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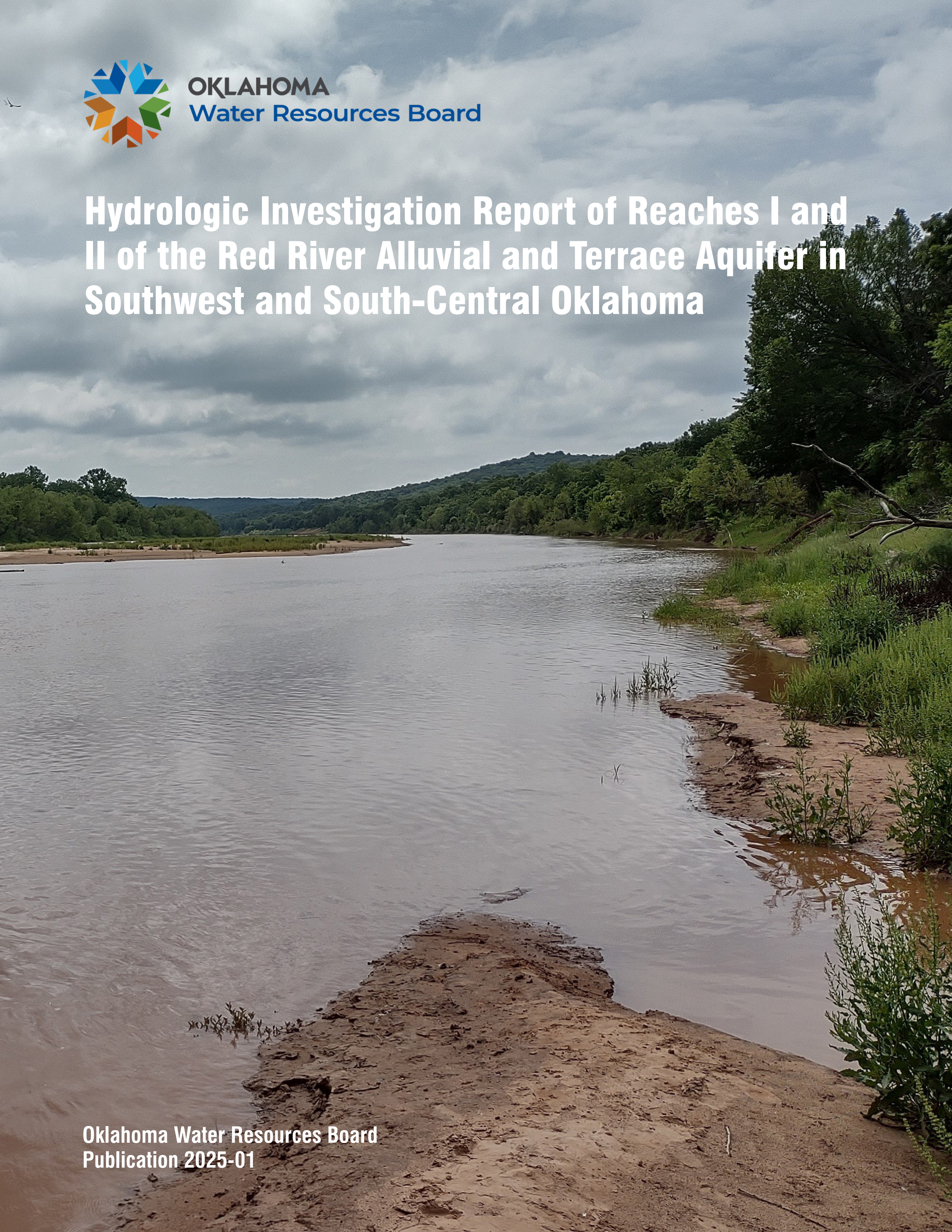
Hydrologic Investigation Report of Reaches I and II of the Red River Alluvial and Terrace Aquifer in Southwest and South-Central Oklahoma



Oklahoma Water Resources Board
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Cover:

Red River near Thackerville, Oklahoma. Photograph by Jon Sanford, Oklahoma Water Resources Board, May 16, 2023.

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

Acknowledgments

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Hydrologic Investigation Report of Reaches I and II of the Red River Alluvial and Terrace Aquifer in Southwest and South-Central Oklahoma

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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 Reaches I and II of the Red River alluvial and terrace aquifer hydrologic investigation and provides information to allow the OWRB to simulate various management scenarios.

Reaches I and II of the Red River alluvial and terrace aquifer are located in Harmon, Jackson, Tillman, Cotton, Jefferson, and Love counties in southwest and south-central Oklahoma. The aquifer consists of Quaternary-age alluvial and terrace deposits that are underlain by Permian- and Cretaceous-age bedrock units. Geologic maps published by the Oklahoma Geological Survey were used to define a study area of 336 square miles in Reach I and 286 square miles in Reach II. Climate data were analyzed from 17 Cooperative Observer (COOP) stations and five Oklahoma Mesonet stations with mean annual precipitation values of 25.35 inches for Reach I and 32.68 inches for Reach II. There were approximately 200 groundwater wells and 92 permits located within the study area in 2022. Depth to water was measured in 31 groundwater wells in 2020 to produce a potentiometric surface map, which indicated that groundwater generally flows to the south-southeast toward the Red River. The saturated thickness of the aquifer ranged up to about 71 feet in Reach I and up to about 103 feet in Reach II. Two wells were equipped with water-level recorders to characterize monthly trends and responses to precipitation. A multi-well pumping test was conducted in May of 2023 in Reach I. With the resultant data, the AQTESOLV modeling program estimated a transmissivity value of 5,011 square feet per day, a hydraulic conductivity value of 135 feet per day, and a specific yield of 0.11. Mean hydraulic conductivity values of 95.7 feet per day (Reach I) and 111.1 feet per day (Reach II) were calculated using single-well pumping tests. Drawdown tests and the percent coarse method resulted in mean hydraulic conductivity values ranging from 49.0 to 83.0 feet per day in Reach I and 46.0 to 105.1 in Reach II.

Groundwater is primarily used for irrigation and public water supply in the study area. Water use data for 1967-2022 were analyzed, with mean annual use of 1,487 acre-feet per year in Reach I and 1,062 acre-feet per year in Reach II. Mean annual recharge was estimated to be 1.18 inches per year in Reach I and 3.57 inches per year in Reach II using a soil-water balance model. Groundwater wells were sampled for selected water quality parameters in five wells in 2015 and 12 wells in 2020. Bicarbonate is the most prevalent anion in the sampled waters. The mean total dissolved solids was 1,069 milligrams per liter in Reach I and 326 milligrams per liter in Reach II. Six wells in Reach I and three wells in Reach II, had nitrate levels that exceed the U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL) for public water supply.

Introduction

The Red River alluvial and terrace aquifer is an unconfined alluvial aquifer composed of sand, silt, clay, and gravel along and north of the Red River in floodplain, terrace, and dune deposits. The aquifer underlies 336 square miles in southwest Oklahoma (Reach I) and 286 square miles in south-central Oklahoma (Reach II). Groundwater from the aquifer is used primarily for irrigation and public water supply. Groundwater wells have a mean yield greater than 150 gallons per minute, which by definition allows the classification of a "major alluvial groundwater basin" by the OWRB (Oklahoma Statutes Title 82 Section 1020.1, 2022).

The aquifer as described in this report is composed of alluvial and terrace deposits along the Red River from the Oklahoma-Texas border in Harmon County to Lake Texoma. For this report, the term "study area" refers to the area within the aquifer boundary defined in this study. The boundary is defined as the geologic contact between alluvial and terrace deposits and underlying bedrock units mapped by the Oklahoma Geological Survey (Chang and Stanley, 2013; Miller and Stanley, 2006; Stanley, 2004; Stanley and Miller, 2004; Stanley and Miller, 2005; Stanley and Chang, 2012). For the study, the aquifer was divided into two reaches to account for differences in precipitation from west to east, which potentially affects recharge rates. Reach I is located in Harmon, Jackson, Tillman, and Cotton counties and extends from the Oklahoma-Texas border to the section

