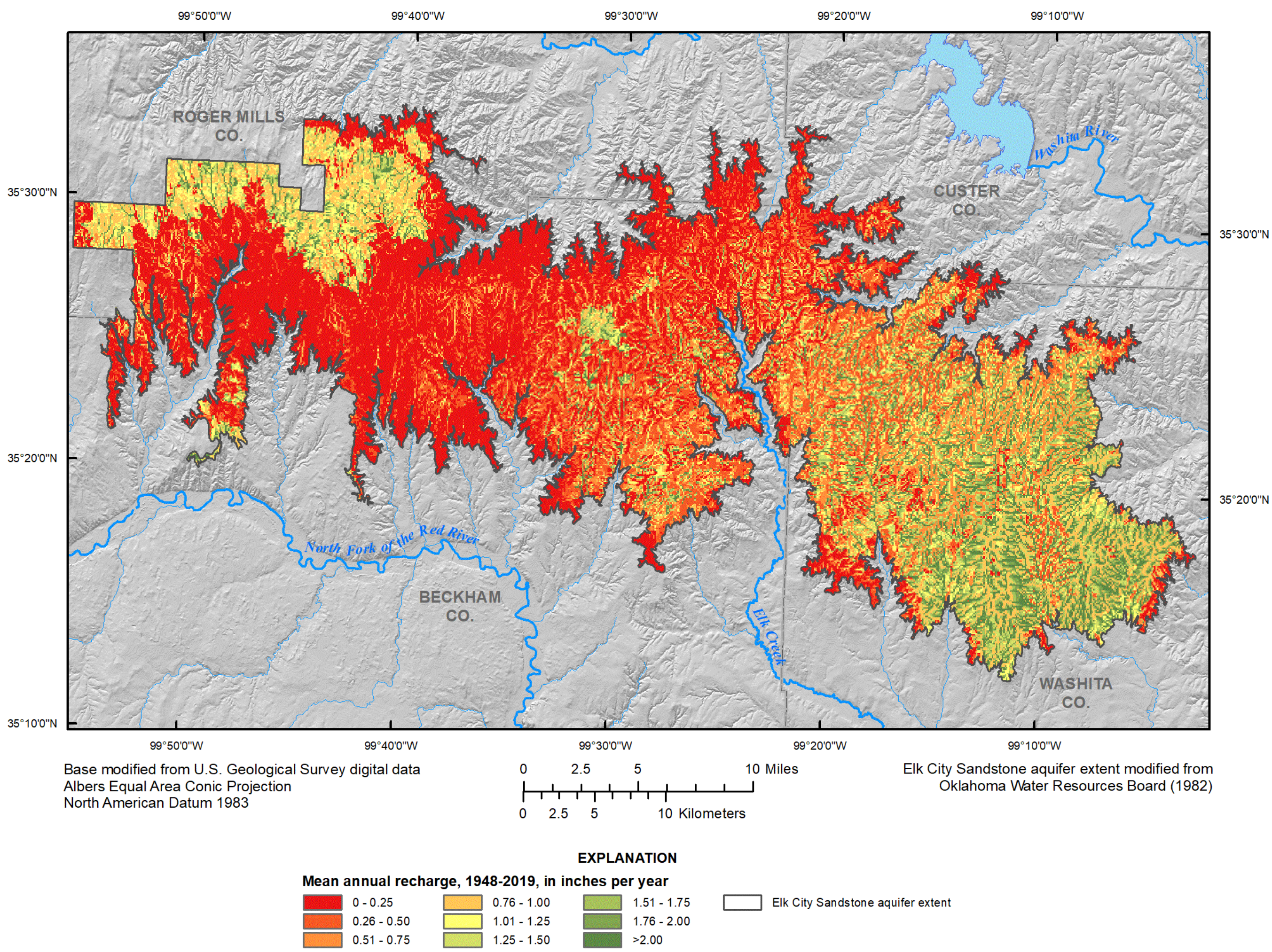


Figure 26. Spatial distribution of mean annual recharge to the Elk City Sandstone aquifer calculated using the SWB code, 1948-2019.

occurred in 1997, with greater than two inches for the majority of the eastern half of the aquifer (Figure 27). The lowest annual recharge during the period of record (<0.01 inches) occurred in 1966, when the majority of the aquifer had fewer than 0.25 inches of recharge (Figure 28).

Water-Table Fluctuation Method

The Water-Table Fluctuation (WTF) method (Healy and Cook, 2002) was also used to estimate recharge to the Elk City Sandstone aquifer. The WTF method uses the premise that rising groundwater levels over hours or a few days in unconfined aquifers are caused by recharge from precipitation events. The method is best applied to groundwater wells with shallow water levels and detailed continuous hydrographs that display sharp increases in water levels after precipitation. Recharge (R) using the WTF method is calculated as:

$$R = S_y(\Delta h/\Delta t)$$

where

S_y is the specific yield (dimensionless)
Δh is the change in water table elevation/altitude, in inches, and
Δt is the change in time of the water-level rise

Three observation wells were used to estimate recharge using the WTF method: OWRB 166421; OWRB 166752; and OWRB 20880 (**Figure 1**). These wells were selected based on the shallow water table and the noticeable rise and fall in water levels after precipitation events at each location. Continuous water-level recording instruments at each well recorded the groundwater level every hour. Recharge was calculated for the period of record for each well, which ranged from January 1, 2015, to December 31, 2019. The precipitation data were recorded at the Elk City, Oklahoma, and Bessie, Oklahoma, Mesonet stations, which

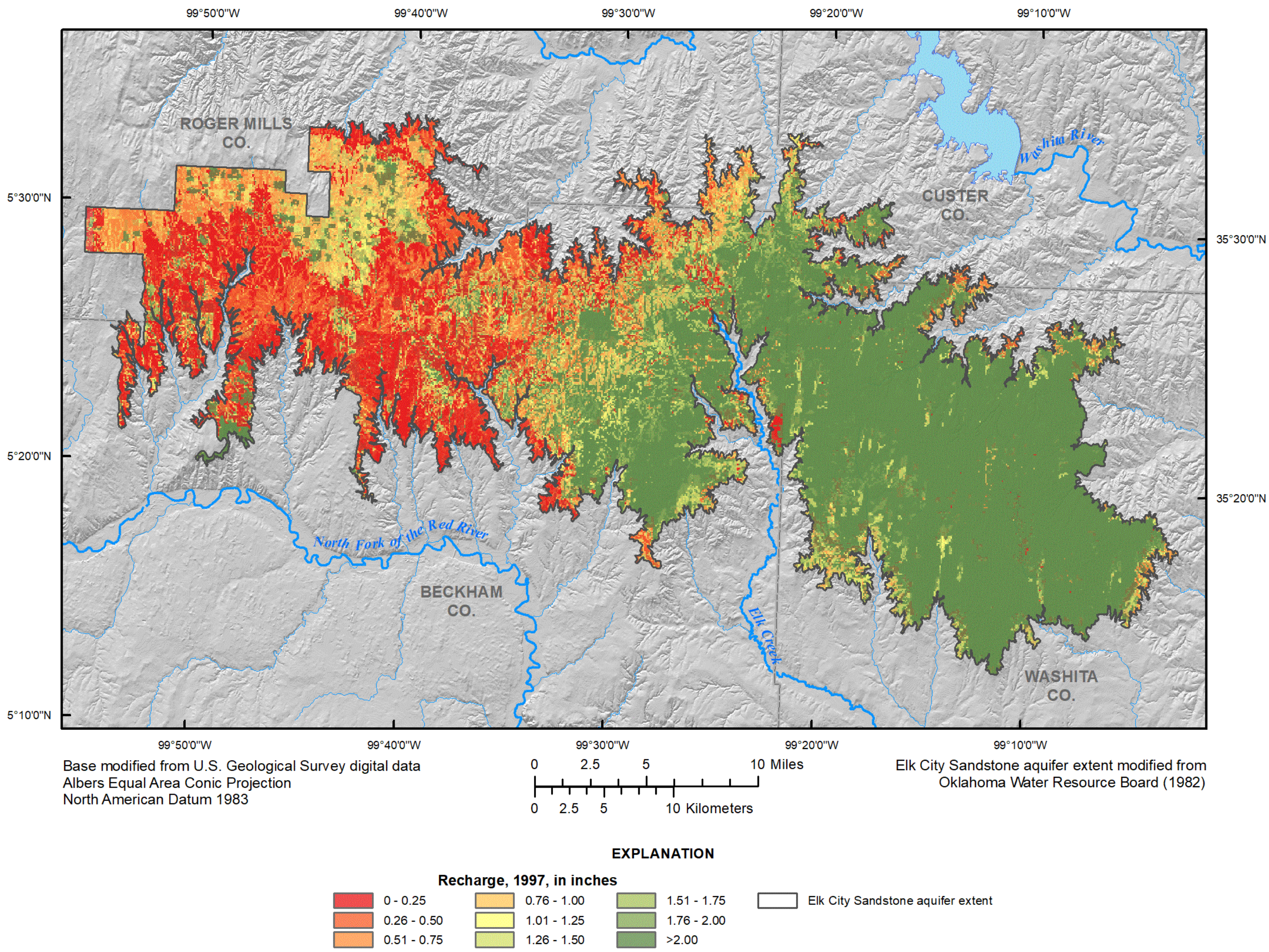


Figure 27. Spatial distribution of recharge calculated using the SWB code for the year 1997, a year of above average recharge.

were selected based on the data available for this time frame as well as the proximity to each well.

The WTF method calculates an approximation of recharge from the change in the water table following precipitation events. The method does not account for other variables, such as surface runoff, pumping, surface water infiltration, and evapotranspiration. The water-level trend prior to the precipitation event was extrapolated below the water-level peak to give a more accurate estimate for recharge. The specific yield of the aquifer at each site had not been measured but was estimated to be 0.08 based on the methods discussed in the “Hydraulic Properties” section of this report. There are two main limitations when using the WTF method: 1) assuming water table increases are caused by recharge solely from precipitation and 2) estimating a reasonable value for specific yield (Healy and Cook, 2002).

The water levels in all three wells ranged between 0.6-14.7 feet below land surface in 2015-2019 and showed similar trends (**Figure 29**). Decreases in water levels occurred during the summer at all of the wells. Increases generally occurred during the fall and spring with sharp increases following precipitation. Decreases in water levels were observed from July-September despite multiple precipitation events, which could be the result of increased pumping from the aquifer as well as high rates of evapotranspiration.

Recharge values calculated by the WTF method were compared to recharge calculated using the SWB code from 2015-2019. The mean annual recharge values were 10.5 inches (WTF), 1.43 (SWB) at OWRB 166421; 3.5 inches (WTF), 1.55 inches (SWB) at OWRB 166752; and 5.7 inches (WTF), 1.27 inches (SWB) at OWRB 20880. Mean precipitation ranged from 32.4-33.7 inches at the three wells during this period. The calculated recharge as a percent of precipitation ranged from 10.7-31.5 percent using the WTF method and from 3.8-4.8 percent using the SWB code. Differences in recharge estimates between the

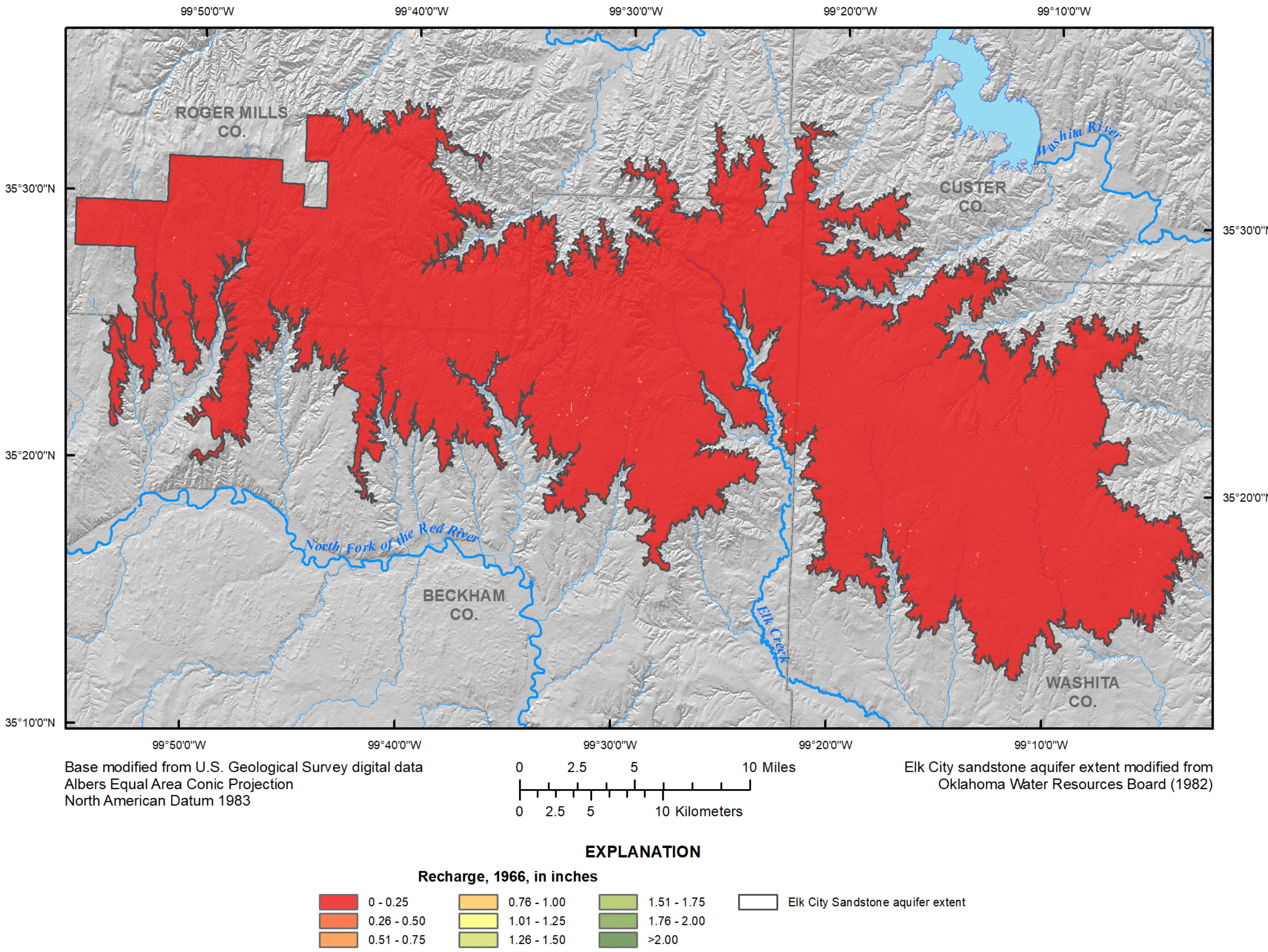


Figure 28. Spatial distribution of recharge calculated using the SWB code for the year 1966, a year of below average recharge.

WTF method and SWB model may be caused by the soil and land-use parameters that are used for the SWB model. The higher recharge estimates using the WTF method could also indicate site specific yield values being lower than the regional estimate or water moving into the aquifer from another source causing recharge to be overestimated.