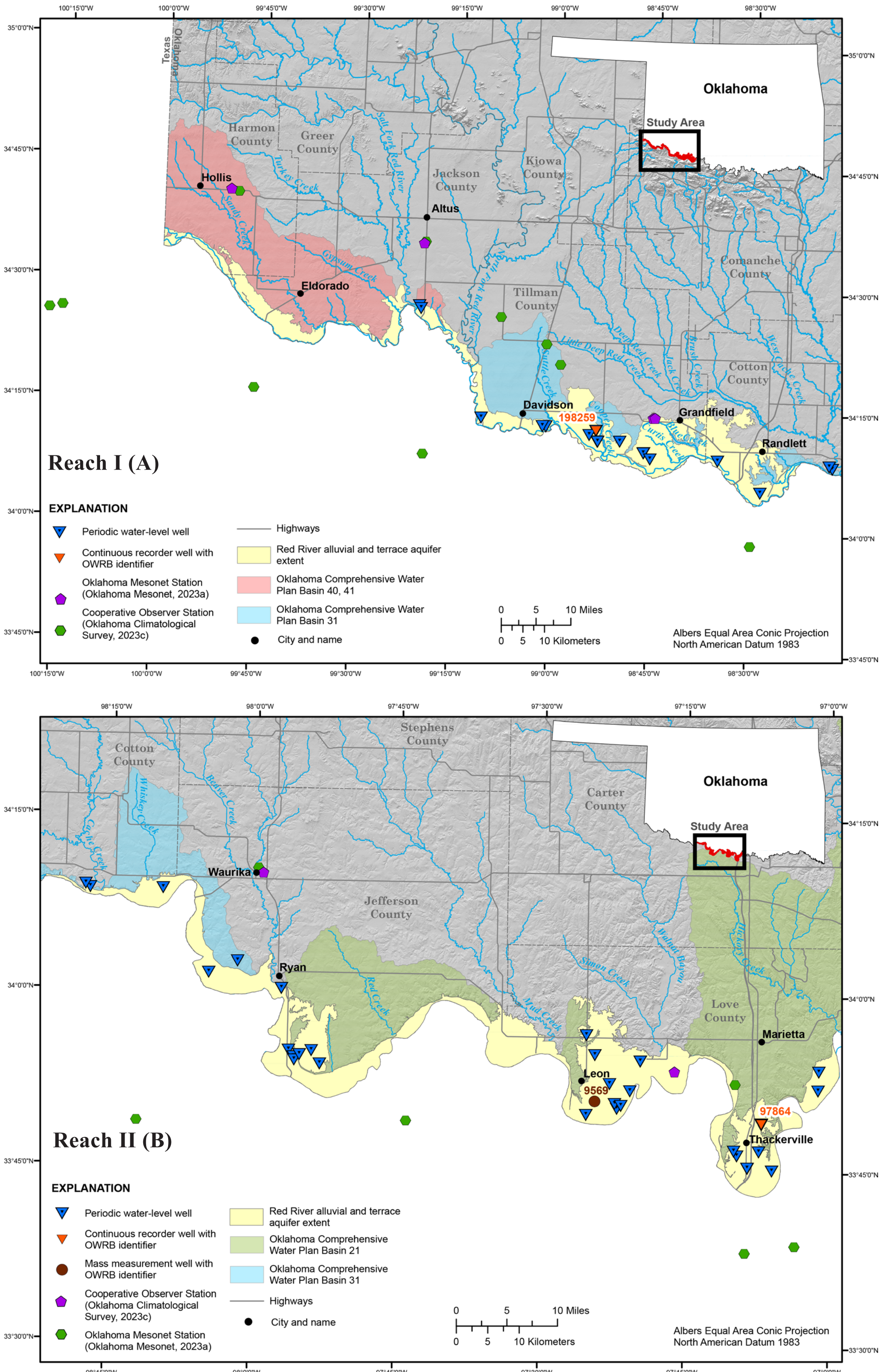


Figure 1. Red River alluvial and terrace aquifer Reach I (A) and Reach II (B) study areas, with locations of continuous water-level recorder wells, water levels collected by the OWRB Mass Measurement Program wells, Cooperative Observer and Mesonet weather stations, and Oklahoma Comprehensive Water Plan basins.

line of sections 4 and 5, Township 5 South (T5S), Range 11 West, Indian Meridian (11WI) in Cotton County where the aquifer extent narrows to less than 0.25 miles (Figure 1A). Reach II is located in Cotton, Jefferson, and Love counties and extends eastward from Cotton County to Lake Texoma in SE1/4 SE1/4 NW1/4 and SW1/4 SW1/4 NE1/4, Section 21, Township 7 South (T7S), Range 3 East, Indian Meridian (3EI) in Love County (Figure 1B). The southern boundary of the aquifer is the Oklahoma-Texas border, and the northern boundary is defined by the mapped extent of alluvial and terrace deposits. Reach I is predominantly rural with crop land and grassland/pasture accounting for 42.2 and 26.6 percent of land cover, respectively (National Agricultural Statistics Service, 2022; Figure 2A). Winter wheat is the predominant crop type in Reach I, accounting for 73.5 percent, followed by cotton, which comprised 18.9 percent of crops in 2022 (National Agricultural Statistics Service, 2022). Reach II is mostly grassland/pasture and crop land, which account for 42.6 and 21.9 percent of land cover, respectively (National Agricultural Statistics Service, 2022; Figure 2B). Forested areas increase to the east and account for 21.2 percent of land cover in Reach II (National Agricultural Statistics Service, 2022). Winter wheat (69.0 percent) is the main crop type in Reach II with other crops (hay/non-alfalfa, triticale, cotton, and rye) each accounting for less than ten percent grown in 2022 (National Agricultural Statistics Service, 2022).

Purpose and Scope

The purpose of this report is to describe an investigation of the Red River alluvial and terrace aquifer that includes analysis of the hydrogeology and hydrologic framework of the aquifer. Oklahoma groundwater law requires the OWRB to complete hydrologic investigations of the State's aquifers and complete updates every twenty years in order to provide the necessary data to determine the MAY and EPS (Oklahoma Statutes Title 82 Section 1020.4, 2022). This report provides information that can be used by the OWRB to determine the MAY and EPS of groundwater from the aquifer. The OWRB bases the MAY upon the amount of groundwater that can be withdrawn while allowing a minimum basin life of twenty years from the order date establishing the MAY (Oklahoma Statutes Title 82 Section 1020.5, 2022). The EPS is the amount of groundwater allocated to each permit, which is proportionate to the amount of land owned or leased by the applicant.

Climate

The Red River alluvial and terrace aquifer is primarily located in a region classified as Cfa, or humid subtropical, in the Köppen-Geiger Climate Classification, but the portion of Reach I located in Harmon County is classified as Bsk, a cold semi-arid climate (Kottek and others, 2006). Mean daily air temperatures range from 38 degrees Fahrenheit in January to 84 degrees Fahrenheit in July (Oklahoma Climatological Survey, 2023a). There are typically about 100 days of temperatures above 90 degrees Fahrenheit and four days of high temperatures below 32 degrees Fahrenheit with a growing season ranging from 200 to 228 days across the region (Oklahoma Climatological Survey, 2023b).

Climate data were analyzed for long-term precipitation trends for the period 1930-2022. Precipitation data were obtained from seventeen COOP stations and five Oklahoma Mesonet stations (Figure 1) located in and near the study area (National Oceanic and Atmospheric Administration, 2023; Oklahoma Climatological Survey, 2023c; Oklahoma Mesonet, 2023a). The National Weather Service Cooperative Observer Program is a network of observation stations with volunteers recording daily temperature and/or precipitation (National Weather Service, 2023). The Oklahoma Mesonet is a network of 120 automated environmental monitoring stations throughout Oklahoma (Oklahoma Mesonet, 2023b). Thirteen stations were utilized for Reach I and eleven stations were utilized for Reach II (Figure 1; Table 1). The compiled data spanned 93 years (1930-2022) with at least one station recording data each month. Years in which data were missing or less than 12 months of data were available were omitted from annual precipitation analysis. Months with incomplete daily precipitation data were omitted from monthly precipitation analysis.

Mean annual precipitation from 1930-2022 was 25.35 inches for Reach I and 32.68 inches for Reach II (Figure 3). Precipitation trends were identified by comparing the 5-year moving mean precipitation and the long-term mean annual precipitation in each reach. Periods of mostly below mean precipitation occurred from 1930-72 and 1998-2014, which generally corresponds with hydrologic drought periods in Oklahoma (Shivers and Andrews, 2013). The annual mean precipitation during those periods was 23.81 inches in Reach I and 30.68 inches in Reach II. Mostly above mean precipitation periods occurred from 1973-97 and 2015-2022, with an annual mean of 28.14 inches in Reach I and 36.31 inches in Reach II. Monthly precipitation data show similar trends between Reach I and Reach II (Figure 4). Maximum mean monthly precipitation occurred in May with 4.16 inches in Reach I and 4.78 inches in Reach II. The minimum mean monthly precipitation occurred in January with 0.91 inches in Reach I and 1.54 inches in Reach II.

Geology

The Red River alluvial and terrace aquifer consists of Quaternary-age deposits composed of sand, silt, clay, and gravel (Figure 5). The alluvial and terrace deposits unconformably overlie sedimentary bedrock units that include Permian-age bedrock in Reach I and Cretaceous-and Permian-age bedrock in Reach II (Figure 6).