A previous recharge estimate by Kent and others (1982) used the WTF method to calculate recharge from seven precipitation events (from May-August 1980) and hydrographs from two observation wells located in Sections 11 and 17, T10N, R19W. The specific yield used for calculations in that study was 0.21. The mean recharge was calculated to be 14.1 percent of total precipitation (Kent and others, 1982). However, using a specific yield value of 0.08 instead of 0.21 would result in a mean recharge of 5.36 percent of total precipitation for those seven precipitation events. This is similar to the mean recharge as a percentage of precipitation calculated with the SWB model for 1948-2019 (3.8-4.8 percent of total precipitation) at the three wells in this study.

Hydraulic Properties

The hydraulic properties of the Elk City Sandstone aquifer include values of hydraulic conductivity, transmissivity, and specific yield. Hydraulic conductivity, also referred to as the coefficient of permeability, is a measure of the ease with which water can flow through a porous media (Schwartz and Zhang, 2003) and is defined as a volume of water that is transmitted in a unit time through a cross section of unit area (Lohman, 1972). In this report, hydraulic conductivity values are expressed in units of feet per day. Transmissivity is the product of the hydraulic conductivity and saturated thickness and describes the ease with which water can flow through an aquifer; it is a measure of the rate at which water is transmitted through a unit width of the aquifer under a unit

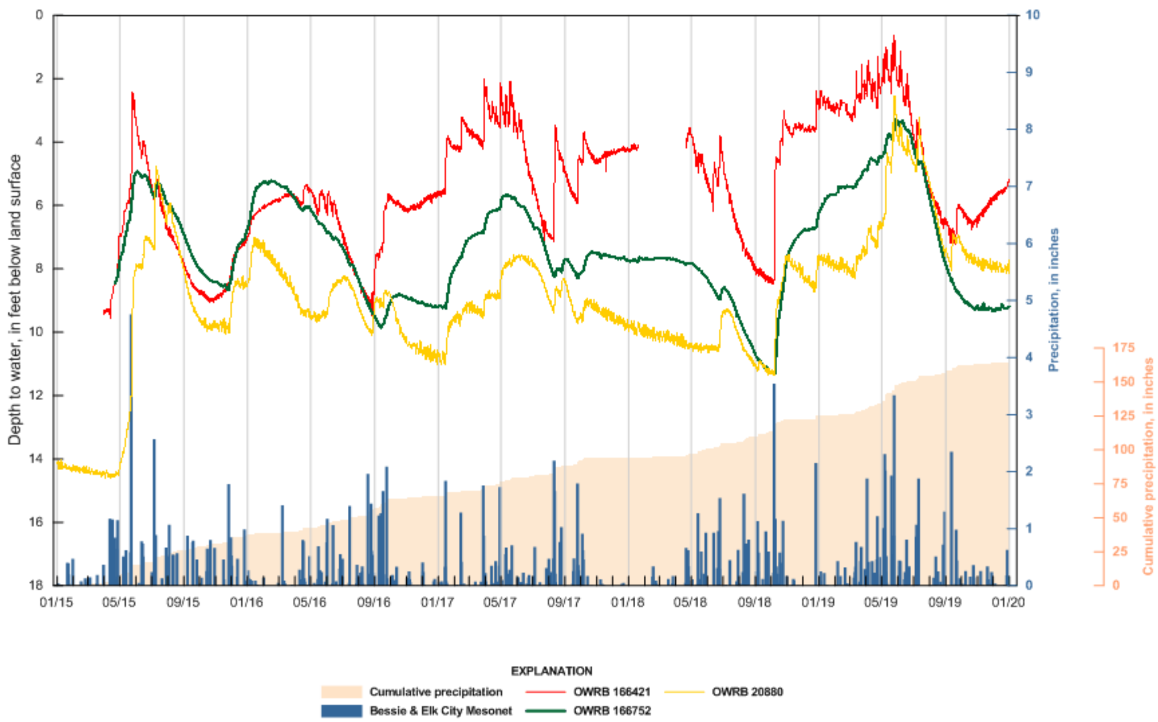


Figure 29. Water-level fluctuations at observation wells (OWRB 166421, 166752, and 20880) with precipitation at the Elk City and Bessie, Oklahoma, Mesonet stations from January 2015 to December 2019.

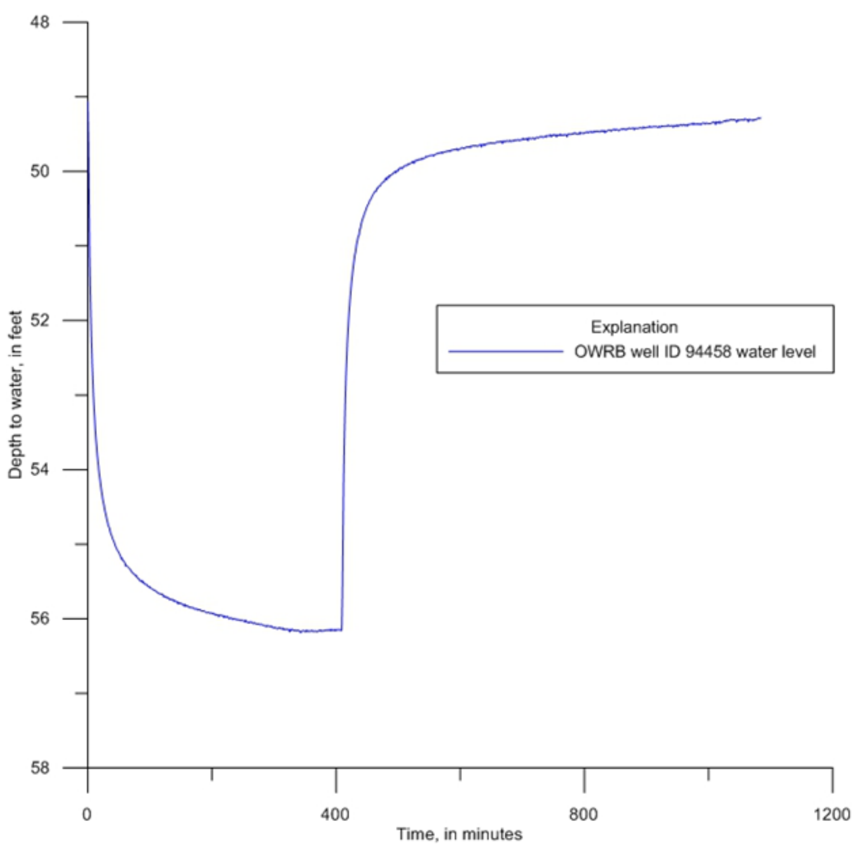


Figure 30. Water levels in observation well during a multi-well aquifer test in the Elk City Sandstone aquifer.

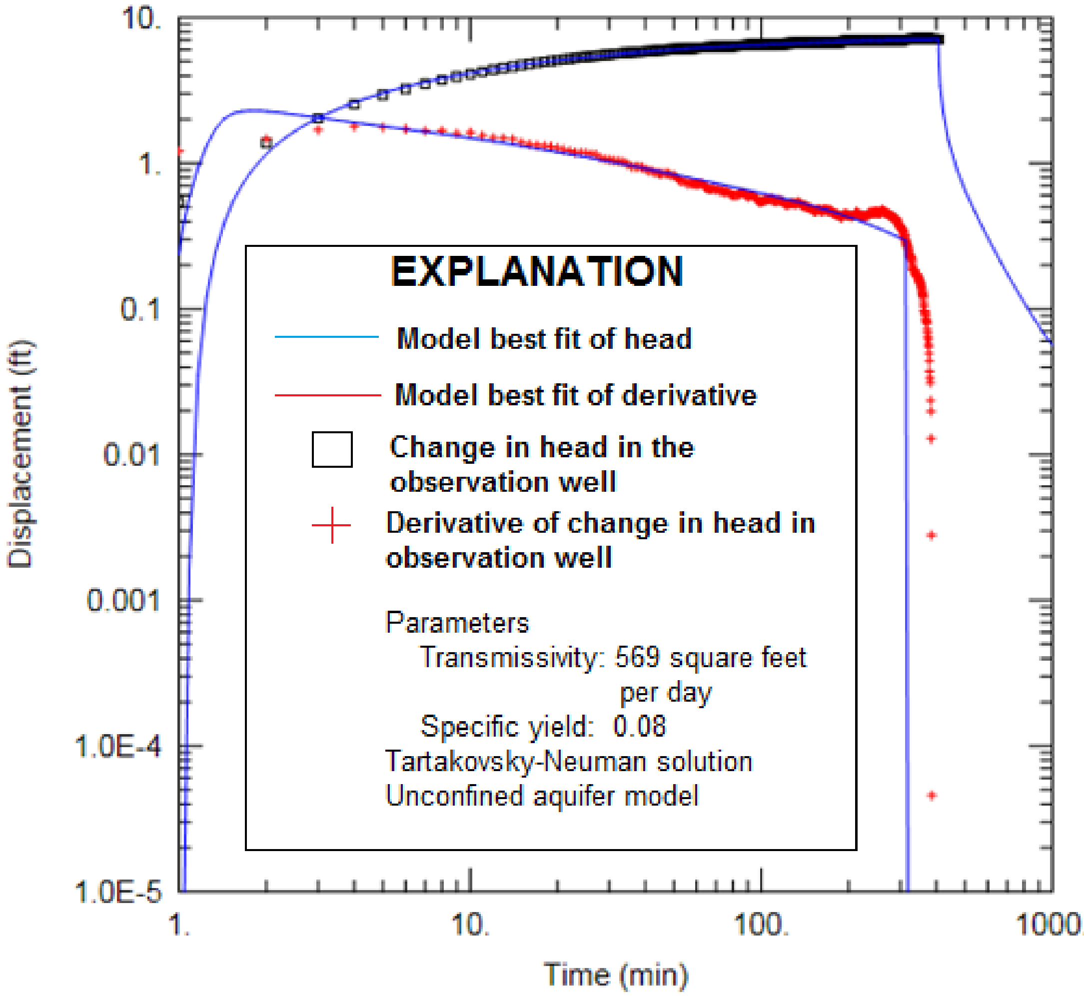


Figure 31. Water-level displacement and derivative curve data from the observation well during a multi-well aquifer test in the Elk City Sandstone aquifer.

hydraulic gradient (Schwartz and Zhang, 2003). In this report, transmissivity values are expressed in square feet per day. In unconfined groundwater systems like the Elk City Sandstone aquifer, water is released from the aquifer matrix by gravity drainage. Specific yield is the ratio of the volume of water that drains from a saturated rock as a result of gravity to the total volume of rock (Fetter, 2001).

Multiple methods were utilized to estimate values of hydraulic conductivity, transmissivity, and specific yield of the Elk City Sandstone aquifer and included slug tests, drawdown tests performed by well drillers, a multi-well pumping test, and a percent coarse method (Mashburn and others, 2014; Ellis and others, 2016; Neel and others, 2018; Christenson and others, 2011). In addition, a regional method to determine specific yield was.

Slug Tests

Slug tests are groundwater well tests for determining the hydraulic conductivity of the aquifer near the well and the connectivity of the well to the aquifer. Slug tests were performed in selected wells using a solid PVC cylinder (slug) of known volume to initiate an instantaneous change in water level and using a data logger to measure depth to water every 0.5 seconds during the return to static water-level conditions.

Slug tests were performed on wells in the Elk City Sandstone aquifer using the procedures of Cunningham and Schalk (2011); 31 wells had drawdown data that met quality control analysis to ensure the wells were in good communication with the aquifer (Figure 1). At least two slug tests were performed at each well; a falling-head slug test began when the slug was inserted into the water column, displacing water upward and measuring the return to static water-level and a subsequent rising-head slug test began when the slug was taken out of the water column, causing the water column to fall and measuring the return to static water-level conditions. When possible, two or three different sized slugs were used at each site, and a falling-head and rising-head test was performed on each size. The response of the water levels to the slug tests were normalized by slug size and expected displacement and the best slug test from each site was selected to represent that site based on actual response of the well versus expected response and the smoothness of the recovery (Butler, 1997). Selected slug tests were analyzed using AQTESOLV software (Duffield, 2007). Tests with initial displacement values closest to expected displacement were used. Two models were used to analyze the slug test data in AQTESOLV based on site conditions for each well: the Bouwer and Rice (1976) unconfined model and the Hyder and others (1994) unconfined model. Analysis of the slug test data indicated hydraulic conductivity ranges from 0.2 feet per day to 9.8 feet per day. The mean hydraulic conductivity was 2.6 feet per day, and the median hydraulic conductivity was 1.9 feet per day.

Multi-Well Aquifer Test

As part of this study, a multi-well aquifer test was performed on public water supply wells operated by Beckham County Rural Water District (RWD) #3 to estimate transmissivity, horizontal hydraulic conductivity, and specific yield of the Elk City Sandstone aquifer. The production well for Beckham County RWD #3 (OWRB 138195), which was used as the pumping well, had a 30-inch borehole with a fine-gravel filter pack from 22.5 feet to 210 feet and was cased with 12-inch PVC to a total depth of 210 feet below land surface. The 12-inch-diameter PVC casing was factory slotted (0.03 inches) from depths of 110 feet to 150 feet and 190 feet to 210 feet below land surface. The observation well (OWRB 94485), approximately 55 feet to the west, was completed to a total depth of 218 feet below land surface. The observation-well borehole was 12.25 inches in diameter and was -completed with a 6 –inch diameter PVC casing. The PVC casing was factory slotted at 0.02 inches from 98 to 138 feet and 178 to 218 feet below land surface. Initial depth-to-water in the observation well was 49.06 feet. The multi-well pumping test was initiated by starting the pump on May 17, 2017 at 10:57 PM at an initial rate of 33 gallons per minute. Depth-to-water measurements were collected at one-minute intervals using an In-Situ Level-Troll 500 probe during pumping and recovery. The pump was shut off, ending the test at 3:43 AM on May 18, 2017. Pumping was approximately 6 hours and 46 minutes after which time the observation well reached a maximum water-level displacement of 7.11 feet (**Figure 30**).

The AQTESOLV software package (Duffield, 2007) was used to analyze the water-level displacement data from the observation well. The solution with the best visual curve match for the pumping period was the Tartakovsky and Neuman (2007) solution. The Tartakovsky and Neuman (2007) solution was derived for unsteady flow to fully or partially penetrating wells under homogeneous, anisotropic conditions with delayed gravity response and allowed for non-instantaneous drainage at the water table (Duffield, 2007). The predominant lithology within the slotted intervals of the pumping and observation wells was sandstone, and vertical flow was assumed to be limited by silt and clay zones of the Elk City Sandstone (Kent and others, 1982); the 30-inch borehole diameter resulted in a strong wellbore storage component in the pumping well. The Tartakovsky and Neuman (2007) solution for the pumping period estimated a transmissivity of 569 square feet per day and a specific yield of 0.08 (**Figure 31**). The pumping well was not open to obtain a water-level reading, so a saturated thickness of 167 feet was obtained from the well driller lithology log for the pumping well and used to calculate a horizontal hydraulic conductivity of 3.4 feet per day using the equation:

$$T=Kb$$

where

T	is the transmissivity of the aquifer near the pumping well (ft²/day)
K	is the hydraulic conductivity near the pumping well (feet per day)
b	is the total saturated thickness of the aquifer at the pumping well (ft)

Regional Method for Estimating Specific Yield

Regional methods can be used to characterize aquifers using hydrologic data at coarse scales (Neel and others, 2018; Christenson and others, 2011). The regional method for estimating specific yield as described in this report uses base-flow discharge and monthly groundwater-level measurements from November 2015 to March 2017. The regional method has been used to provide an estimate of storage over an entire subsurface watershed within an aquifer (Schilling, 2009) including aquifer characterizations in Oklahoma (Christenson and others, 2011; Neel and others, 2018).