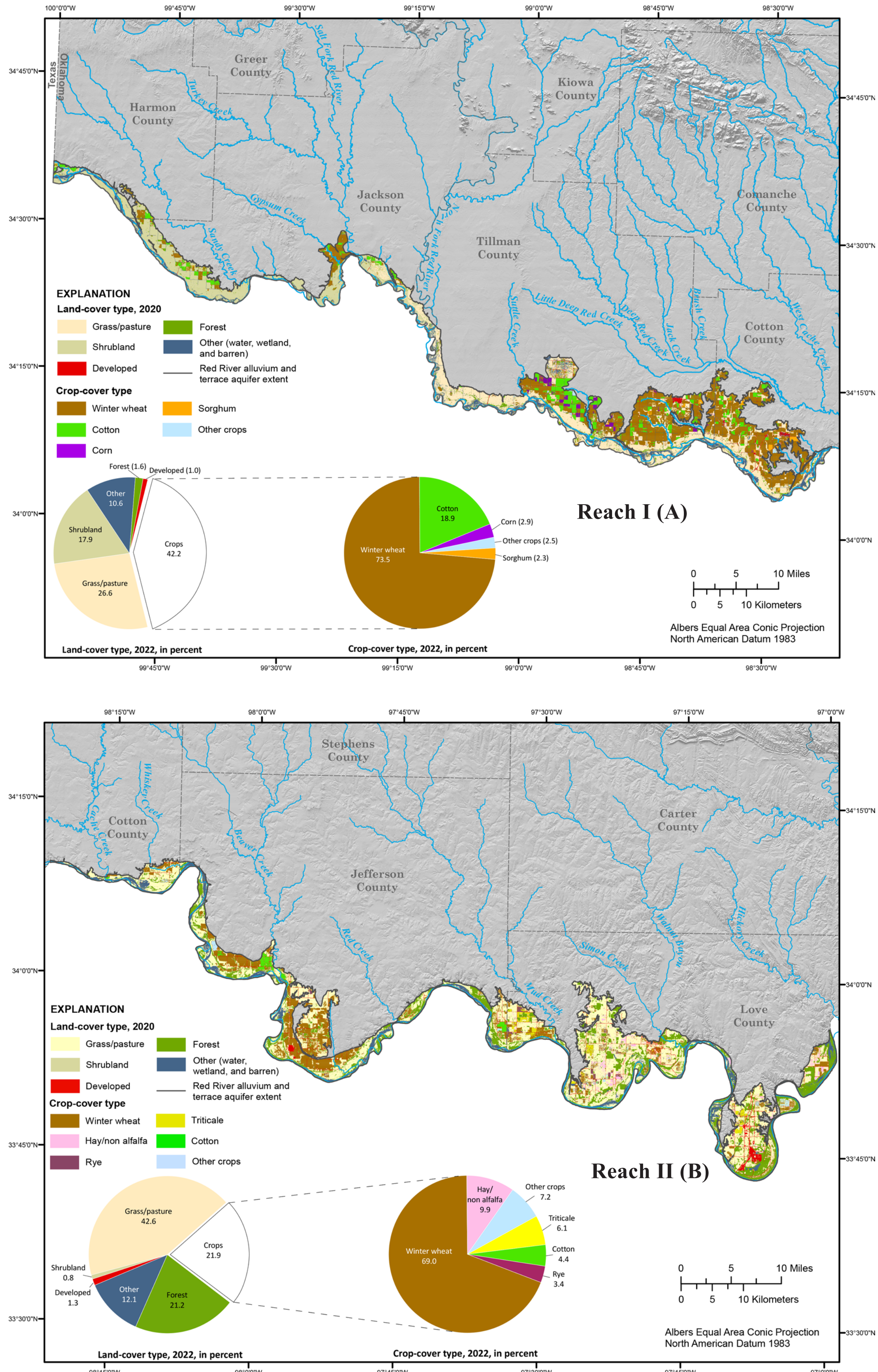


Figure 2. Land and crop cover over Reach I (A) and Reach II (B) of the Red River alluvial and terrace aquifer, 2022.

Table 1. Mean annual precipitation, data collection time periods, and number of years of annual precipitation data from the Cooperative Observer and Oklahoma Mesonet stations analyzed for the Red River alluvial and terrace aquifer study.

Station number	Station name	Period of analysis[1]	Number of years	Mean annual precipitation, in inches
	Reach I			
340179	Altus Irrigation Station & Dam	1930-2014	67	26.16
411696	Childress, TX 3 W	1930-1946	17	23.02
411698	Childress, TX Municipal Airport	1948-2022	75	21.59
343353	Frederick	1930-1993	42	27.01
003981	Frederick Municipal	2003-2017	5	22.70
343709	Grandfield 4 NW	1943-1990	25	29.79
344249	Hollis 5E	1950-2008	35	23.03
417336	Quanah, TX 2 SW	1930-2007	67	24.42
348879	Tipton 4S	1939-2020	53	26.10
419346	Vernon, TX	1935-2022	66	25.66
340180	Altus Mesonet	1994-2022	25	26.25
343707	Grandfield Mesonet	1994-2022	25	28.83
344258	Hollis Mesonet	1994-2022	25	24.41
	Reach II			
410926	Bonita, TX 7 NW	2005-2020	12	35.23
410984	Bowie, TX	1956-2022	58	34.11
413415	Gainesville, TX	1930-2022	83	37.38
343709	Grandfield 4 NW	1943-1990	25	29.79
414093	Henrietta, TX	1930-2003	67	30.76
345563	Marietta 5SW	1938-2017	70	36.26
349395	Waurika	1930-2005	44	31.35
13966	Wichita Falls, TX Municipal Airport	1930-2022	93	27.56
341266	Burneyville Mesonet	1994-2022	26	36.98
343709	Grandfield Mesonet	1994-2022	25	28.83
349400	Waurika Mesonet	1994-2022	25	34.26

[1]Not Continuous

Quaternary-Age Alluvial and Terrace Deposits

Terrace deposits occur along much of the north side of the Red River and are typically less than two miles in width with the widest terraces (5-10 miles in width) occurring in parts of Tillman, Cotton, and Love counties (Miller and Stanley, 2006; Stanley, 2004; Stanley and Chang, 2012). Terraces are generally up to 50 feet thick but are up to 70 feet thick in Tillman and Cotton counties and 150 feet in Love County.

Alluvium in the present-day floodplain primarily consists of sand and fine gravel deposits up to 75 feet thick and extend about 0.1-1.5 miles north of the Red River counties (Miller and Stanley, 2006; Stanley, 2004; Stanley and Chang, 2012; Stanley and Miller, 2004). Eolian dune deposits formed by southerly winds also occur on the terrace deposits and are prevalent in the western half of the study area.

Bedrock Units and Depositional Environments

During the Permian Period, a semi-arid/arid depositional environment occurred across the study area (Poland, 2011). Siliclastics, carbonates, and evaporites were deposited in the Anadarko and Hollis basins in what is now southwest and west-central Oklahoma and adjacent portions of Texas (Johnson, 2008). Fine-grained sediments were likely supplied from the east/southeast and northwest (Davis, 1955; Johnson, 2008).

During the Triassic and Jurassic periods, most of the study area was likely above sea-level resulting in an unconformity between Permian rocks and Cretaceous rocks (Johnson, 2008). During the Cretaceous Period, a shallow sea covered most of Oklahoma with shales, sandstones, and limestones being deposited across the study area (Johnson, 2008). Uplift occurred in the late Cretaceous and early

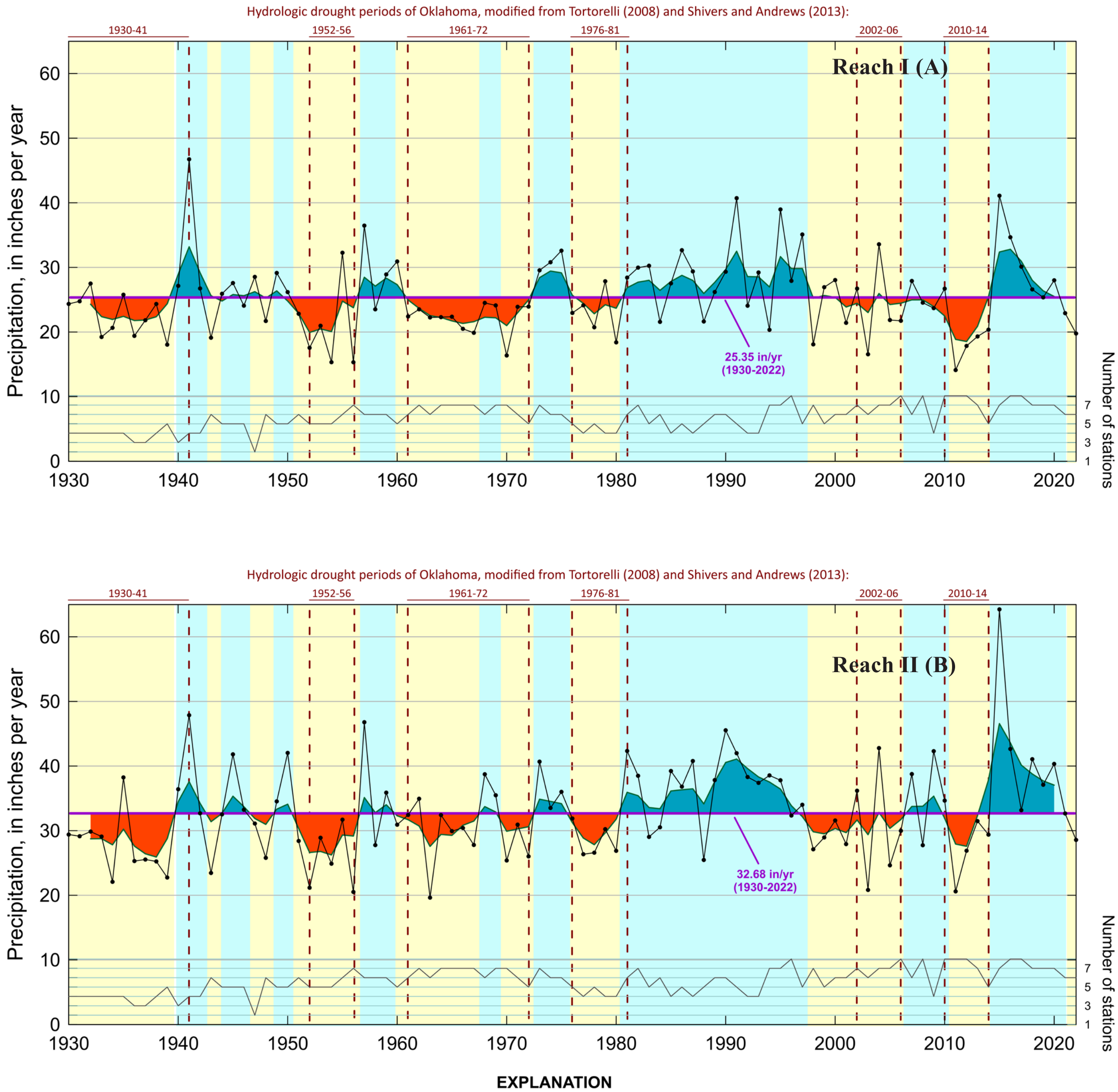


Figure 3. Annual precipitation 1930-2022, wet and dry periods defined as the departure of the 5-year moving average from mean annual precipitation, and the number of observer stations recording during each year for Reach I (A) and Reach II (B) of the Red River alluvial and terrace aquifer.