An equation to estimate the specific yield can be derived from the concept that base flow is often considered a proxy for diffuse recharge in subsurface watersheds with gaining streams (Scanlon and others, 2002, Risser and others, 2005). The water-table fluctuation method of calculating recharge (Healy and Cook, 2002) defines a relationship between specific yield, the change in the depth to water over time, and recharge. If base flow is substituted for recharge, and little to no recharge occurs, then the base flow in a stream is the water being released from storage, an equation can be written as follows:

$$S_y = Q_b/\Delta DTW$$

Table 10. Specific yield calculated from streamflows and change in water stored in subsurface watersheds, 2016-2017.

Subsurface watershed	Subsurface watershed area (acres)	Period of analysis	Total base flow based on daily gaged flow (acre-feet)	Volume of aquifer drained in subsurface watersheds (acre-feet)	Mean water level decline (feet)	Estimated specific yield (dimensionless) for the period	Mean estimated specific yield (dimensionless)
Buffalo Creek	16,768	January 2016 - February 2016	279	2,515	0.15	0.111	0.10
		December 2016 - January 2017	99.5	1,174	0.07	0.085	
		January 2017 - February 2017	127	1,341	0.08	0.095	
		February 2017 - March 2017	144	1,509	0.09	0.095	
Little Elk Creek	15,360	June 2016 - July 2016	107	2,764	0.18	0.039	0.06
		October 2016 - November 2016	118	1,229	0.08	0.096	
		November 2016 - December 2016	216	3,227	0.21	0.067	
Trail Creek	19,520	June 2016 - July 2016	173	2,538	0.13	0.068	0.07
		July 2016 - August 2016	204	5,075	0.26	0.040	
		November 2016 - December 2016	611	6,637	0.34	0.092	

where

S_y is the specific yield (dimensionless)

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

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

To utilize this method, the OWRB installed streamflow gauging stations on Buffalo, Little Elk, and Trail creeks as described in the Streamflow section of this report. The streamflow gauging stations were located near the boundary of the Elk City Sandstone and the Doxey Shale to quantify base-flows draining from the Elk City Sandstone. These gauges defined the lower reaches for each subsurface watershed with the contributing groundwater area upgradient from each gauge. To estimate the total volume of groundwater gained or lost from each subsurface watershed defined by each streamflow gauging station, the boundaries of each subsurface basin were delineated (**Figure 15**). The subsurface watershed for each basin was defined as the area of aquifer that contributes base flow to each stream and was determined using the potentiometric surface and identifying the local groundwater divides that separate each subsurface watershed. The Buffalo Creek subsurface watershed is 26.2 square miles, the Little Elk Creek subsurface watershed is 24.0 square miles, and the Trail Creek subsurface watershed is 30.5 square miles.

The regional method for estimating specific yield was used in the Elk City Sandstone aquifer for selected periods between November 2015 and March 2017 (**Table 10**). The method was initially planned to be used only through March 2016, but aquifer recharge occurred throughout the months of November 2015 to March 2016, as seen in continuous recorder data (**Figure 14**), resulting in rising groundwater levels in most of the aquifer, making this method unusable for that period as the assumption of minimal recharge was not met. Groundwater-level measurements were collected monthly through March 2017 to capture additional data to allow the analysis to be adequately utilized. Water use in the subsurface watersheds was mostly sparse leading to the assumption that summer months with little to no recharge may also be acceptable to use for the analysis. Summer months will likely have increased evapotranspiration, which may affect the base flows recorded at streamflow gauging stations, but since the basins did not have many large farms or forested areas, it was assumed those inputs may be less impactful in these areas than in areas with more vegetation. Recharge to the aquifer, or lack thereof, was observed by analyzing hourly depth-to-water measurements recorded in nearby wells with continuous recorders and reviewing precipitation data from the nearest climate station (**Table 1**, **Figure 1**). The following timeframes were selected for this analysis: January 2016-February 2016, December 2017-January 2018, January 2017-February 2017, and February 2017-March 2017 for the Buffalo Creek subsurface watershed; June 2016-July 2016, October 2016-November 2016, and November 2016-December 2016 for the Little Elk Creek subsurface watershed; and June 2016-July 2016, July 2016-August 2016, and November 2016-December 2016 for the Trail Creek subsurface watershed.

Forty-nine wells were located in the three subsurface watersheds: 22 in the Buffalo Creek subsurface watershed, 14 in the Little Elk Creek subsurface watershed, and 13 in the Trail Creek subsurface watershed. This method uses the base-flow discharge estimated using base-flow separation from the daily streamflow measurements and the monthly change in groundwater levels to estimate an averaged specific yield value for each of these subsurface watersheds within the Elk City Sandstone aquifer. The regional method for estimating specific yield assumes that if an aquifer is not being recharged during a specific time, “but is only draining, the ratio of the volume of groundwater discharged to the volume of the aquifer drained is the storage coefficient (or specific yield as in this aquifer) for that volume of aquifer drained” (Christenson and others, 2011). This method is best used when aquifer recharge and water use are minimal, which is usually during the winter months in the study area. A limitation of this method is that it only estimates the storage in the small portion of the aquifer that was drained by lowering the water table from month-to-month. However, compared to using multi-well pumping tests to provide estimates of specific yield, the spatial area being analyzed in the regional method is much larger than the area of influence around wells tested in a multi-well pumping test and may provide a better estimate of specific yield over the entire basin.

For this analysis, water-level declines were observed throughout each subsurface watershed during each month analyzed. The Buffalo, Little Elk, and Trail creek subsurface watersheds had a mean water-level decline of 0.10, 0.16, and 0.24 feet, respectively, for the selected periods.

The volume of aquifer drained in each subsurface watershed was estimated by finding the mean water-level change in each subsurface watershed. The volume of water drained was the base-flow component as computed by the BFI program for each streamflow gauging station. Dividing the volume of water drained by the area of the subsurface watershed and multiplying by the amount of water-level decline gave monthly specific yield estimates for each subsurface watershed and ranged from 0.04 to 0.11 (**Table 10**). Mean specific yield values of 0.10, 0.06, and 0.07 were estimated for the Buffalo, Little Elk, and Trail creek subsurface watersheds. Previous work (Kent and others, 1982) estimated a specific yield for the Elk City Sandstone aquifer of 0.15, which was based off of literature values not derived from field investigations in the aquifer.

Percent-Coarse Analysis

A percent-coarse analysis method was used to estimate horizontal hydraulic conductivity, vertical hydraulic conductivity, and specific yield for the Elk City Sandstone aquifer. This method was used to estimate horizontal hydraulic conductivity and specific yield in previous hydrologic investigations of Oklahoma’s aquifers by the OWRB (Neel and others, 2018, Sanford, manuscript submitted for review) and adapted from the USGS method used in Oklahoma (Mashburn and others, 2014; Ellis and others, 2016; Smith and others, 2017) and utilizes lithologic descriptions in groundwater well driller’s logs. Results from this method were included among other inputs for horizontal hydraulic conductivity and specific yield for the USGS groundwater-flow model of the Rush Springs aquifer (Ellis, 2018). While specific yield depends on grain sorting and cementation of the aquifer (Cohen, 1963, Ellis, 2018), which are textural properties that are often not well derived from lithologic logs, specific yield values used in the Rush Springs aquifer model agreed with the results of this method (Ellis, 2018).

Groundwater well driller logs were compiled from 1,639 groundwater well and test hole sites across the Elk City Sandstone aquifer (**Figure 32**). Based on a review of these logs, 121 basic lithologic categories were identified: clay, fine sandstone, medium sand, topsoil, fine sand, medium sandstone, coarse sand, coarse sandstone, silt, siltstone, loess, and gravel (**Table 11**). Slug, drawdown, and multi-well aquifer tests were used to determine horizontal hydraulic conductivity values for each lithologic interval and cross referenced with published hydraulic conductivity ranges (Morris and Johnson, 1967; Freeze and Cherry, 1979; Domenico and Schwartz, 1998; Fetter, 2001). The slug and multi-well aquifer tests may have a horizontal hydraulic conductivity value that represents the coarser-grained lithologies and will not provide an estimate for finer-grained lithologies like clay and silt. Values for lithologies not characterized by slug tests or the multi-well pumping test were assigned from the literature references. Assigned values for each lithologic interval were weighted by thickness and used to calculate the mean specific yield and

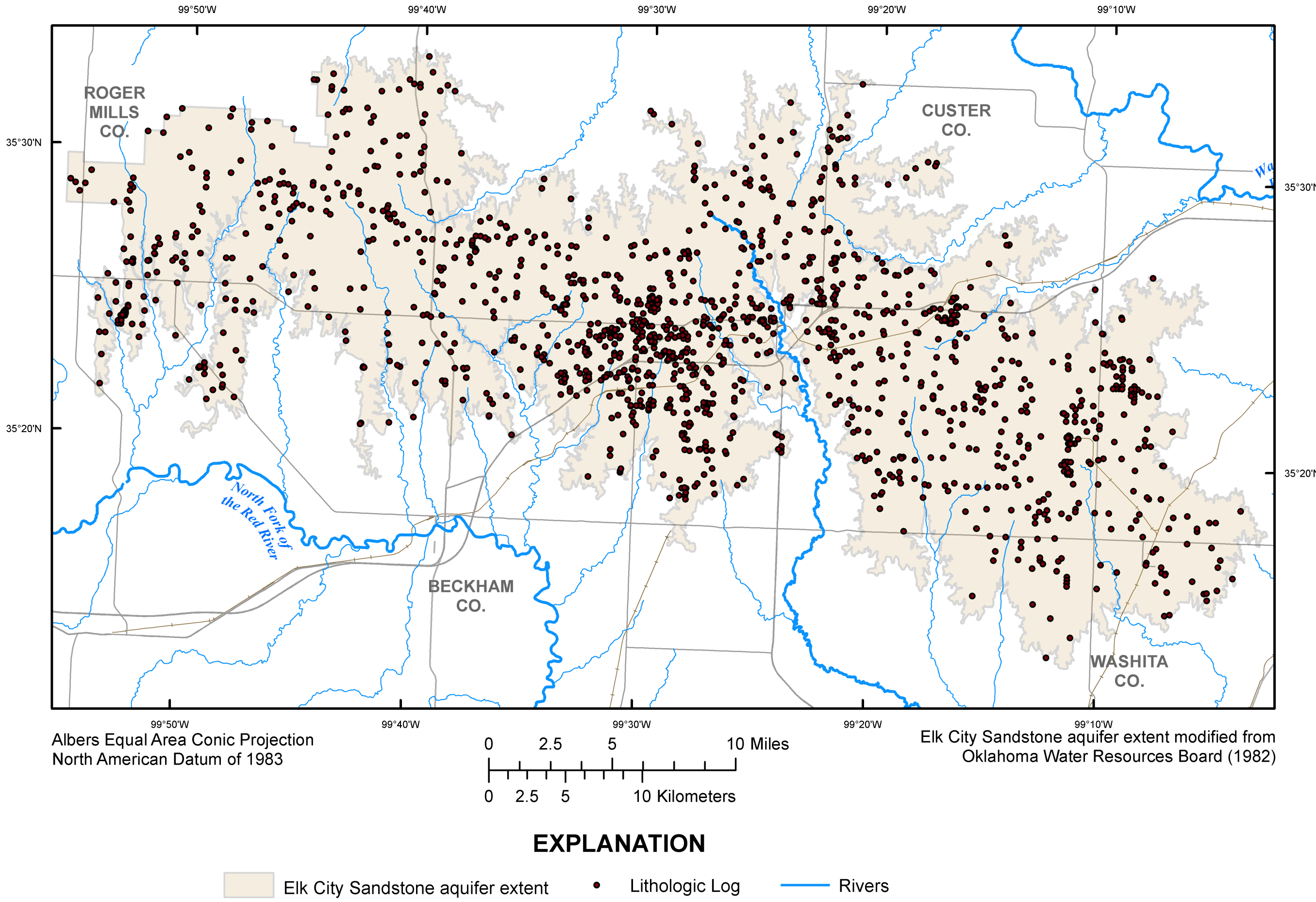


Figure 32. Groundwater wells with lithologic descriptions used in the percent-coarse analysis of the Elk City Sandstone aquifer.

Table 11. Standardized lithologic categories and estimated specific yield and horizontal hydraulic conductivity from lithologic logs in the Elk City Sandstone aquifer.

Lithologic distribution

Lithology	Distribution Within the Elk City Sandstone	Horizontal Hydraulic Conductivity in feet per day
Clay	26.15%	0.000
Fine sandstone	24.10%	0.1
Medium sand	14.56%	4
Topsoil	10.56%	6
Fine sand	9.19%	2
Medium sandstone	8.35%	1
Coarse sand	2.17%	50
Coarse sandstone	1.70%	5
Silt	1.25%	0.04
Siltstone	1.14%	0.000
Loess	0.56%	0.26
Gravel	0.27%	300

Table 12. Summary statistics show the count, minimum, maximum, mean, 25th percentile, 50th percentile, 75th percentile, and area-weighted mean values for hydraulic conductivity, in feet per day, derived from slug tests, drawdown analysis, and percent coarse analysis.

Horizontal hydraulic conductivity (feet per day)			
Statistic	**Percent Coarse**	**Slug Test**	**Drawdown Test**
Count	1,639	33	46
Mean	2.8	2.6	2.7
Standard Deviation	8.4	2.5	3.2
Minimum	$1x10^{-4}$	0.2	0.4
25th Percentile	0.5	1	0.9
75th Percentile	2.2	2.9	3.1
50th Percentile	1.2	1.9	1.5
Maximum	98.9	9.8	15.3
Range	98.9	9.6	14.9

Vertical hydraulic conductivity (feet per day)			
Statistic	**Percent Coarse**	**Slug Test**	**Drawdown Test**
Count	1,639	--	--
Mean	0.6	--	--
Standard Deviation	4.4	--	--
Minimum	0.000	--	--
25th Percentile	0.000	--	--
50th Percentile	0.002	--	--
75th Percentile	1	--	--
Maximum	165	--	--
Range	165	--	--

Specific Yield (dimensionless)			
Statistic	**Percent Coarse**	**Slug Test**	**Drawdown Test**
Count	1,639	--	--
Mean	0.08	--	--
Standard Deviation	0.05	--	--
Minimum	0.01	--	--
25th Percentile	0.10	--	--
50th Percentile	0.07	--	--
75th Percentile	0.05	--	--
Maximum	0.33	--	--
Range	0.32	--	--

Multi-well aquifer test: Beckham County RWD #3	
Specific Yield (dimensionless)	0.08
Hydraulic conductivity (feet per day)	3.4
Transmissivity (square feet per day)	569.3

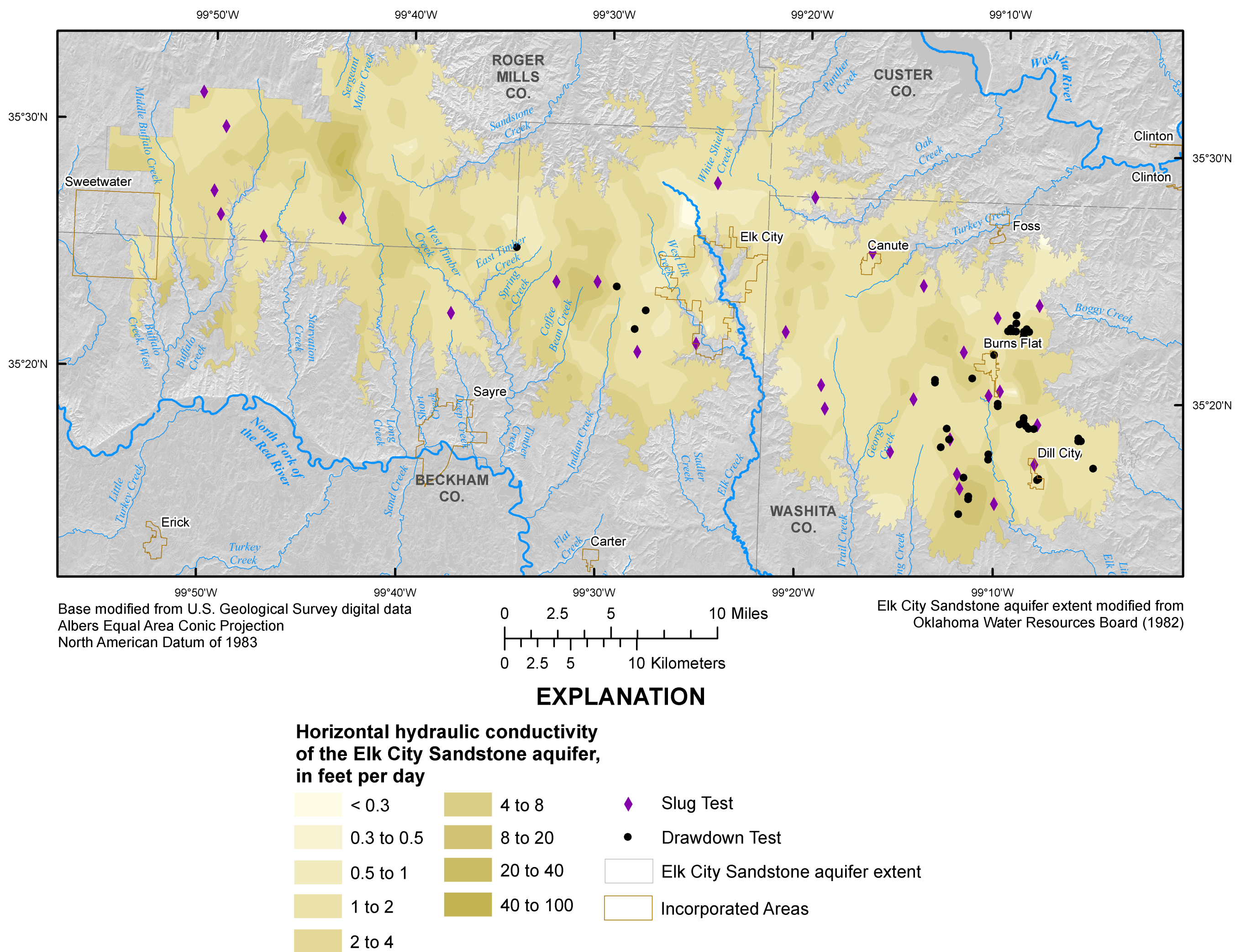


Figure 33. Horizontal hydraulic conductivity of the Elk City Sandstone aquifer based on percent-coarse analysis of lithologic descriptions from 1,639 well logs.

mean hydraulic conductivity values for the aquifer at the well location using the following equations for horizontal (equation 1) and vertical (equation 2) hydraulic conductivity (Todd, 1980):

$$1)\quad K_h = \frac{\sum_{i=1}^{M} b_i K_i}{\sum_{i=1}^{M} b_i}$$

$$2)\quad K_v = \frac{\sum_{i=1}^{M} b_i}{\sum_{i=1}^{M} (b_i/K_i)}$$

Where,

K_h is the mean horizontal hydraulic conductivity (feet per day)

K_v is the mean vertical hydraulic conductivity (feet per day)

b_i is the thickness of the discrete lithology interval (feet)

K_i is the assigned hydraulic conductivity value for a lithology interval (feet per day)

Estimated values of mean horizontal hydraulic conductivity for wells ranged from 1x10-4 to 98.9 feet per day with a mean value of 2.8 feet per day, a median of 1.2 feet per day, and a standard deviation of 8.4. Estimated values of mean

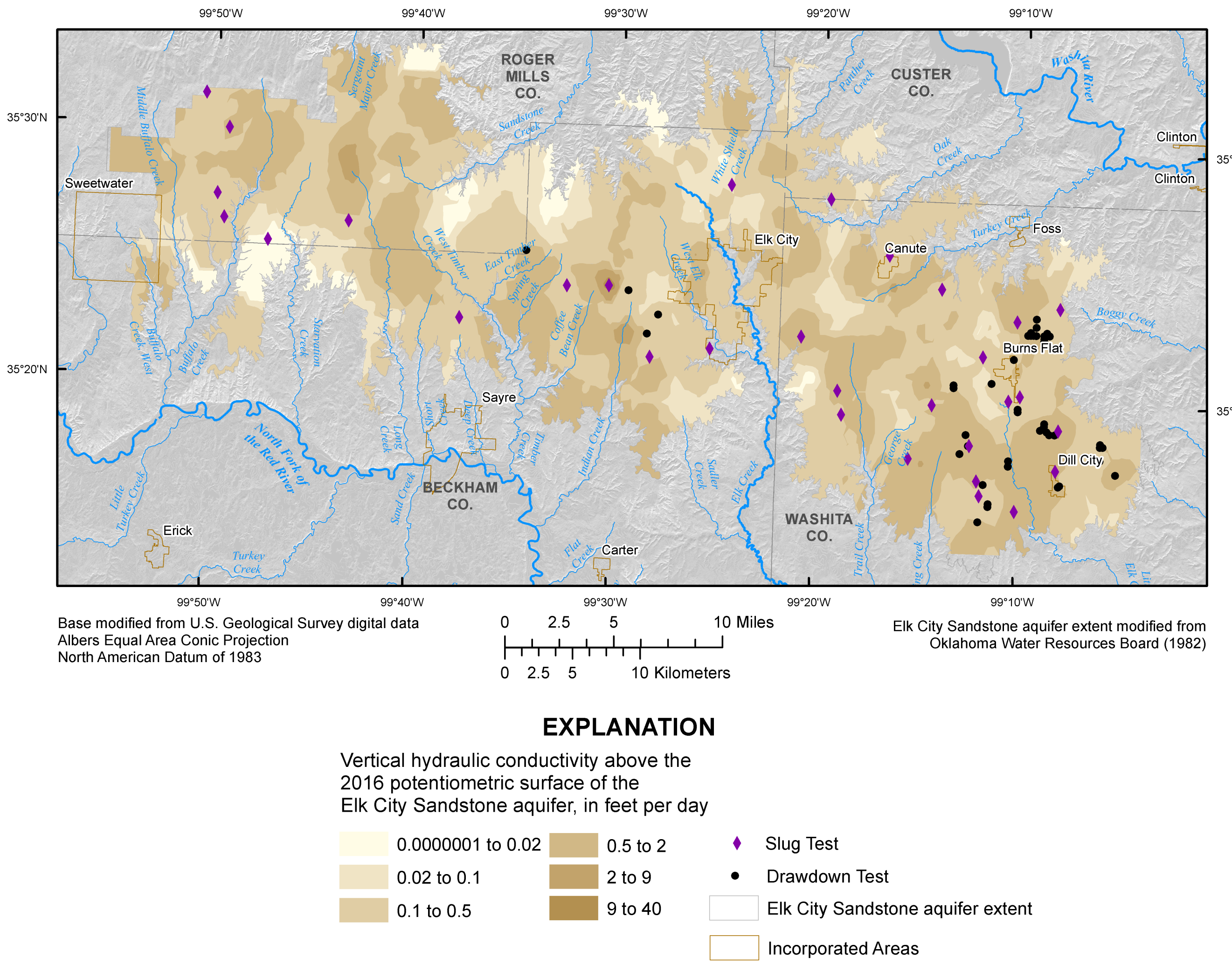


Figure 34. Vertical hydraulic conductivity of the portion of the Elk City Sandstone aquifer above the 2016 potentiometric surface, based on percent-coarse analysis of lithologic descriptions from 1,639 well logs.

vertical hydraulic conductivity ranged from 1x10-40.6 and a median of 0.002 and a standard deviation of 4.4. (**Table 12**). Vertical hydraulic conductivity is dominated more by fine-grained sediment like clays and silts than horizontal hydraulic conductivity because the fine-grained material significantly slows the downward migration of water (Harbaugh and others, 2000; Todd, 1980).

There is local hydraulic variability in areas near tributaries along the southern boundary near Dill City where shale, siltstone, and clay stringers are less prevalent, resulting in higher horizontal hydraulic conductivity values (**Figure 33**). Maps of horizontal and vertical hydraulic conductivity were created in ArcGIS using the mean conductivity values for each well and using a kriging interpolation cut to the boundary of the Elk City Sandstone aquifer.

Higher horizontal hydraulic conductivity values are also present in the central portion of the aquifer five miles west of Elk City, mostly from quaternary gravel deposits assumed to be in hydraulic connection with the underlying Elk City Sandstone. Another area of higher horizontal hydraulic conductivity is in the northwest portion of the aquifer near Cheyenne. However, a limited number of wells in the area with lithologic descriptions leaves some uncertainty about how large that area extends. Areas of lower horizontal hydraulic conductivity in the west and southwest portions of the aquifer east of Sweetwater, and in the north-central portion of the aquifer north of Elk City, match with field observations of finer grained material with more silt and clay than in the areas with higher horizontal conductivity estimates.

Vertical hydraulic conductivity was estimated for the Elk City Sandstone thickness above the 2016 potentiometric surface to assess areas with a greater potential for quick recharge to the aquifer. These estimates were compared to SWB recharge estimates as well as continuous water-level records to determine if any correlation exists between wells with a more rapid water-level response to recharge and areas of higher mapped vertical hydraulic conductivity. Maps of the vertical hydraulic conductivity (**Figure 34**) and SWB recharge

(**Figure 26**) show similar trends. Both maps show above mean values in the eastern lobe of the Elk City Sandstone and in an area just west of Elk City and the northwest portion of the study area, and below mean values in the middle portion near Burns Flat and to the southwest and along the northern-central boundary.

Water-level response to recharge at continuous water-level recorder sites in the Elk City Sandstone aquifer (Figure 10) was compared to the map of vertical hydraulic conductivity to determine if vertical hydraulic conductivity could be used to estimate whether an area will experience faster or slower recharge of the water table. Some wells in areas of higher vertical hydraulic conductivity did show faster water-level response (OWRB 166421, OWRB 26822) and some wells in areas of lower vertical hydraulic conductivity showed slower water-level response (OWRB 166752, OWRB 168998). However, these responses can also be caused by shallow depth to water as the wells with faster responses are under 20 feet to water and one of the wells with slower response is over 70 feet to water. Two wells (OWRB 166752 and OWRB 166421) with similar depths to water and different response times to recharge showed that the well with a higher mapped vertical hydraulic conductivity (OWRB 166421) had a more rapid response than the well with lower mapped vertical hydraulic conductivity (OWRB 166752). The connection between mapped vertical hydraulic conductivity and water-level response is not as well observed in other wells in the aquifer, however. OWRB 166435 is mapped in an area of higher conductivity but shows a slower response to recharge than OWRB 39831, in an area of lower conductivity. OWRB 118010 is also in an area of higher conductivity but also shows a slower response to precipitation than OWRB 20828, in an area with lower conductivity, and both wells have similar depths to water. One potential explanation for OWRB 20828 having a more rapid response to water levels might be that it is located on an old military base, near the runway and the natural state around the well may have been changed by a number of excavations that took place while the base was active (C. Smith, personal communication, January 15, 2015). Overall, there is not good correlation between the mapped vertical hydraulic conductivity and response of water levels to recharge, but the scale of creating an aquifer-wide map based on well log descriptions may be too large to pinpoint water-level response in single wells.

Analysis of Drawdown Data From Specific Capacity Tests

Drawdown data from specific capacity tests of 46 wells performed by well drillers the Elk City Sandstone aquifer were compiled from completion reports submitted to the OWRB and used to estimate hydraulic conductivity of the aquifer materials near the well. These data included the screened interval, static water level, amount of drawdown from pumping, rate of pumping, duration of pumping, and well radius. Drawdown data had to meet two criteria to be considered in this analysis: 1.) the well had to be completed and screened only within the Elk City Sandstone aquifer and 2.) the pumping duration of the test performed by the well driller had to be a minimum of six hours to ensure the test represented the hydraulic properties of the aquifer matrix. The hydraulic conductivity for each well location was estimated using an equation based on the Cooper and Jacob (1946) solution, which was derived from the Theis (1935) nonequilibrium method, and utilized type curves described by Jacob (1940), Wenzel and Fishel (1942), and Wenzel and Greenlee (1944). The Cooper and Jacob (1946) equation is:

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

Where,

Q is discharge rate the well was pumped (ft3/day),

S_w is the total length of equilibrated drawdown (ft),

T is the transmissivity of the aquifer near the well (ft2/day),

t is time (days),

S is the storativity of the aquifer (dimensionless), and

r_w is the well radius.