Tertiary as the Rocky Mountains formed to the west causing the sea to withdraw resulting in the erosion of Cretaceous rocks from most of western Oklahoma.

In the Tertiary Period, alluvial sediments eroded from the Rocky Mountains creating the Ogallala Formation across the western half of Oklahoma (Johnson, 2008). Tertiary deposits have since been eroded across the study area. The present-day river positions in Oklahoma formed in the Quaternary Period because of glacial meltwater and increased precipitation (Johnson, 2008). River channels shifted and down cut over time into underlying bedrock units, creating valleys that were eventually filled with sand and gravel. Multiple deposition and erosion cycles resulted in alluvial sand and gravel terraces tens to hundreds of feet above modern flood plains (Johnson, 2008).

Cretaceous-Age Bedrock Units

Cretaceous-age bedrock units have been eroded from most of the study area and only underlie the Red River Alluvial and terrace aquifer in Love County. The six Cretaceous-age bedrock units present in the study area

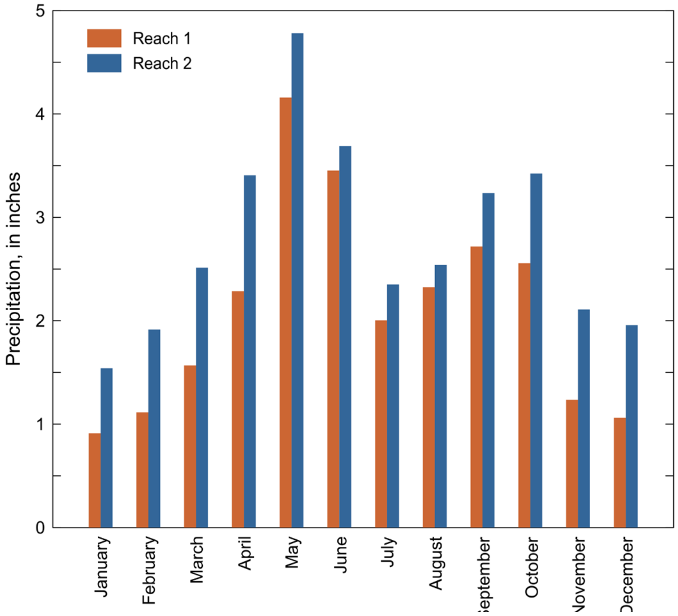


Figure 4. Mean monthly precipitation during the time period 1930-2022 for Reach I and Reach II of the Red River alluvial and terrace aquifer.

include the Bokchito Formation, Caddo Formation, Kiamichi Formations, Goodland Limestone, Walnut Clay, and Antlers Formation. The Bokchito Formation, Caddo Formation, Kiamichi Formations, Goodland Limestone, and Walnut Clay form the Marietta aquifer, which is defined as a minor aquifer by the OWRB. These formations are primarily composed of clayshale, limestone, and sandstone (Stanley and Chang, 2012). The Antlers Formation consists of white to light brownish yellow, medium-grained sandstone (Chang and Stanley, 2013) and is defined as a major aquifer by the OWRB.

Permian-Age Bedrock Units

Permian-age formations underlie the Red River alluvial and terrace aquifer from Harmon County to western Love County. Four bedrock units of the El Reno Group underlie the Red River aquifer in Harmon and Jackson counties, including the Dog Creek Shale, Blaine Formation, Flowerpot Shale, and San Angelo Sandstone. The Dog Creek Shale and Flowerpot Shale consist primarily of reddish-brown shale with thin beds of gypsum (Stanley and Miller, 2004). The Blaine Formation is composed of thick layers of gypsum and shale (Stanley and Miller, 2004). The Blaine aquifer is defined as a major aquifer by the OWRB. The San Angelo Sandstone is a light gray to reddish-brown, fine-grained, sandstone with interbedded shale (Stanley, 2004).

Four Permian-age bedrock units underlie the Red River alluvial and terrace aquifer from eastern Jackson County to western Love County, including the Hennessey Shale, Waggoner Ranch Formation, Petrolia Formation, and Nocono Formation. These formations are composed of shale, mudstones, and sandstones with some thin interbedded limestone and dolomite beds (Miller and Stanley, 2006; Stanley and Chang, 2012; Stanley and Miller, 2005).

Characteristics of the Red River Alluvial and Terrace Aquifer

Streamflow and Base Flow

The portion of streamflow that originates from groundwater discharge is called base flow. Many streams in the study area do not originate in the alluvial and terrace deposits and have little to no flow during the summer because of high temperatures and low precipitation as well as increased evapotranspiration and groundwater use. However, several streams in Reach I originate on or near the aquifer while in Reach II, streams are generally larger and originate farther to the north of the study area.

Streamflow measurements were made on six different streams in Reach I with a FlowTracker2 to gain insight into interactions between the aquifer and surface water (Figure 7). Twenty-five other sites were investigated but not measured because of ponding or shallow conditions--less than 0.25 cubic feet per second (cfs). Sites were chosen based on the lack of nearby impoundments and access to the stream. The synoptic measurements were recorded during base flow conditions on February 6, 2023, when evaporation, evapotranspiration, and withdrawals were minimal. There were also assumed to be no contributions to streamflow from runoff due to only 0.10 inches of precipitation in the previous 12 days.

All of the measured streams were gaining streams at the time of measurement because of increases in flow toward the edges of the aquifer (Figure 7). The majority of streams near the edges of the aquifer boundary were ponded or had flow that was too shallow to measure and generally only had measurable flow 1-2 miles from the Red River. Measurements were taken at one location each on Blue, Curtis, Cooper, Augur, Gypsum, and Suttle creeks. Streamflow ranged from 0.21 cfs per mile at Blue Creek to 7.17 cfs at Gypsum Creek (Figure 7).

Water-Level Fluctuations

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

Period	Group	Formation	Member	Description	Thickness, in feet	Hydrogeologic Unit
Quaternary		Alluvial, terrace, and dune deposits		Unconsolidated sand, silt, clay and gravel	0 - 150	Red River Alluvium and Terrace Aquifer
Cretaceous	Washita	Bokchito		Mostly clay and clayshale, with some tan-colored limestones and fine-grained sandstones	[d]0 - 197	Marietta Minor Aquifer
		Caddo		Light gray, silty limestones and marls interbedded with blue-gray, silty clayshale or mudshale	[d]0 - 150	
	Fredericksburg	Kiamichi		Dark gray, clayshales and claystones, with interbedded limestone and sandstone	[d]0 - 30	
		Goodland Limestone and Walnut Clay		Medium to light gray limestone with thin, dark gray clayshale partings and an olive brown, calcareous claystone	[d]0 - 60	
		Antlers		White to light brownish yellow, medium-grained, sandstone with red to maroon conglomerates locally	[d]197 - 705	Antlers Aquifer
Permian	Whitehorse	Marlow and Rush Springs		Reddish-brown and orange-brown, fine-grained sandstone and minor siltstone	[b]0 - 98	
	El Reno	Dog Creek Shale		Red-brown shale with thin gypsum-dolomite beds in the lower 50 feet	[b]0 - 180	Confining
		Blaine	Van Vacter Member	Thick gypsum beds with underlying dolomite seperated by thin shales	[a]90 - 110	Blaine Aquifer
			Elm Fork Member	Alternating thick beds of shale and gypsum with thin underlying dolomite beds	[a]90 - 110	
		Flowerpot Shale		Reddish-brown, silty shale with thin interbeds of greenish-gray shale and several thin layers of gypsum and dolomite in the upper part	[b]150 - 300	Confining
		San Angelo		Interbedded reddish-brown, unstratified silty mudstones and trough-cross-bedded, medium to fine-grained sandstones	[b]65 - 100	
		Hennessey		Reddish-brown shale, with some reddish-brown siltstone beds	[b]130 - 200	
	Wichita	Waggoner Ranch		Interbedded reddish-brown laminated silty mudstones and thin limestone and dolomite beds	[c]130 - 195	
		Petrolia		Interbedded reddish-brown, silty mudstones and medium to fine-grained sandstones, with local conglomeratic beds	[a,c]230 - 400	
		Nocona		Reddish-brown, locally gray, mudstone interbedded with thin intervals of tan to dark gray, fine-grained sandstones and siltstones	[d]280 - 350	

[a]Stanley, 2004
[b]Stanley and Miller, 2004
[c]Miller and Stanley, 2006
[d]Stanley and Chang, 2012

Figure 5. Stratigraphic column of geologic and hydrogeologic units in the study area.

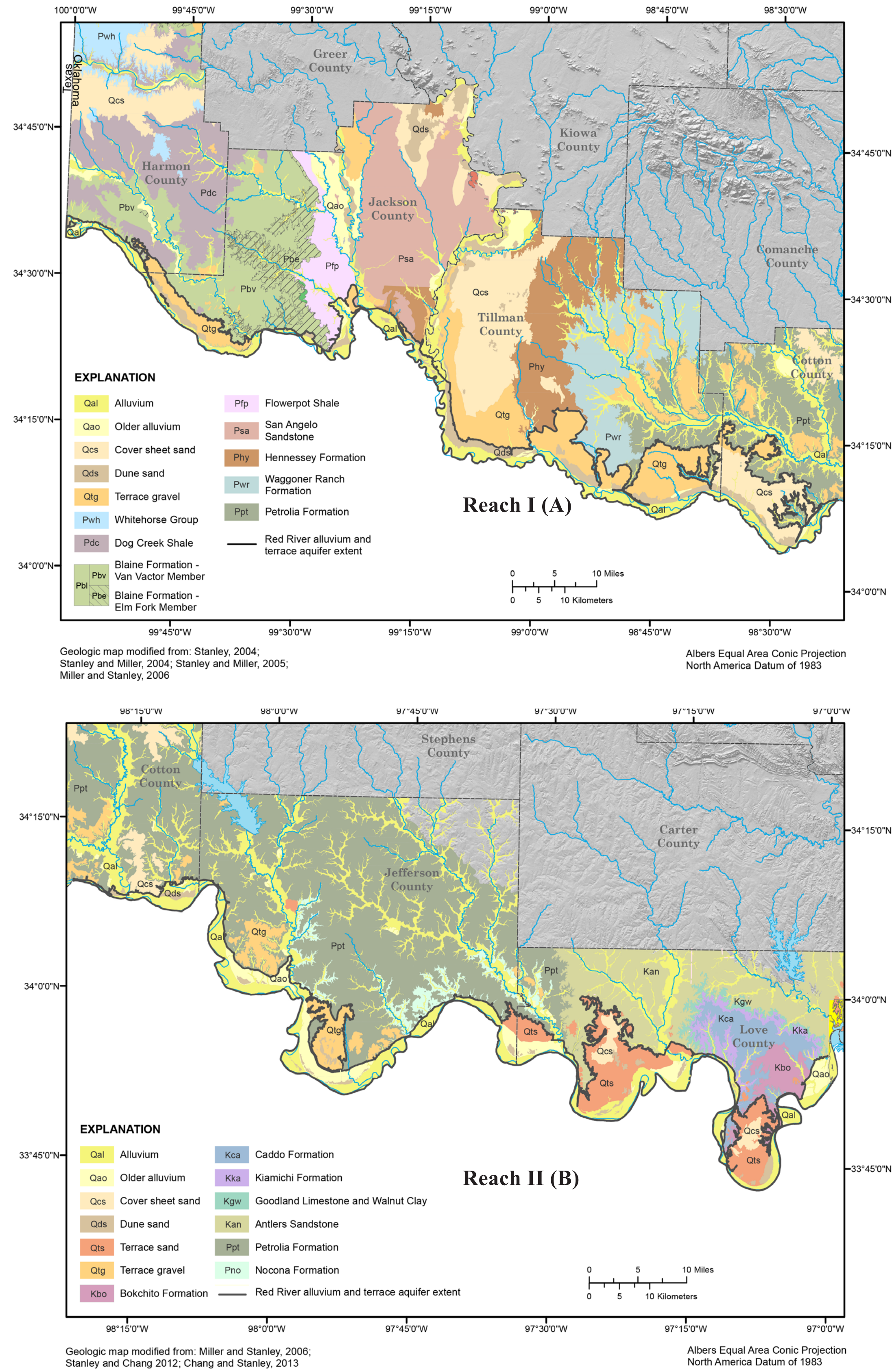


Figure 6. Surficial geologic units in Reach I (A) and Reach II (B) of the Red River alluvial and terrace aquifer.

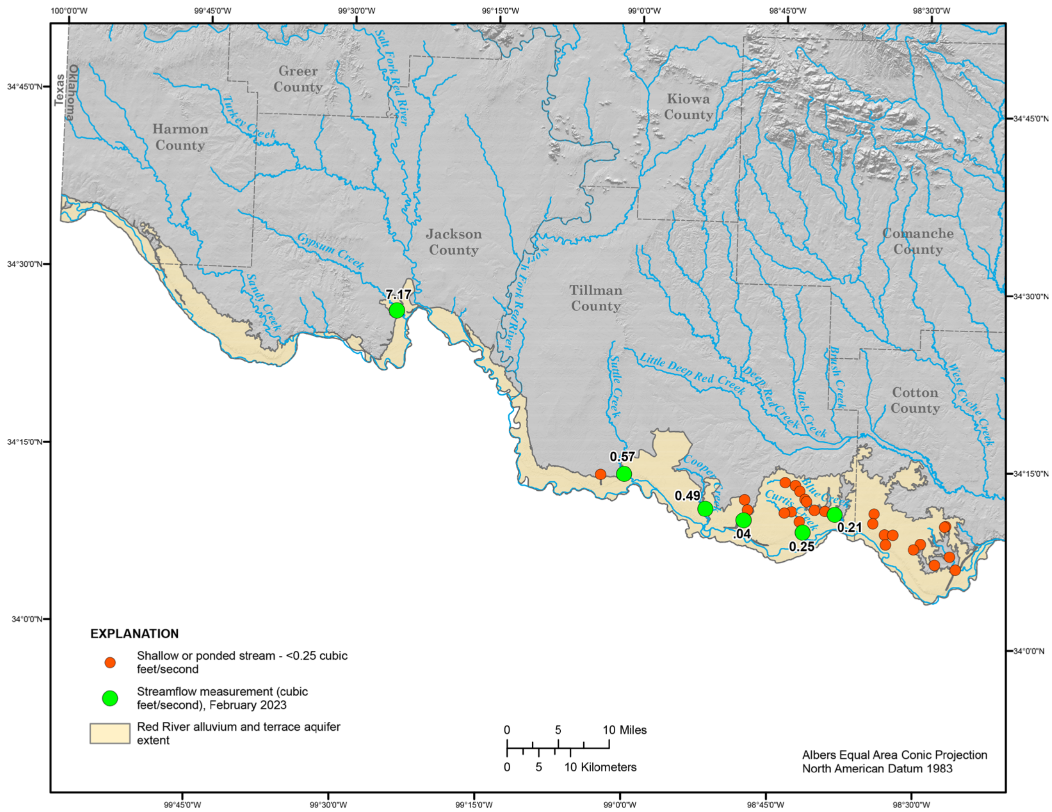


Figure 7. Streamflow measurements in Reach I of the Red River alluvial and terrace aquifer in cubic feet per second and locations.

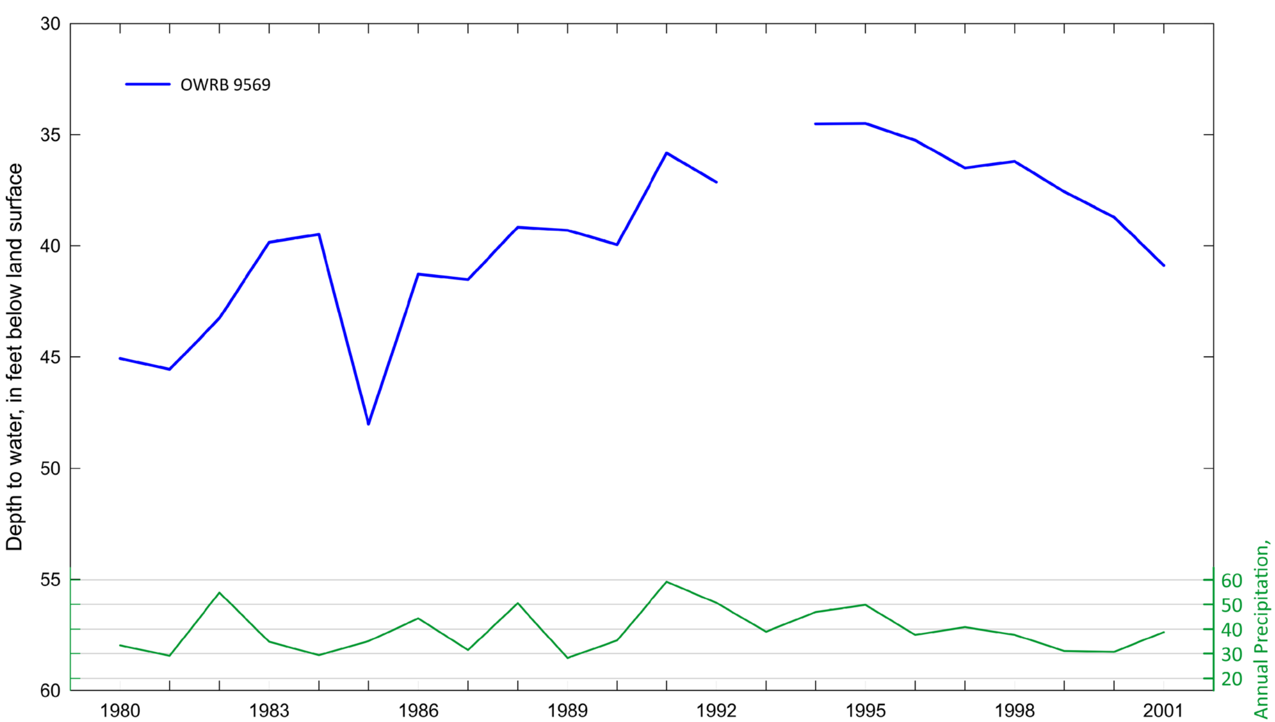


Figure 8. Water levels from OWRB Mass Measurement Program well 9569 showing long-term response (see figure 1 for location).

for showing seasonal pumping trends and responses to precipitation events.

Historical Water Levels

Long-term periodic water-level observations have been collected in the Red River alluvial and terrace aquifer by the OWRB since the early 1980s. These data are stored by the OWRB using OWRB well identifiers and in the USGS National Water Information System database using unique USGS site numbers. As of 2022, two wells in the study area are measured annually for groundwater levels with an additional 16 wells with historical groundwater-level observations that were discontinued for various reasons such as obstructions or landowner changes. One well (OWRB 9569) with long-term measurements between 1980 and 2001 was analyzed for this investigation (Figure 8). This well was chosen because it had the longest period of record and least amount of data gaps.