To solve for transmissivity the Cooper and Jacob (1946) equation can be written as follows:

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

Because transmissivity is in the logarithm term of the equation, successive approximation may be used to solve for transmissivity. Transmissivity may then be used to determine hydraulic conductivity:

$$T=Kb$$

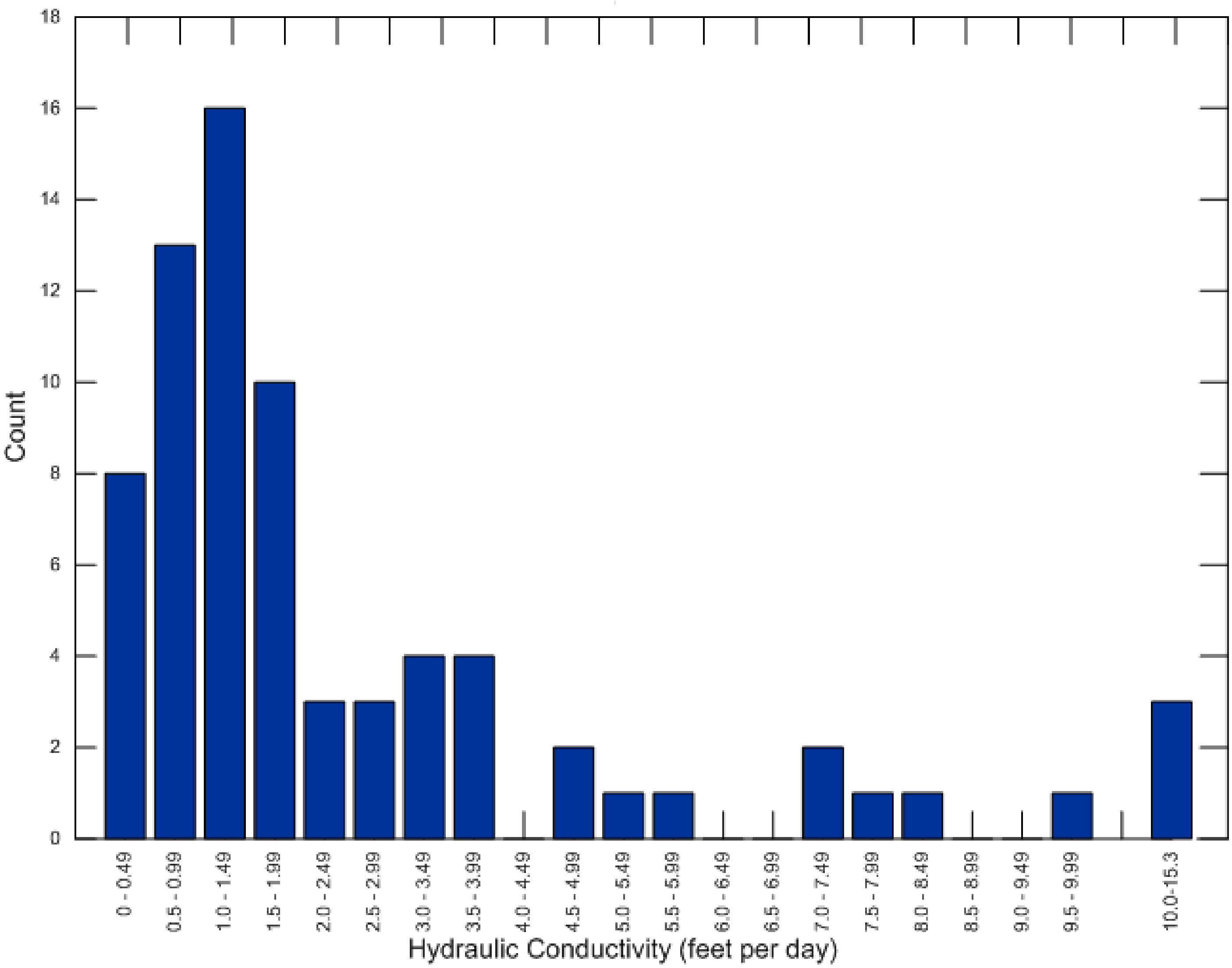


Figure 35. Horizontal hydraulic conductivity distribution of slug tests and drawdown data.

Where,

K is the hydraulic conductivity of the aquifer near the well (feet per day)

b is the saturated thickness of the aquifer (ft), or the base of the aquifer minus the static water level

The storativity, which is equivalent to specific yield in unconfined aquifers, was 0.08 and was derived from the regional method, multi-well pumping test method, and the percent coarse method.

Most of the usable drawdown data were from wells located in the eastern half of the aquifer; only four wells located in the central portion and no wells in the western portion of the aquifer had usable drawdown data. The minimum horizontal hydraulic conductivity estimated from the drawdown data was 0.4 feet per day and the maximum was 15.3 feet per day (**Table 12**). The median was 1.5 feet per day and the mean was 2.7 feet per day. The mean is slightly higher than the median, indicating that there are some higher horizontal hydraulic conductivity outliers in the dataset. The area of highest horizontal hydraulic conductivity occurs in the Little Elk Creek watershed where values range from 2.6 feet per day to 15.3 feet per day with a mean of 7.1 feet per day.

Comparing the drawdown and slug test datasets (**Table 12**), estimated horizontal hydraulic conductivity is within the range of published values for a sandstone aquifer (Domenico and Schwartz, 1998). Estimated horizontal hydraulic conductivity of sandstone ranges from less than 0.01 feet per day to 1.70 feet per day, and the range for unconsolidated sand is between 0.26 feet per day to 141 feet per day. Other publications estimated horizontal hydraulic conductivities for sandstone to range between 0.66 feet per day to 10.17 feet per day (Morris and Johnson, 1967). The ranges of horizontal hydraulic conductivity identified in the drawdown data and slug tests indicate that some portions of the Elk City Sandstone aquifer are texturally consistent with coarse-grained sandstone, poorly cemented sandstone, or unconsolidated material. The distribution of horizontal hydraulic conductivity on a histogram plot shows a right-skewed distribution, which is expected, with the mean much higher than the median (**Figure 35**).

Leakage from the Ogallala-Roger Mills aquifer

The Ogallala Formation, which forms the Ogallala-Roger Mills aquifer in the study area, overlies 43.9 square miles in the northwest portion of the Elk City Sandstone aquifer. To assess whether the two geologic units are in hydrologic communication, a water budget for the portion of the Ogallala Formation overlying the Elk City Sandstone aquifer was made using base flow estimated from streamflow measurements taken on December 27, 2017, reported groundwater use for 2017-18, and recharge estimated for the Ogallala-Roger Mills aquifer (Sanford, unpublished) in 2017-18. Two continuous water-level recorders were installed in wells completed in the Ogallala-Roger Mills aquifer where it overlies the Elk City Sandstone (OWRB 25326 and OWRB 81942) to determine water-level stability. A notable limitation of this method is the assumption that mean base flow in 2017 for these streams is represented by the measurements made on December 27, 2017.

Base flow was estimated in Sergeant Major, Sandstone, Buffalo, and Middle Buffalo creeks on December 22, 2017, when the creeks were under base flow conditions. Based on those measurements from that single point in time, these creeks were estimated to have a combined base flow of 2.3 cubic feet per second, which would equal 1,666 acre-feet per year if that value was the mean annual base flow. This is estimate is very rough because no streamflow gauging stations exist on these creeks, no other data existed to analyze. Permitted groundwater use from 2017-18 in this portion of the Ogallala-Roger Mills aquifer averaged 95.1 acre-feet per year, and 2017-18 recharge averaged 3,477 acre-feet per year. The portion of the Ogallala Formation overlying the Elk City Sandstone aquifer spans a groundwater divide with water flowing both north and south. While the groundwater divide does not perfectly fit the northern border of the Elk City Sandstone aquifer in the area, it does very closely follow the boundary, so for this analysis, the boundary line is considered equal to the groundwater divide. The scale and timing of the Ogallala-Roger Mills potentiometric surface, which was created using water levels taken in 2018, create enough uncertainty to be exact. Because of this setting, little to no groundwater would be flowing into the area from other parts of the Ogallala-Roger Mills aquifer. Therefore, the total inflows to this portion of the Ogallala-Roger Mills aquifer were assumed to be entirely from recharge, and the total outflows from this portion of the aquifer were assumed to be entirely to base flow, leakage to the underlying Elk City Sandstone aquifer, and groundwater use. Total outflows from the aquifer were estimated to be 1,761 acre-feet per year while total inflows were estimated to be 3,477 acre-feet per year, leaving a surplus of 1,716 acre-feet per year. Water levels in the two continuous recorder wells were relatively stable throughout the monitoring period of December 2016 to December 2018, and the change in storage in the Ogallala-Roger Mills aquifer was assumed to be zero acre-feet per year. According to the contours of the potentiometric surface map in the Ogallala-Roger Mills aquifer (Sanford, manuscript submitted for review) and observations of the surface drainage, all groundwater in the overlapping area moves toward the aquifer edge, not north into the main body of the Ogallala-Roger Mills aquifer. Since groundwater levels remain constant, despite a net surplus, the only option for groundwater to flow is into the Elk City Sandstone below the Ogallala Formation. Assuming the 1,716 acre-feet per year surplus is infiltrating into the Elk City Sandstone, that equates to 4.7 acre-feet per day over the 43.9 square miles (28,096 acres) of Ogallala Formation overlying the Elk City Sandstone aquifer, or 1.67 x 10-4 feet per day, meaning that while there is enough flux between the units to accommodate the excess water, the difference in hydraulic conductivity between the more permeable Ogallala Formation and the less permeable Elk City Sandstone results in a type of aquitard for the downward migration of water from the Ogallala-Roger Mills aquifer. This allows the saturated thickness of the Ogallala-Roger Mills aquifer to largely stay constant in the area, while providing some recharge to the Elk City Sandstone.

All methods produced similar estimations for horizontal hydraulic conductivity and specific yield with aquifer-wide estimations of mean horizontal hydraulic conductivity ranging between 2.6 feet per day to 2.8 feet per day and a multi-well pumping test west of the city of Elk City estimate of 3.4 feet per day. Specific yield estimations from percent-coarse analysis, multi-well pumping tests, and regional methods were similar with values ranging from 0.07 to 0.10. With a mean saturated thickness of 56 feet (see Aquifer Saturated Thickness) and a mean horizontal hydraulic conductivity of 2.8 feet per day, estimated transmissivity over the aquifer is 156.8 square feet per day. Previous literature (Palmquist and Koopman, 1964; Kent and others, 1982) supports current findings for the average horizontal hydraulic conductivity. Estimations of horizontal hydraulic conductivity and specific yield for the Elk City Sandstone aquifer are similar to published values for the nearby Rush Springs aquifer (Neel and others, 2018).

Slug test data are typically collected from existing wells that become less efficient over time because of silt or mineralization progressively obstructing the well screen resulting in slug tests potentially underestimating horizontal hydraulic conductivity (Butler and Healy, 1998). In addition, the hydraulic conductivity estimate from a drawdown test is, on average, considerably larger than the estimate obtained from a series of slug tests in the same formation, and these differences can be caused by incomplete well development (Butler and Healy, 1998). While a greater difference between slug tests and drawdown tests was observed in the OWRB hydrologic investigation of the Rush Springs aquifer (Neel and others, 2018), the difference between the two techniques was much smaller in this investigation. This may be a result of only using wells with six or more hours of drawdown data, which should have led to an increased reliability of the results or may be caused by the smaller number of both slug tests and drawdown tests in this study resulting in a closer distribution randomly. The slightly lower median horizontal hydraulic conductivity of the percent-sand compared to the slug tests and drawdown tests is likely caused by the large number of wells used in the percent-coarse analysis accounting for different lithologies in parts of the aquifer where no slug or drawdown test was performed, especially the west-central portion of the aquifer, which had more areas of lower than mean horizontal hydraulic conductivity.

The remnant of a buried channel exists in the central area which trends south-southeast and consists of coarse alluvial sediments with a maximum thickness of 65 feet (Palmquist and Koopman, 1964). Areas of high horizontal hydraulic conductivity in the southeast portion of the Elk City Sandstone aquifer could also be caused by the deposition of buried alluvial channels. The shape of the erosional top of the Doxey Shale as seen in cross sections D-D' (**Figure 21**) and E-E' (**Figure 22**) indicate single or multiple incised valleys in the Doxey Shale, filled by Elk City Sandstone, evidence of possible buried alluvial channels trending in a south southeast direction in the southeast portion of the Elk City Sandstone aquifer. These paleochannels may be the result of Elk City Sandstone material reworked within the Elk Creek basin alluvium creating area of increased vertical and horizontal permeability.

The percent-coarse method, which utilized groundwater well driller's lithology logs, indicated that about 60 percent was composed of sandstone, and the remaining 40 percent was mostly shale. A previous study (Palmquist and Koopman, 1964) on the Elk City Sandstone aquifer estimated mean transmissivity at 815.5 square feet per day and specific yield at 0.14. That study determined a mean saturated thickness of 88.5 feet which would equate to an estimated mean horizontal hydraulic conductivity of 9.2 feet per day. The mean horizontal hydraulic conductivity of the four methods in this study was 2.8 feet per day, and the mean specific yield was 0.08. As the mapped area of Elk City Sandstone increased by 167,200 acres for this study as compared to previous works, the decrease in average values of horizontal hydraulic conductivity and specific yield could be attributed to this increase in aquifer area since much of the added area to the west of the original western boundary is composed of fine-grained material with lower mean horizontal hydraulic conductivity as indicated in the percent-coarse analysis (**Figure 33**).

Groundwater Quality

Groundwater Quality Sampling

Groundwater quality in an aquifer may limit groundwater use for some purposes. Groundwater-quality data were collected from 15 wells throughout the Elk City Sandstone aquifer in 2013 (**Figure 36**) (Oklahoma Water Resources Board, 2014). The groundwater samples were analyzed for selected parameters including physical properties (specific conductance, temperature, and pH), major ions, nutrients, and trace metals (**Table 13**). Groundwater from the Elk City Sandstone aquifer is suitable as drinking water with a mean total dissolved solids (TDS) of 361.2 milligrams per liter and a mean pH of 7.26 (Oklahoma Water Resources Board, 2014). TDS from the 15 groundwater samples ranged from 254 to 478 milligrams per liter with a median of 364 milligrams per liter. The highest recorded TDS value was at OWRB well 90488, in the northwest part of the aquifer where the Ogallala Formation drapes over the Elk City Sandstone aquifer (**Figure 36**). The TDS at this location was 478 milligrams per liter and could be the result of groundwater leaking from the Ogallala Formation into the Elk City Sandstone below. Mineral content of the groundwater is low to moderate, but the groundwater is hard and moderately alkaline. The most prevalent anion is bicarbonate (HCO3) with a mean concentration of 321.5 milligrams per liter, a minimum of 239 milligrams per liter, and a maximum of 394 milligrams per liter. Sulfate and chloride are the other most abundant anions present in the groundwater samples (**Table 13**). Cations calcium, magnesium, potassium, and sodium are present in all the samples at mean concentrations of 65.72, 22.85, 1.48, and 38.9 milligrams per liter, respectively. All of the samples collected in the aquifer were found to be bicarbonate type as seen in the Stiff (1951) diagrams (**Figure 36**) and the Piper (1944) plot (**Figure 37**). The diagrams are plotted showing relative concentrations in milliequivalents per liter and demonstrate the general major dissolved ions across the aquifer with the dominant anion being bicarbonate and with most waters containing a slightly higher relative concentration of calcium amongst cations, along with sodium+potassium cations with higher concentrations at several sites. Groundwater sampled throughout the aquifer ranged from 254 milligrams per liter to 478 milligrams per liter in total dissolved solids at an average temperature of 70.56 degrees Fahrenheit. The highest recorded TDS value was at OWRB well 90488, in the northwest part of the aquifer where the Ogallala Formation drapes over the Elk City Sandstone aquifer. The TDS at this location was 478 milligrams per liter and could be the result of groundwater leaking from the Ogallala Formation into the Elk City Sandstone below. The median TDS for the Ogallala-Roger Mills aquifer is 411 milligrams per liter and ranges from 232 to 1,084 milligrams per liter (Oklahoma Water Resources Board, 2002).

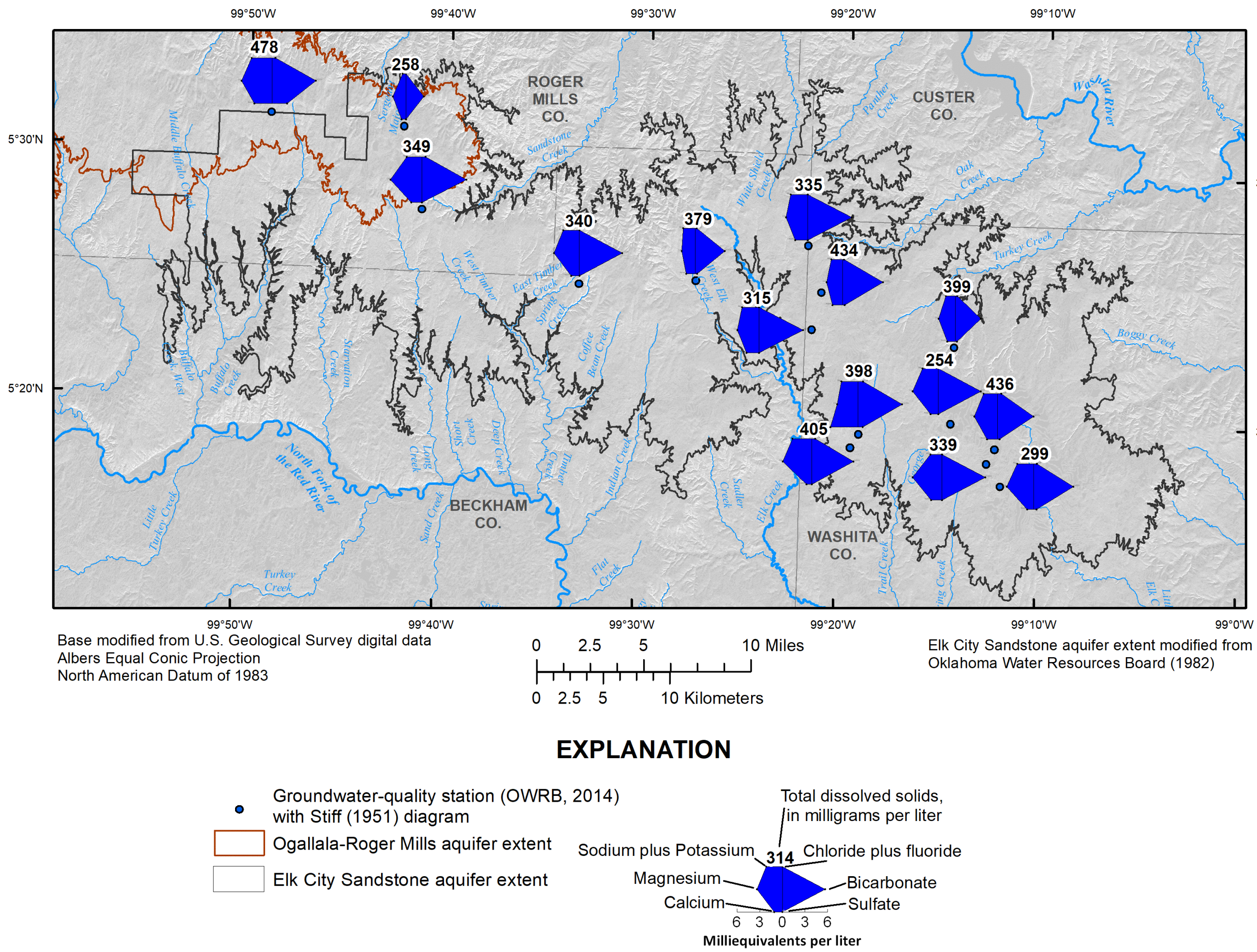


Figure 36. Groundwater-quality stations in the Elk City Sandstone aquifer with total dissolved solids and Stiff diagrams, west Oklahoma, 2013.

Depth-to-water measurements in ten wells were measured in the Trail Creek subsurface watershed monthly from November 2015 to March 2017 as part of the Regional Method to Estimate Specific Yield Section in this report with a probe that recorded electrical conductivity with depth to water and converted to TDS equivalent (**Figure 38**). The resulting mean TDS for this watershed was 458 milligrams per liter. The mean TDS for individual wells ranged from 285 to 696 milligrams per liter. On a month-to-month basis, the TDS of groundwater in most wells decreased in March 2016 before increasing by approximately 200 milligrams per liter, on average, the following month. TDS remained fairly constant until August 2017 when electrical conductivity started to decline. Well 170259 had a maximum TDS of 820 milligrams per liter, which was nearly double the maximum TDS measured in 2013 (**Table 13**). No known reason was ascertained regarding why this well measured higher. It is adjacent to a farm, as were other wells in the study area. An oil and gas pad site is located 0.6 miles to the northeast and upgradient of the groundwater flow to the well, but no known contamination issues were found for that site. The Elk City Sandstone creates a topographic high isolating it from impact by nearby sources of contamination and as a result is recharged predominantly from precipitation with little likely deep groundwater flow from lower units, resulting in water quality with low TDS.

Primary drinking-water standards are established by the United State Environmental Protection Agency for chemical constituents that may have an adverse effect on human health when present at excessive concentrations. None of the groundwater quality samples collected in the Elk City Sandstone aquifer in 2013 (**Table 13**) contained contaminants in concentrations above EPA maximum contaminant levels (MCL). Uranium was detected in 9 of the 14 samples taken throughout the aquifer, and the maximum uranium concentration was 10.6 micrograms per liter, which is still below the EPA MCL of 30 micrograms per liter. Permian sandstones throughout Oklahoma commonly contain trace amounts of uranium (Al-Shaieb and others, 1976). Transition metals such as vanadium, zinc, copper, manganese, cadmium, and iron were found in concentrations that were slightly above the detection limit in some of the wells (**Table 13**). Nitrate

Table 13. Summary statistics for groundwater-quality data for 13 samples collected from the Elk City Sandstone aquifer, 2013.

Parameter	Mean	Minimum	Maximum	Number of Samples below detection limit	Percentile		
					25	50	75
Temperature (□F)	70.6	63.6	76.6	0	67.6	69.9	74.5
Specific Conductance	627.5	446.5	854.1	0	567.9	611.6	728.9
pH	7.3	7.0	7.5	0	7.2	7.2	7.4
Total Dissolved Solids*	361.2	254.0	478.0	0	330.0	364.0	412.3
Hardness*	260.4	168.0	329.0	0	237.3	262.0	281.5
Calcium*	65.7	45.4	81.8	0	57.7	65.7	71.5
Magnesium*	22.9	6.1	32.3	1	20.6	25.3	27.2
Sodium*	38.9	13.3	106.0	0	23.5	38.3	46.7
Potassium*	1.5	0.5	4.5	0	1.1	1.4	1.7
Bicarbonate*	332.5	239.0	537.0	0	288.5	325.0	351.0
Sulfate*	19.9	13.6	30.1	5	16.8	19.4	24.8
Chloride*	23.0	10.6	58.4	8	12.1	14.2	25.1
Flouride*	0.3	0.2	0.5	0	0.3	0.3	0.4
Bromide**	371.1	175.0	1090.0	0	281.0	314.5	369.3
Silica*	25.3	22.8	29.8	0	23.9	25.1	26.2
Nitrate as N*	5.3	0.1	8.6	0	3.4	6.3	7.7
Phosphorous*	0.0	0.0	0.0	13	++	++	++
Aluminum**	++	++	++	16	++	++	++
Arsenic**	++	++	++	16	++	++	++
Barium**	398.7	85.9	629.0	0	273.3	401.0	503.5
Boron**	75.5	63.6	118.0	9	64.6	68.4	68.6
Cadmium**	++	++	++	16	++	++	++
Chromium**	++	++	++	16	++	++	++
Copper**	9.3	5.0	16.2	10	6.5	8.0	11.4
Iron**	++	++	++	15	++	++	++
Lead**+	++	++	++	16	++	++	++
Manganese**	42.4	42.4	42.4	15	++	++	++
Molybdenum**	++	++	++	16	++	++	++
Uranium**	2.4	1.0	10.6	5	1.3	1.6	2.2
Vanadium**	19.3	10.6	26.0	1	16.0	19.5	21.6
Zinc**	47.5	10.8	83.9	6	31.6	45.4	61.8

++, analyses were below analytical detection limit and statistics could not be estimated

Specific conductance is in microseimens per centimeter at 25° C

*, are presented in milligrams per liter

**, are presented in micrograms per liter

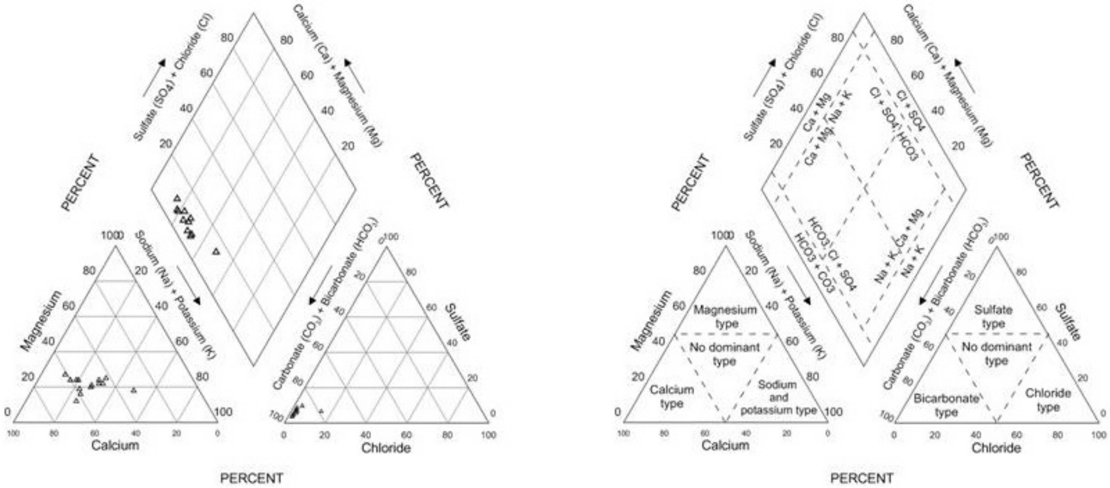


Figure 37. Piper plot of GMAP wells in the Elk City Sandstone aquifer, 2013.

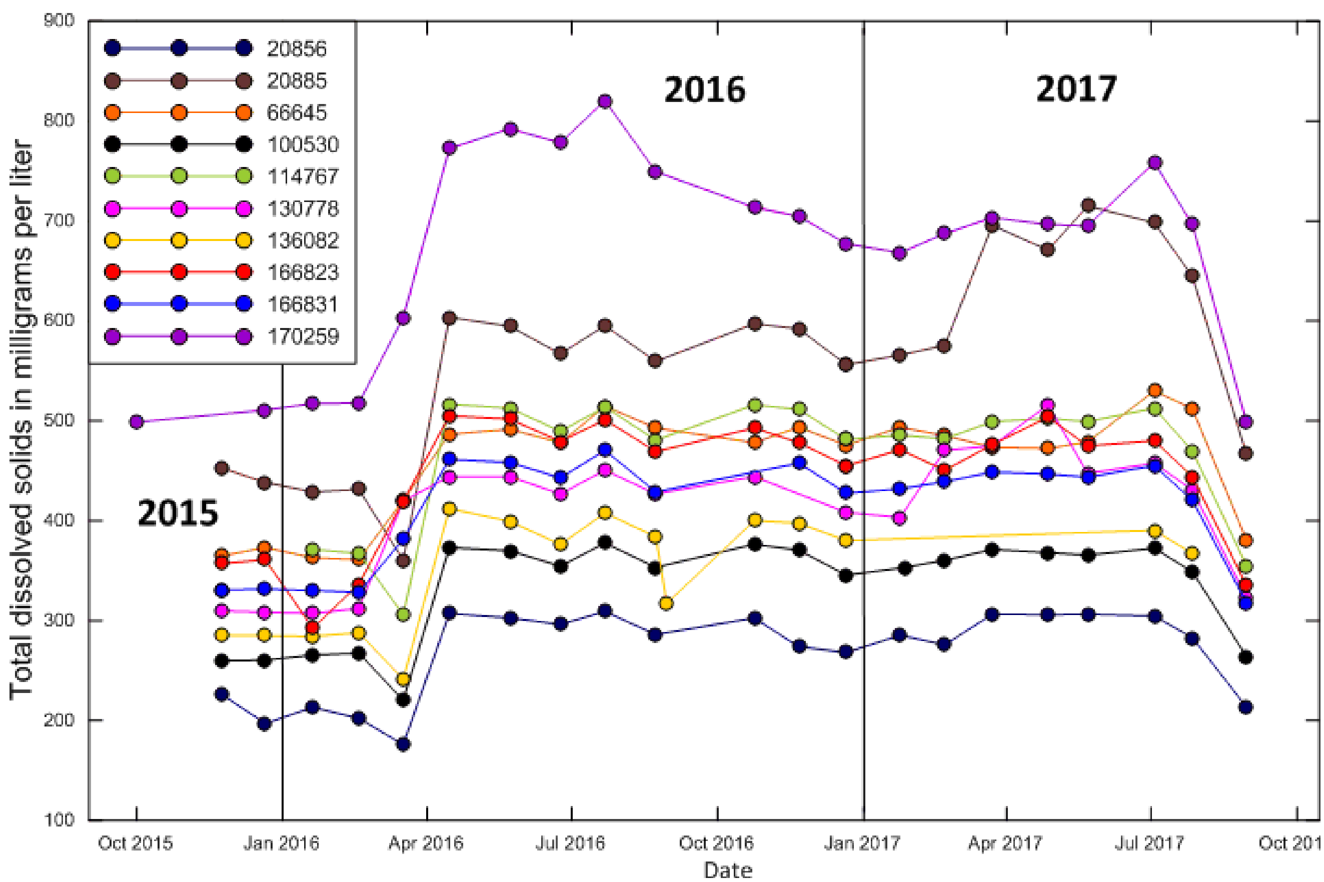


Figure 38. Total dissolved solids in 10 wells in the Trail Creek subsurface watershed, collected monthly from December 2015-August 2017.

is present in detectable quantities in all 14 samples with a maximum of 8.58 milligrams per liter, which is below the EPA MCL of 10 milligrams per liter. Nitrate concentrations exceeding maximum contaminant levels can cause health issues, most notably, shortness of breath, blue baby syndrome, and fatality (U.S. Environmental Protection Agency, 2015). The USGS reported that background nitrate concentrations in groundwater are generally less than 2 milligrams per liter (Mueller and Helsel, 1996). A municipal well provided water quality monitoring records from one of their public water supply wells which was out of operation because of the nitrate concentrations exceeding 14 milligrams per liter in 2016 and 2017.