Trends in groundwater-level data show fluctuations primarily with climate cycles. Water levels typically rose in years of increased precipitation and declined in years of decreased precipitation. Water-level responses to precipitation can sometimes be seen in the following year because of the timing of precipitation in relation to the annual water-level measurements. The groundwater level ranged from 48.0 to 34.5 feet below land surface with an increase of 4.2 feet at this site during the period of record.

Continuous Water Levels

Water-level recorders were installed at two wells in October and November 2019: OWRB 198253 located in Reach I and OWRB 97864 located in Reach II (Table 2). Depth to water was recorded continuously at 1-hour intervals with water levels ranging from 15.5 to 11.2 feet below land surface at OWRB 198259 and 28.2 to 21.7 feet below land surface at OWRB 97864 (Figure 9). Both wells show evidence of water-level responses because of precipitation and had small increases in water levels in the spring and summer of 2020 and 2021. During the winter months, each well had relatively stable or declining water levels. Seasonal water-level changes were greater in OWRB 97864, notably in 2020, most likely due to the higher mean precipitation in Reach II (41.2 inches) compared to Reach I (24.4 inches) in 2020.

Regional Groundwater Flow

A potentiometric surface map of an aquifer is an estimated surface of the water table and reflects the altitude to which a column of water will rise in a cased well at any given point. The water table in an unconfined aquifer is defined by the upper limit of the zone of saturation and is the same as the potentiometric surface for the Red River alluvial and terrace aquifer in this report since the aquifer flows under unconfined conditions. A potentiometric surface map is constructed by contouring static water-level measurements in wells and can be used to determine the direction of horizontal groundwater flow.

To create a potentiometric surface map for Red River alluvial and terrace aquifer, depth-to-water was measured in 31 wells as a part of this investigation in January and February 2020 (Figure 1). Depth-to-water measurements recorded on 380 well driller completion reports were used to supplement areas where measurements were not obtained. Most of the water levels were collected from wells used for domestic supply, irrigation, and livestock. The 2020 measurements ranged from 67.6 to 8.3 feet below land surface with a mean depth of 22.9 feet. Land surface altitude was collected at each well site using high-precision GPS receivers with decimeter accuracy, and a 10-meter digital elevation model was used for wells in which well drillers completion reports were used. The depth-to-water measurements were subtracted from land surface elevations referenced to the North American Datum of 1988 (NAVD 88) to estimate the potentiometric surface and contours were interpolated to illustrate groundwater flow (Figure 10).

Regional groundwater flow in the aquifer is generally from north to south and west to east toward the Red River with water-level contours bending upstream near the Red River. In the high terrace deposits, groundwater flow is locally toward streams and the edges of the aquifer. A “V” pattern in the water-level contours occurs within the larger terraces in Tillman, Cotton, and Love counties indicating groundwater flow toward streams and drainages within the terrace deposits.

Groundwater Use

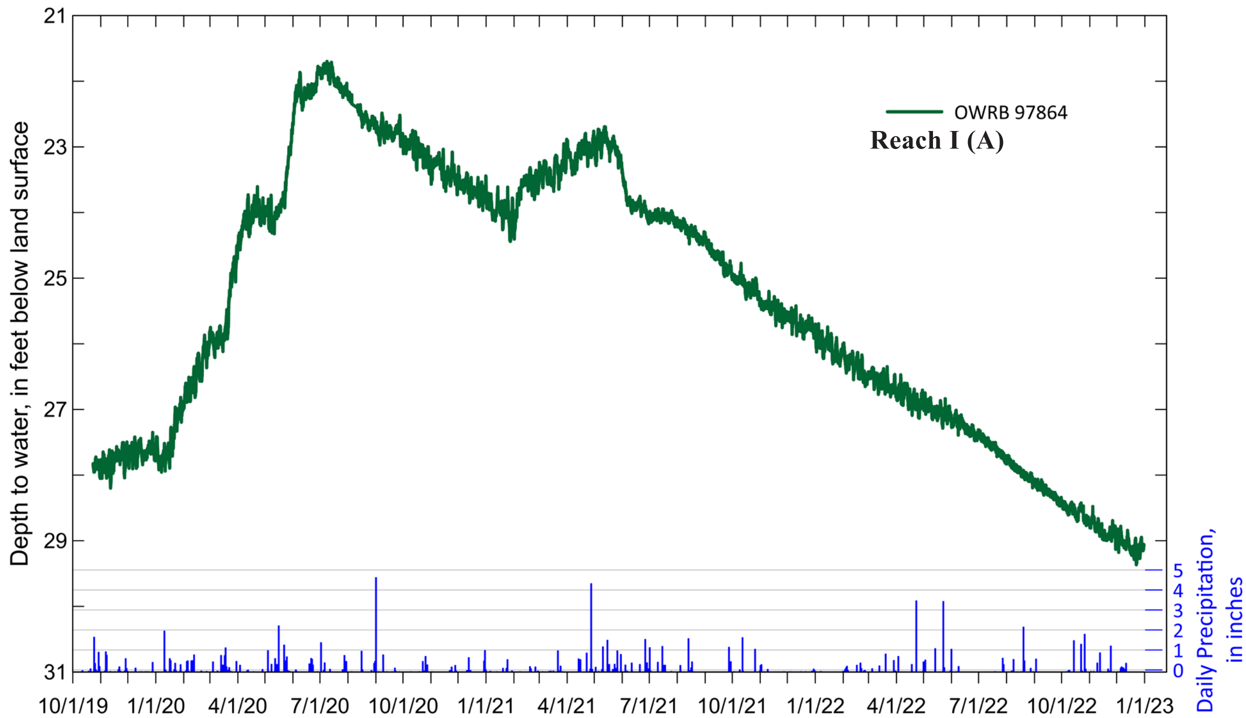
The OWRB permits groundwater for long-term, non-domestic beneficial use including public water supply; irrigation; industrial; power; mining; commercial; agricultural; and fish, recreation, and wildlife. Permit holders submit annual water-use reports to the OWRB with complete records beginning around 1967. Prior to 1980, irrigation water use amounts were estimated based on crop type, acres, and frequency of application. In 1980, the method was changed to include inches applied to increase accuracy of the estimated irrigation use (Oklahoma Water Resources Board, 2022).

Groundwater in both reaches of the Red River alluvial and terrace aquifer is used primarily for irrigation and public water supply. The term “public water supply” is used to describe groundwater use by municipalities, rural water districts, housing additions, trailer parks, churches, and schools. As of 2022, the OWRB had over 200 well completion reports for groundwater wells screened or partially screened in the Red River alluvial and terrace aquifer. Mean well yields are about 189 gallons per minute and range from 2 to 1,200 gallons per minute. Non-domestic water uses such as irrigation; public supply; industrial;

Table 2. Groundwater well sites with continuous water-level recorders in the Red River alluvial and terrace aquifer.

OWRB Well ID	Latitude	Longitude	Total well depth, in feet below land surface	Period of analysis
198253	34.20949288	-98.88862967	37	11/22/2019 - present*
97864	33.81969333	-97.11808455	40	10/23/2019 - present*

*recording at time of publication



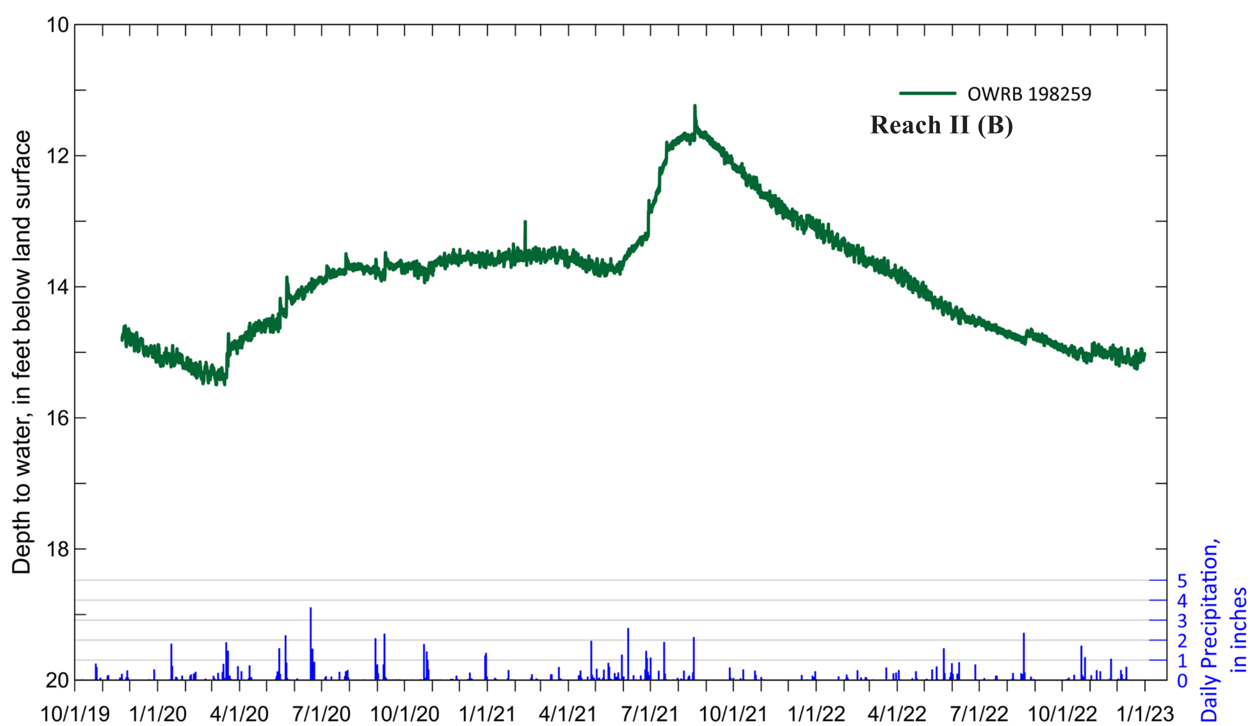


Figure 9. Water level from OWRB continuous water-level recorder wells 198253 in Reach I (A) and 97864 (B) in Reach II (see figure 1 for locations).