Increased nitrates can be the result of agricultural practices such as nitrogen-based fertilizers, septic systems, confined animal feeding operations, animal waste lagoons, application of animal manure as fertilizer, or municipal sewage effluent. All of these practices were observed in various parts of the Elk City Sandstone aquifer. The City of Dill City had stopped using one of their municipal wells due to nitrate levels in the well being above the 10 milligrams per liter MCL with a reported value of 14.1 on April 22, 2019 (Oklahoma Department of Environmental Quality, 2019a). The cities of Canute (11 milligrams per liter, measured on December 19, 2019) and New Cordell (11.1 milligrams per liter, measured on July 25, 2019) also had wells with nitrate measuring above 10 milligrams per liter (Oklahoma Department of Environmental Quality, 2019b,c). Brine-water contamination often occurs as the result of oil-field operations including salt-water injection or downward infiltration of brine from abandoned mudpits or brine impoundments (Kent and others, 1982).

Water Quality Modeling

Water quality data were imported into the computer modeling software PHREEQC Version 2 (Parkhurst and Appelo, 1999) to perform hydrogeochemical equilibrium calculations that determine mineral saturation indices. PHREEQC is based on chemical equilibrium which occurs when the concentrations and charges of reactants and products in an aqueous solution are balanced so forward and reverse reactions occur at equal rates (Hem, 1961). Equilibrium calculations are used to establish if groundwater is in equilibrium with respect to one or more minerals and to predict the presence of reactive minerals in the groundwater system and estimating mineral reactivity. If minerals like calcite or barite are commonly found in equilibrium with groundwater, it can be assumed that they are reactive in a standard groundwater environment and control concentration in solution.

Saturation index is defined as the negative log of the activity product of the mineral divided by the mineral solubility product (Deutsch, 1997). Mineral equilibrium calculations can predict the presence of minerals in the groundwater system, and how reactive they are. Groundwater, with respect to various minerals, may be under-saturated, saturated, over-saturated. Groundwater that is under-saturated with respect to a mineral will dissolve that mineral until the water is in equilibrium, or saturated. Groundwater that is over-saturated with respect to a mineral will precipitate that mineral. Minerals which are in equilibrium with groundwaters often control aqueous ion concentrations and, potentially, pH and redox conditions as well. If a reactive mineral has a saturation index near zero, it is likely that the mineral occurs in the aquifer and affects the composition of the solution. A mineral in equilibrium with groundwater will have a saturation index near zero; a negative saturation index means the mineral is undersaturated and a positive saturation index means the mineral is oversaturated. As the saturation index calculation involves uncertainties such as the accuracy of groundwater sampling and laboratory analysis, a range of saturation index values of -0.50.5 is considered to be in equilibrium.

In order to run PHREEQC, the redox potential (pE), which is the negative log of electron activity (Deutsch, 1997), must be input for each sample. This parameter can usually be derived from field measurements of oxidation-reduction potential (ORP). The groundwater samples collected by the OWRB in 2013 did not include field collection of ORP so for these data, a pE of 6.0 was used based on pe calculated from wells in similar unconfined sand and sandstone aquifers in western Oklahoma like the Rush Springs and Ogallala aquifers, with similar depths to water and similar concentrations of iron and dissolved oxygen used as a proxy to assume similar oxidizing conditions. One sample did have higher concentrations of iron and low dissolved oxygen, and a pe of 3 was used.

The most abundant dissolved constituents in most groundwater are called major ions and include the cations calcium, sodium, potassium, and magnesium and the anions bicarbonate, chloride, and sulfate (Bartos and Ogle, 2002). Water should be electrically neutral, meaning the charges of the positively charged cations equal the charges of the negatively charged anions. However, unmeasured constituents or analytical errors can result in an unbalanced electrical charge for a groundwater sample, referred to as the charge-balance error, and can be used to assess the quality of the sample. A charge-balance error under 15% is often considered to be acceptable when measuring mostly major ions (Parkhurst and Appelo, 1999). Of the 15 analyzed groundwater samples, 14 had a charge-balance error under 10% and one (117937) had a charge-balance error of 18%.

Minerals that were determined to be commonly reactive using PHREEQC were barite (BaSO4), calcite (CaCO3), and dolomite (CaMg(CO3)2) with talc (Mg3Si4O10(OH2)) also identified at three sites. Calcite was in equilibrium in all 15 sites and was likely controlling the concentrations of dissolved calcium and bicarbonate in the groundwater system. Calcite is known to be present as cement in the matrix of the Elk City Sandstone (Kent and others, 1982). Dolomite, which is present as layers and possibly a matrix cement in the Elk City Sandstone, was in equilibrium in 12 of 15 samples and may control the magnesium concentration in the groundwater. Talc may also provide some control of magnesium concentration in the groundwater, but has not been identified as a significant part of the Elk City Sandstone mineralogy before. Barite was in equilibrium in 11 of the 15 samples and is likely controlling the sulfate concentration in the groundwater. Barite is likely present in the matrix of the Elk City Sandstone as a cement in the. Another possible source of sulfate often present in western Oklahoma is gypsum (CaSO4), but gypsum was undersaturated in all of the 15 samples, having saturation indices of -2 or more negative. Because gypsum is a highly reactive mineral, the low saturation index indicates that it likely is not present and was dissolved long ago (Deutsch, 1997). Quartz (SiO2) was also generally not in equilibrium. Quartz, which is generally a non-reactive mineral in the aquifer system, is likely in control of the dissolved silica concentration because the dominant mineralogy of the Elk City Sandstone is quartz. One sample contained dissolved iron, likely originating from cement, and the mineral siderite (FeCO3) was found to be in equilibrium in that sample.

Summary

The Elk City Sandstone aquifer consists of the Permian-age Elk City Sandstone, which is a reddish-brown, fine-grained sandstone with minor amounts of silt and clay. The aquifer covers 519 square miles in west Oklahoma, underlying portions of Beckham, Custer, Roger Mills, and Washita counties. The aquifer area for this hydrologic investigation was expanded from a 1982 report to include areas of the Elk City Sandstone outcropping to the west of the Elk City hydrologic basin as defined in 1982 (Kent and others, 1982) that were identified in more recent mapping completed after the 1982 report and have well yields that are indicative of a “major groundwater basin” as defined by the OWRB.

The study area received mean annual precipitation of 25.2 inches from 1924-2019 an recharge occurs through diffuse precipitation and discharges from the aquifer through base flow in streams and groundwater withdrawals. Recharge to the aquifer was estimated using the soil water balance code and water-table fluctuation method. SWB estimates of recharge ranged from 0.01 inches in 2011 to 3.16 inches in 1948 with a mean of 0.64 inches. Estimates of recharge using the WTF method, which utilizes precipitation values along with hourly water levels recorded using a continuous recorder at three different sites from 2015-2019 ranged from 3.5-10.5 inches per year.

Mean reported groundwater use from the Elk City Sandstone aquifer from 1967-2018 was 2,315 acre-feet. The lowest reported use was 900 acre feet in 1981 and the highest reported use was 5,031 acre feet in 1971. Over the period of record, 47.7 percent of all water use was for public water supply, 41.8 percent was for irrigation, 8.9 percent was for commercial use, and 1.6 percent was for other purposes. Water use trends for the period of record largely correspond to changing precipitation patterns, with higher reported water use during recent drought years from 2011-13 and lower reported water use in wetter years.

Lithologic descriptions from groundwater well logs were used to determine the base of the aquifer. The base of the aquifer was generally indicated in well logs by a description of “red bed” or “red shale”, which was assumed to be the Doxey Shale. There were 134 water wells measured in 2016 to create a potentiometric surface map. Saturated thickness of the aquifer was estimated by subtracting the elevation of the base from the potentiometric surface. Mean saturated thickness is 56 feet with a maximum thickness of 199 feet. The highest saturated thicknesses in the Elk City Sandstone range from 150-199 feet and are located near the axis of the Anadarko Basin in the central and eastern portions of the. The water table intersects some streams emanating within the aquifer based on a surface water synoptic measurement of the aquifer which measured 21 streams and determined that seven were gaining streams where the aquifer discharges as base flow to the streams.

Horizontal hydraulic conductivity was estimated from drawdown tests analysis, slug tests, a multi-well aquifer test, and a percent-coarse analysis from lithologic logs. Vertical hydraulic conductivity was estimated from percent-coarse analysis. Hydraulic conductivity estimated from drawdown test analysis ranged from 0.4-15.3 feet per day with a mean of 2.7 feet per day and a median of 1.5 feet per day. Slug test hydraulic conductivity ranged from 0.2-9.8 feet per day with a mean of 2.6 feet per day and a median of 1.9 feet per day. Hydraulic conductivity estimated from a multi-well aquifer test was 3.4 feet per day. The percent-coarse analysis used lithologic logs and assigned hydraulic conductivity to lithologic descriptions; mean and median horizontal hydraulic conductivity were estimated to be 2.8 and 1.2 feet per day. Vertical hydraulic conductivity estimated from the percent-coarse method had an estimated mean and median of 0.58 and 0.002. Transmissivity estimated from the multi-well aquifer test was 569 square feet per day. With a mean saturated thickness of the aquifer of 56 feet and a mean horizontal hydraulic conductivity of 2.8 feet per day, overall aquifer transmissivity is estimated at 156.8 square feet per day.

Specific yield for the aquifer was estimated using a regional method, a multi-well aquifer test, and a percent-coarse analysis from lithologic logs. Base flow and monthly groundwater-level measurements were used together to estimate specific yield in the Buffalo Creek, Little Elk Creek, and Trail Creek subsurface watersheds. The method uses the ratio of the volume of groundwater discharged as base flow to the volume of the aquifer drained, to estimate specific yield, which ranged from 0.07-0.10. Specific yield estimated from the multi-well aquifer test was 0.08. Mean and median specific yield estimated from the percent-coarse analysis was 0.08 and 0.07, respectively.

Water quality samples were collected from 15 wells throughout the aquifer, with a mean total dissolved solids of 361 milligrams per liter. Concentrations ranged from 254-478 milligrams per liter with a median of 364 milligrams per liter. The sampled waters were dominated by the bicarbonate anion, with major cations being more even in distribution. No samples collected contained concentrations above the maximum contaminant level for arsenic, nitrate, or uranium.

Selected References

Al-Shaieb, K., Olmsted, R.W., Shelton, J.W., May, R.T., Owens, R.T., and Hanson, R.E., 1976, Uranium potential of Permian and Pennsylvanian sandstones in Oklahoma: American Association of Petroleum Geologists Bulletin, v. 61, p. 360-375.

Bartos, T.T. and Ogle, K.M., 2002, Water quality and environmental isotopic analyses of groundwater samples collected from the Wasatch and Fort Union Formations in areas of coalbed methane development-Implications to recharge and groundwater flow, eastern Powder River Basin, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 02-4045 88 p.

Bouwer, H. and Rice, R.C., 1976, A slug test method for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells, Water Resources Research, vol. 12, no. 3, p. 423-428.

Breit, G.N., 1998, The diagenetic history of Permian rocks in the central Oklahoma aquifer, in Christenson, Scott; and Havens, J.S. (eds.), 1998, Ground-water quality assessment of the central Oklahoma aquifer, Oklahoma: results of investigations: U.S. Geological Survey Water-Supply Paper 2357-A, p. 45-61.

Butler, Jr., J.J., 1997, The design, performance, and analysis of slug tests: Lewis Publishers, Boca Raton, Florida, 252 p.

Butler, Jr., J.J., and Healy, J.M., 1998, Relationship between pumping-test and slug-test parameters: Scale effect or artifact?: Groundwater, vol. 36, no. 2, p.305-313.

Carr J.E. and Bergman D.L., 1976, Hydrologic Atlas 5: Reconnaissance of the water resources of the Clinton Quadrangle, West-Central Oklahoma.

Christenson, S., Osborn, N.I., Neel, C.R., Faith, J.R., Blome, C.D., Puckette, J., and Pantea, M.P., 2011, Hydrogeology and simulation of groundwater flow in the Arbuckle-Simpson aquifer, south-central Oklahoma: U.S. Geological Survey Scientific Investigations Report 2011-5029, 104 p.

Cohen, P., 1963, Specific-yield and particle-size relations of Quaternary alluvium Humbolt River Valley, Nevada: U.S. Geological Survey Water-Supply Paper 1669-M, 24 p.

Cooper, H.H. and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well field history: American Geophysics Union Transactions, vol. 27, p. 526-534.

Cunningham, W.L. and Schalk, C.W., 2011, Groundwater Technical Procedures of the U.S. Geological Survey: U.S. Geological Survey Techniques and Methods 1-A1, p. 145-151.

Curtis, N.M., Ham, W.E., and Johnson, K.S., 2008, Geomorphic Provinces of Oklahoma: Oklahoma Geological Survey Educational Publication 9, 6 p.

Deutsch, W.J., 1997, Groundwater geochemistry. CRC Press, Boca Raton, Florida, 221 p.

Domenico, P.A., and Schwartz, F.W., 1998, Physical and chemical hydrogeology (2d ed.): New York, N.Y., John Wiley & Sons, Inc., 528 p.

Duffield, G.M., 2007, AQTESOLV for Windows aquifer test analysis software, professional edition: Reston, Virginia, HydroSOLVE, Inc. version 4.5

Ellis, J.H., Mashburn, S.L., Graves, G.M., Peterson, S.M., Smith, S.J., Fuhrig, L. T., Wagner, D.L., and Sanford, J. E., 2016, Hydrogeology, numerical simulation of groundwater flow (1998-2013), and analysis of future water use (2013-62) for the Canadian River Alluvial aquifer, west and central Oklahoma: U.S. Geological Survey Scientific Investigations Report 2016-5180, 64 p.

Ellis, J.H., 2018, Simulation of groundwater flow and analysis of projected water use for the Rush Springs aquifer, western Oklahoma: U.S. Geological Survey Scientific Investigations Report 2018-5136, 156 p.

Fay, R.O., 2010, Preliminary geologic map of the Foss Reservoir 30' X 60' quadrangle, Beckham, Custer, Dewey, Ellis, and Roger Mills Counties, Oklahoma: Oklahoma Geologic Quadrangle 78A, scale 1:100,000.

Fay, R.O. and Hart, D. L., 1978, Geology and mineral resources (exclusive of petroleum) of Custer County, Oklahoma: Oklahoma Geological Survey Bulletin 114, 88 p.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J., 2011, Completion of the 2006 National Land Cover Database for the conterminous United States: Photogrammetric Engineering and Remote Sensing, v. 77, no 9, p. 858-864.

Fetter, C.W., 2001, Applied hydrogeology. 4th ed. Upper Saddle River; NJ, Prentice-Hall, 598 p.

Freeze, R.A. and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, NJ, Prentice-Hall, 604 p.

Gould, C.N., 1902, General geology of Oklahoma: Oklahoma Department of Geology and Natural History 2d Biennial Report, p. 17-74.

Green, D.A., 1936, Permian and Pennsylvania sediments exposed in central and west-central Oklahoma: Bulletin of the American Association of Petroleum Geologists, v. 20, p. 1454-1475.

Guru, M.V. and Horne, J.E., 2001, The Ogallala aquifer, Water Resource Management, 48, p. 321-329.

Ham, W.E., Merritt, C.A. and Frederickson, E.A., 1957, Field conference on geology of the Wichita Mountain region in southwestern Oklahoma, May 2-4, 1957: Oklahoma Geological Survey Guidebook 5, 58 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model-user guide to modularization concepts and the ground-water flow process., U.S. Geological Survey Open-File report 2000-92, 130 p.

Harlton, B.H., 1963, Frontal Wichita fault system of southwestern Oklahoma: American Association of Petroleum Geologists Bulletin, v. 35, p.988-999.

Hargreaves, G.H. and Samani, Z.A., 1985, Reference crop evapotranspiration from temperature: Applied Engineering in Agriculture, vol. 1, no. 2, p. 96-99.

Healy, R.W. and Cook, P.G., 2002, Using ground-water levels to estimate recharge: Hydrology Journal, v. 10, p. 91-109.

Hem, J.D., 1961, Calculation and use of ion activity, U.S. Geological Survey Water Supply Paper 153

5-C, 17 p.

Hyder, Z., Butler, J.J., McElwee, C.D., Liu, W., 1994, Slug tests in partially penetrating wells, Water Resources Research, v. 30, no. 11, p. 2945-2957.

Jacob, C.E., 1940, On the flow of water in an elastic artesian aquifer: American Geophysics Union Transactions, 1940, pt. 2, p. 574-586.

Johnson, K.S., 1978, Stratigraphy and mineral resources of Guadalupian and Ochoan rocks in the Texas panhandle and western Oklahoma; in Austin, G.S. (ed), Geology and mineral deposits of Ochoan rocks in Delaware Basin and adjacent areas: New Mexico Bureau of Mines and Mineral Resources, Circular 159, pp. 57-62.

Johnson, K.S., 1989, Geologic evolution of the Anadarko basin, in Johnson, K.S., ed., Anadarko basin symposium, 1988: Oklahoma Geological Survey Circular 90, p. 3-12.

Johnson, K.S., Stanley, T.M., and Miller, G.W., 2003, Geologic map of the Elk City 30’ X 60’ quadrangle, Beckham, Custer, Greer, Harmon, Kiowa, Roger Mills, and Washita Counties, Oklahoma: Oklahoma Geological Quadrangle 44, scale 1:100,000.

Kent, D.C., Lyons, T., and Witz, F.E., 1982, Evaluation of aquifer performance and water supply capabilities of the Elk City aquifer in Washita, Beckham, Custer, and Roger Mills counties, Oklahoma: Oklahoma State University, 96 p.

Köppen -Geiger, 2018, World map of the Köppen –Geiger climate classification updated map for the United States of America: accessed July 20, 2018 at http://koeppen-geiger.vu-wien.ac.at/usa.htm.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, p. 70.

Lyons, T.D., 1978, A ground-water management model for the Elk City aquifer in Washita, Beckham, Custer and Roger Mills counties, Oklahoma: Master’s Thesis, Oklahoma State University, 102 p.

Martell, J.E., Camrud, M.B., Hall, G.J., 1992, Alternate water supply study Clinton-Sherman Industrial Airpark Burns Flat, Oklahoma, US Army Corps of Engineers, 94 p.

Mashburn, S.L., Ryter, D.W., Neel, C.R., Smith, S.J, and Magers, J.S., 2014. Hydrogeology and simulation of groundwater flow in the Central Oklahoma (Garber-Wellington) Aquifer, Oklahoma, 1987 to 2009, and simulation of available water in storage: U.S. Geological Survey Scientific Investigations Report 2013-5219, 92 p.

Morris, D.A. and Johnson, A.I., 1967, Summary of hydrologic and physical properties of rock and soil materials, as analyzed Hydrogeologic Laboaratory of the U.S. Geological Survey 1948-60, U.S. Geological Survey Water-Supply Paper 1839-D, 42 p.

Mueller, D.K. and Helsel, D.R., 1996, Nutrients in the nations waters too much of a good thing?: U.S. Geological Survey Circular 1136, 15 p.

Multi-Resolution Land Characteristics Consortium, 2000, National Land Cover Database: U.S. Geological Survey, accessed February 2, 2017, at http://www.mlrc.gov/nlcd01_data.php.

Multi-Resolution Land Characteristics Consortium, 2011, National Land Cover Database: U.S. Geological Survey, accessed February 2, 2017, at http://www.mlrc.gov/nlcd01_data.php.

Natural Resources Conservation Service, 2014, Gridded soil survey geographic map, accessed February 2, 2017, at http://datagateway.nrcs.usda.gov.

National Weather Service, 2014, What is the COOP Program?, accessed November 2016, at http://www.weather.gov/om/coop/what-is-coop.html.

Neel, C.R., Wagner, D.L., Correll, J.S., Sanford, J.E., Hernandez, R. J., Spears, K.W., Waltman, P.B., 2018, Hydrologic investigation report of the Rush Springs aquifer in west-central Oklahoma, 2015, Oklahoma Water Resources Board, 61 p.

Nuccio, V.F., Popov, M.A., Dyman, T.S., Gognat, T.A., Johnson, R.C., Schmoker, M.S., and Bartberger, C., 2001, Basin-centered gas systems of the U.S., U.S. Geological Survey Open-File report 2001-135, 506 p.

O'Callagan, J.F. and Mark, D.M., 1984, The extraction of drainage networks from digital elevation data: Computer Vision, Graphics and Image Processing, v. 28, no. 3, p. 323-344.

Oklahoma Climatological Survey, 2013, Monthly Summaries: accessed August 15, 2017, at http://climate.ok.gov/summaries/ monthly/2013/MCS_February_2013.pdf.

Oklahoma Climatological Survey, 2019a, Daily time series using cooperative observer (COOP) data: accessed February 12, 2019 at http://climate.ok.gov/cgi-bin/public/climate.timeseries.one.cgi.

Oklahoma Climatological Survey, 2019b, Monthly Summaries: accessed February 14, 2019, at http://climate.ok.gov/index.php/climate/summary.

Oklahoma Department of Environmental Quality, 2019a, Consumer confidence report – 2020 Covering Calendar Year – 2019, Dill City OK2007507

Oklaoma Department of Environmental Quality, 2019b, Consumer confidence report – 2020 Covering Calendar Year – 2019, New Cordell Utility Authority OK2007502

Oklahoma Department of Environmental Quality, 2019c, Consumer confidence report – 2020 Covering Calendar Year – 2019, Canute OK2007503

Oklahoma Mesonet, 2017, Daily data retrieval, accessed December 19, 2017, at http://www.mesonet.org/index.php/weather/daily_data_retrieval.

Oklahoma Statutes Title 82 Section 1020.1, 2011, Definitions.

Oklahoma Water Resources Board, 2011, Oklahoma Comprehensive Water Plan west-central Watershed planning region draft report, 84 p.

Oklahoma Water Resources Board, 2014, 2013 Oklahoma groundwater report – Beneficial Use Monitoring Program, 82 p.

Oklahoma Water Resources Board, 2017, Taking and use of groundwater, Title 785, Chapter 30: accessed September 17, 2017, at http://www.owrb.ok.gov/util/rules/pdf_rul/current/Ch30.pdf.

Oklahoma Water Resources Board, 2018, Data and Maps – Groundwater: Oklahoma Water resources Board web page, accessed April 3, 2018 at http://www.owrb.ok.gov/maps/index.php

Palmquist, W.N. and Koopman, F.C., 1964, Occurrence availability of groundwater in northwestern Washita County, Oklahoma: unpublished report for the U.S. government, 60 p.

Parkhurst, D.L. and Appelo, C.A.J., 1999, User's guide to PHREEQC (Version 2): a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Water-Resources Investigations Report 99-4259, 312 p. http://doi.org/10.3133/wri994259

Perry, W.J., 1989, Tectonic evolution of the Anadarko basin: U.S. Geological Survey Bulletin 1866-A, 19 p.

Piper, A.M., 1944, A graphic procedure in the geochemical interpretation of water analyses: American Geophysical Union Transactions, v. 25, p. 914–923.

Richardson, J.L., 1970, Areal geology of western Washita county, Oklahoma: Unpublished master's thesis, University of Oklahoma, 67 p.

Roth, R., Newell, N.D., Burma, B.H., 1941, Permian Pelecypods in the lower Quartermaster Formation, Texas, Papers in the Earth and Atmospheric Sciences. Paper 320. http://digitalcommons.unl.edu/geosciencefacpub/320

Risser, D.W., Conger, R.W., Ulrich, J.E., and Asmussen, M.P., 2005, Estimates of ground-water recharge based on streamflow-hydrograph methods: Pennsylvania: U.S. Geological Survey Open-File Report 2005-1333, 30 p.

Scanlon, B.R., Healy, R.W., Cook, P.G., 2002, Choosing appropriate techniques for quantifying groundwater recharge: Hydrogeology Journal, vol. 10, p.18-39.

Schilling, K.E., 2009, Hydrological processes inferred from water table fluctuations, Walnut Creek, Iowa: University of Iowa, Master's Thesis, 172 p.

Schwartz, F. W. and Zhang, H., 2003, Fundamentals of ground water, John Wiley and Sons, p. 583.

Smith, S.J., Ellis, J.E., Wagner, D.L., Peterson, S.M., 2017, Hydrogeology and Simulated Groundwater Flow and Availability in the North Fork Red River Aquifer, Southwest Oklahoma, 1980-2013.

Stiff, H.A., Jr., 1951, The interpretation of chemical water analysis by means of patterns: Journal of Petroleum Technology, v. 3, no. 10, p. 15–17.

Tartakovsky, G.D. and Newman, S.P., 2007, Three-dimensional saturated-unsaturated flow with axial symmetry to a partially penetrating well in a compressible unconfined aquifer: Water Resources Research 43, W01410, doi: 1029/2006WR005153

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, American Geophysical. Union Transaction., vol. 16, p. 519-524.

Thornthwaite, C.W., and Mather, J.R., 1957, Instructions and tables for computing potential evapotranspiration and the water balance: Centerton, N.J., Laboratory of Climatology, Publications in Climatology, v. 10, no. 3, p. 185-311.

Todd, D.K., 1980, Groundwater Hydrology, 2nd ed., John Wiley & Sons, New York, 535p.

U.S. Department of Agriculture, 2009, USDA NRCS National Engineering Handbook, Part 630 Hydrology, Chapter 7 Hydrologic Soil Group.

U.S. Environmental Protection Agency, 2013, Level III ecoregions of the continental United States: Corvallis, Oregon, U.S. EPA-National Health and Environmental Effects Research Laboratory, map scale 1:7,500,000, https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states.

U.S. Environmental Protection Agency, 2015, Basic information about nitrate in drinking water, accessed February 8, 2015, at http://water.epa.gov/drink/contaminants/basicinformation/nitrate.cfm#three.

U.S. Geological Survey, 2019, USGS 3D elevation program, 1/3 arc-second digital elevation model, accessed November 16, 2020 at https://viewer.nationalmap.gov/.

Wahl, K.L. and Wahl, T.L., 1995, Determining the flow of Comal Springs at New Braunfels, Texas, in Proceedings of Texas Water '95, August 16-17, 1995, San Antonio, Texas: American Society of Civil Engineers, p. 77-86, accessed March 24, 2017 at http://www.usbr.gov/pmts/hydraulics_lab/twahl/bfi/texaswater95/comalsprings.html.

Weems, C., 1968, Sandstone Creek: The effect of upstream flood prevention on local land use, Proceedings of the Oklahoma Academy of Science for 1967.

Wenzel, L.K. and Fishel, V.C., 1942, Methods for determining permeability of water-bearing materials: United States Geological Survey Water-Supply Paper 887, 192 p.

Wenzel, L.K., and Greenlee, A.L., 1944, A method for determining transmissibility and storage coefficients by tests of multiple well systems: American Geophysics Union Transactions, 1943, pt. 2, p. 547-560.

Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., and Bradbury, K.R., 2010, SWB – A Modified Thornthwaite-Mather Soil-Water-Balance code for estimating groundwater recharge: U.S. Geological Survey Techniques and Methods, Book 6, chap. A31, 60 p.

Zabawa, P.J., 1976, Investigation of surficial structural geology of portions of Beckham, Custer, Roger Mills, and Washita counties, Oklahoma: Master's Thesis, University of Oklahoma, 98 p.

Ziegler, P.A. 1990. Geological Atlas of Western and Central Europe. 2nd. Ed. Shell International Petroleum Mij. B.V., distributed by Geological Society, London, Publishing House, Bath, 239 p.

Appendix 1. Detailed Boundary Description of the Elk City Sandstone Aquifer

The boundary of the Elk City Sandstone aquifer is mostly defined by the mapped contact between the Elk City Sandstone and Doxey Shale in Oklahoma Geological Survey maps published in 2003 (Johnson and others) and 2010 (Fay). The mapped contact defines the Elk City Sandstone aquifer's boundary in all areas except where alluvium from streams that overlie the edge of the aquifer are present where an interpolated contact is used and in portions of the northern boundary in Townships 11N and 12N and Ranges 22W and 23W where detailed field mapping by OWRB staff resulted in a modified boundary where the boundary follows specific elevations identified by OWRB staff as being the contact between the Elk City Sandstone and Doxey Shale. New mapping in this area was required to reconcile discrepancies between what Johnson and others (2003) and Fay (2010) had identified as Elk City Sandstone when the two quadrangles were line up.

Additionally, the area where the Elk City Sandstone is overlain by the Ogallala Formation starting along the northern border of Section 04 of Township 12N, Range 24W and extending southwest to Section 31 of Township 12N, Range 25W also does not follow the mapped contact between the Elk City Sandstone and the Doxey Shale as that contact is below surface and undefined. Analysis of well driller logs in this area identified areas the Elk City Sandstone is being utilized, and these areas were then included in the Elk City Sandstone aquifer extent. This area is defined as beginning at the northern border of Section 04 of Township 12N, Range 24W and extending 0.7 miles west to the northwest corner of Section 04, then south two miles to the southwest corner of Section 09, then east for one mile to the northeast corner of Section 16 then south two miles to the southwest corner of Section 21, then west one mile to the southwest corner of the same section, then north one mile to the northwest corner of the same section, then west one mile to the southwest corner of section 17, then north one mile to the northwest corner of the same section, then west five miles to the northwest corner of Section 16 of Township 12 N, Range 25W, then south two miles to the southwest corner of Section 21, then west four miles to the northwest corner of section 26 of Township 12N, Range 26W, then south two miles to the southwest corner of Section 35, then east 2.65 miles to the southern border of Section 31 of Township 12 N, Range 25W where the boundary again follows the Elk City Sandstone and Doxey Shale contact.