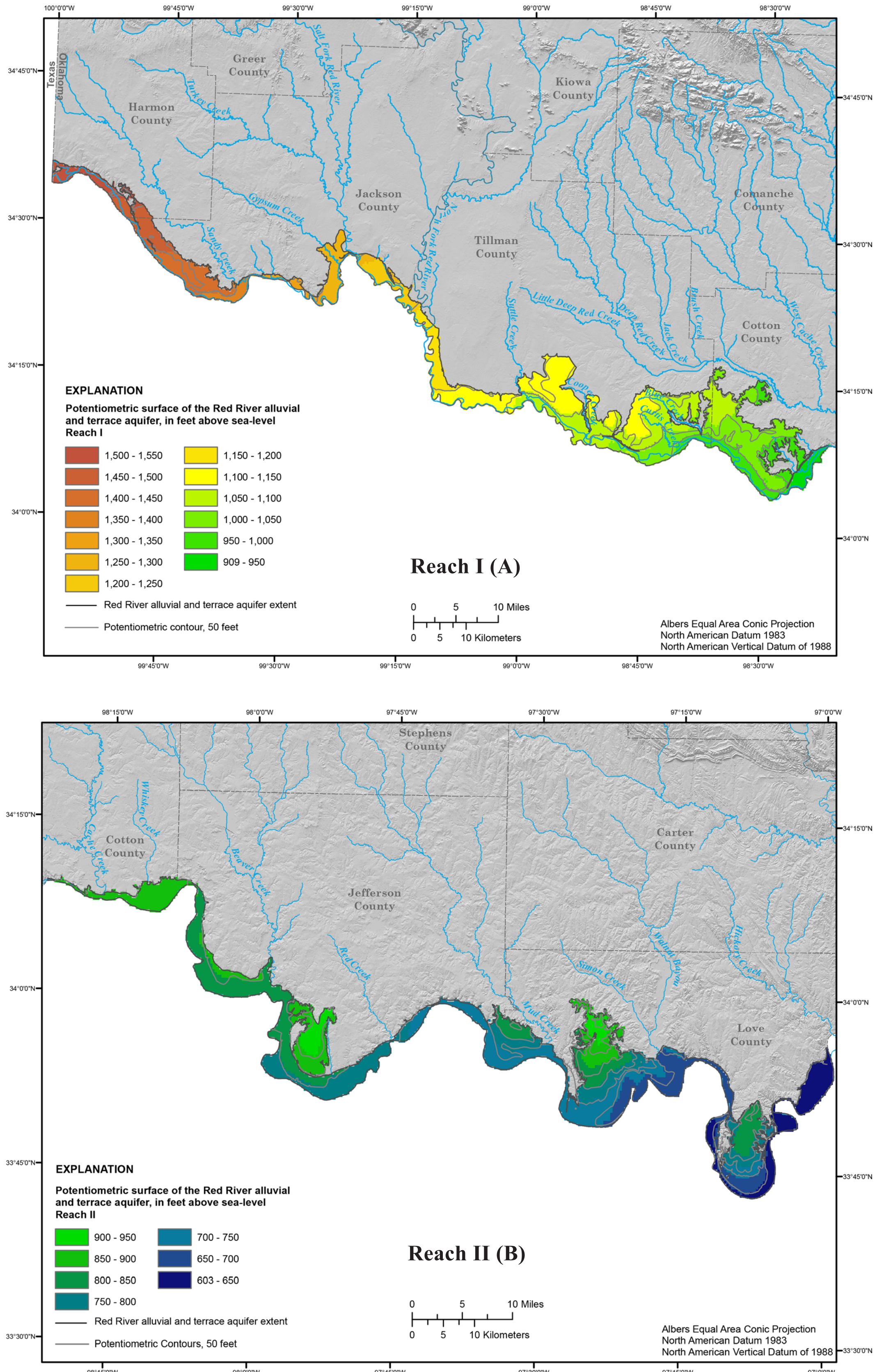


Figure 10. Raster map showing the potentiometric surface (2020) in Reach I (A) and Reach II (B) of the Red River alluvial and terrace aquifer.

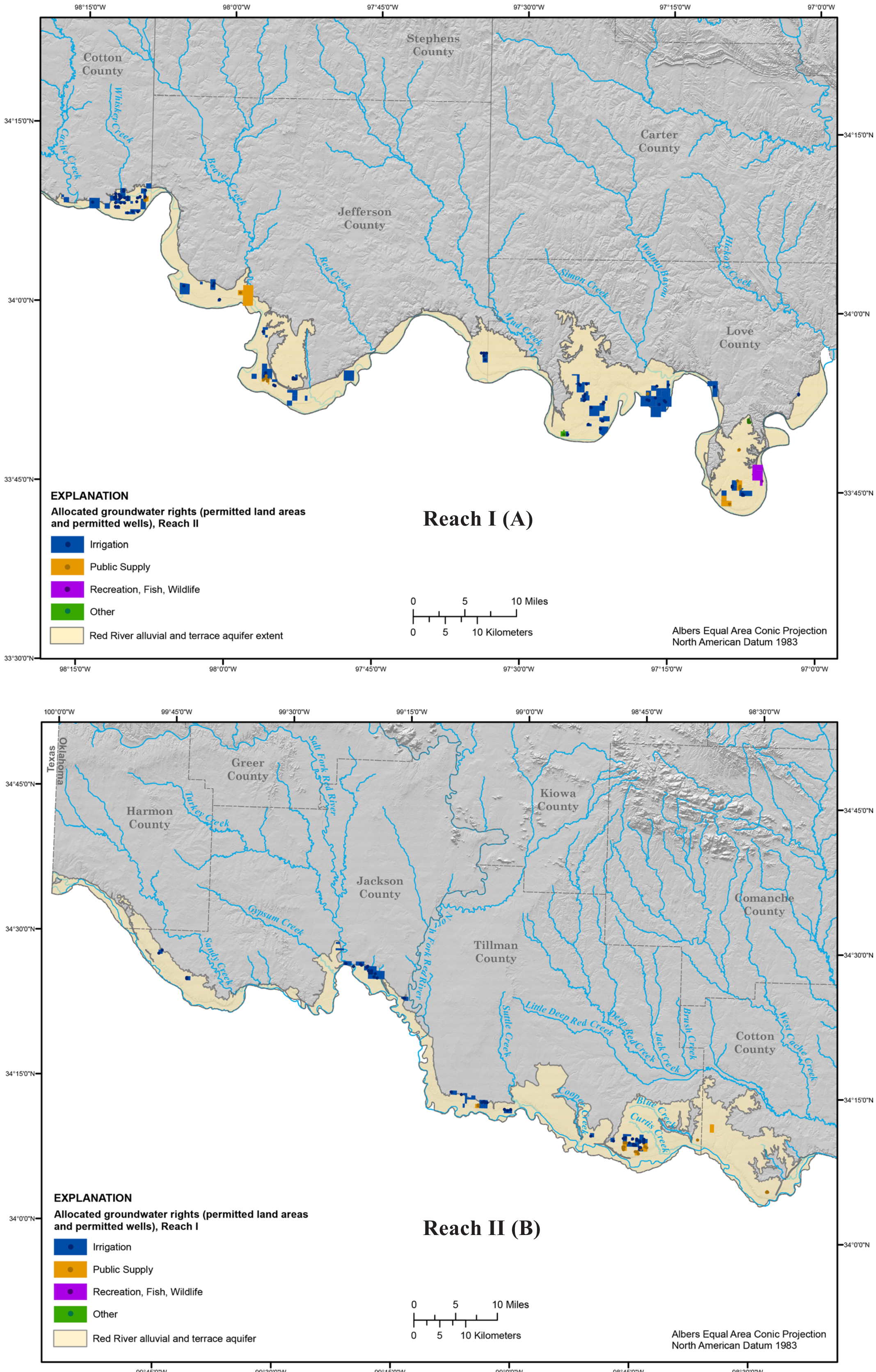


Figure 11. Permitted land areas and well locations permitted for groundwater use in Reach I (A) and Reach II (B) of the Red River alluvial and terrace aquifer, 2022.

power; mining; commercial; agricultural; and recreation, fish, and wildlife are self-reported to the OWRB annually with complete records beginning around 1967. Water use reports are not required for domestic groundwater use.

Long-Term Permitted Groundwater Use

The number of active long-term temporary or prior right groundwater permits in 2022, include 45 in Reach I and 45 in Reach II (Figure 11). There are an additional 6 inactive permits in Reach I and 15 inactive permits in Reach II. Annual groundwater use has been reported for 47 permits in Reach I and 52 permits in Reach II to the OWRB by permitted users between 1967-2022. In Reach I, irrigation accounted for 84.0 percent of groundwater use and public water supply accounted for 16.0 percent, with other use accounting for less than 0.1 percent (Figure 12; Table 3). In Reach II, irrigation accounted for 87.1 percent and public water supply accounted for 9.3 percent (Figure 12; Table 3). Recreation, fish, and wildlife accounted for 3.5 percent of use

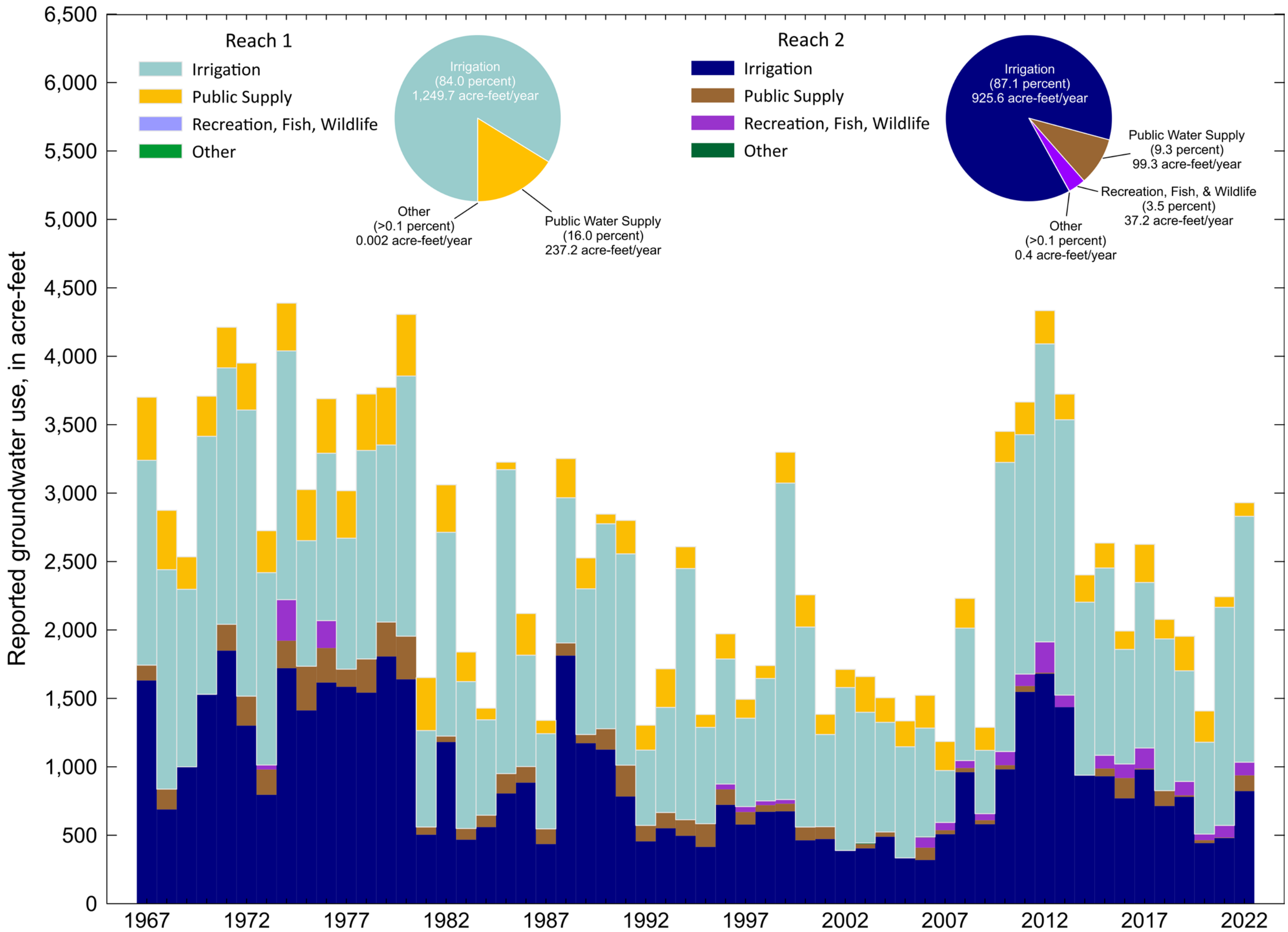


Figure 12. Annual reported groundwater use in Reach I and II of the Red River alluvial and terrace aquifer, 1967-2022.

Table 3. Reported mean annual groundwater use by type in the Red River alluvial and terrace aquifer, 1967-2022.

	Mean annual reported water use by type, in acre-feet per year, 1967-2022			
	Irrigation	Public water supply	Recreation, Fish, & Wildlife	Other
Reach 1	1,250	237	0	< 0.1
Reach 2	926	99	37	0.4

with less than 0.1 percent for other uses. The mean reported groundwater use between 1967-2022 was 1,487 acre-feet per year in Reach I with a median of 1,406 acre-feet per year. In Reach II, the mean reported groundwater use was 1,062 acre-feet per year with a median of 975 acre-feet per year. The lowest reported annual use in Reach I was 592 acre-feet in 2007, excluding 1992 due to incomplete records, and the lowest reported annual use in Reach II was 334 acre-feet in 2005. The highest reported annual use was 2,538 acre-feet (Reach I) in 1999 and 2,221 acre-feet (Reach II) in 1974.

Three time periods (1967-91, 1992-2007, and 2008-22) were identified in both reaches based on trends in the reported groundwater use data (Table 4). The first period, 1967-91, had the highest mean annual reported groundwater use with 1,664 acre-feet per year (Reach I) and 1,365 acre-feet per year (Reach II). A period of lower mean annual reported groundwater use occurred from 1992 to 2007 with 1,195 acre-feet per year (Reach I) and 590 acre-feet per year (Reach II). A period of higher mean annual reported groundwater use occurred from 2008 to 22 with 1,535 acre-feet per year (Reach I) and 1,063 acre-feet per year (Reach II). The years with the highest reported groundwater use during this period (2010-13) coincide with drought conditions in the region.

Table 4. Summary statistics of reported groundwater use in the Red River alluvial and terrace aquifer, 1967-2022.

Reported annual groundwater use, in acre-feet per year				
Reach I				
Statistic	**1967-2022**	**1967-1991**	**1992-2007**	**2008-2022**
Mean	1,487	1,664	1,195	1,535
Median	1,406	1,713	1,035	1,488
Minimum	562	782	592	631
Maximum	2,538	2,434	2,538	2,421
Reach II				
Statistic	**1967-2022**	**1967-1991**	**1992-2007**	**2008-2022**
Mean	1,062	1,365	590	1,063
Median	975	1,278	584	1,034
Minimum	334	547	334	509
Maximum	2,221	2,221	874	1,913

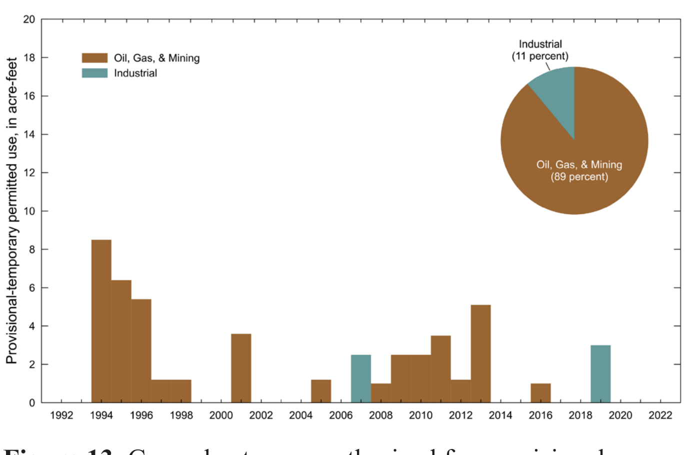


Figure 13. Groundwater use authorized for provisional-temporary permits, 1992-2022.

Provisional-Temporary Groundwater Permits

The OWRB issues provisional-temporary groundwater permits that expire 90 days after issuance. These permits are used to provide a short-term water supply or supplement the water supply of existing permit holders. Unlike long-term permits, water use reports are not required for provisional-temporary permits with volumes assumed not to exceed the authorized amount. The OWRB has records for provisional-temporary permits dating back to 1992. A more detailed description of provisional-temporary permits is available in OWRB Rules Chapter 30: Taking and Use of Groundwater (Oklahoma Water Resources Board, 2022). From 1992-2022, 32 provisional-temporary permits were issued in the aquifer. Oil, gas, and mining accounted for 30 permits and 89 percent of authorized use; industrial use accounted for 2 permits and 11 percent of authorized use (Figure 13). The mean authorized use for the entire period was 1.7 acre-feet per year.

Hydrogeology

Base of the Red River Alluvial and Terrace Aquifer

The base of the aquifer is the contact between Quaternary-age alluvial and terrace deposits of the Red River and the underlying Permian-age and Cretaceous-age formations. The base is typically distinguished in well drillers logs by a change in color and lithology. Lithology descriptions at the base typically include a transition from sands, clays, or gravels to shales, clays, and sandstones of the underlying bedrock formations. Color descriptions of alluvial and terraces deposits are primarily tan or brown with underlying Permian-age formations described as red or reddish-brown and Cretaceous-age formations described as gray, white, brownish-yellow, blue-gray, and tan.

The altitude of the base of the aquifer (Figure 14) was determined from 358 well driller lithologic descriptions in well completion reports from the OWRB groundwater well records database (Oklahoma Water Resources Board, 2020). The altitude of the base generally decreases from west to east and north to south, especially in areas with extensive terrace deposits. In Reach I, the altitude of the base ranges from about 1,599 feet above NAVD 88 near the Oklahoma-Texas border in Harmon County to about 875 feet above NAVD 88 along the Red River in Cotton County (Figure 14). The altitude of the base in Reach II ranges from about 960 feet above NAVD 88 at the westernmost point of Reach II in Cotton County to about 575 feet above NAVD 88 along

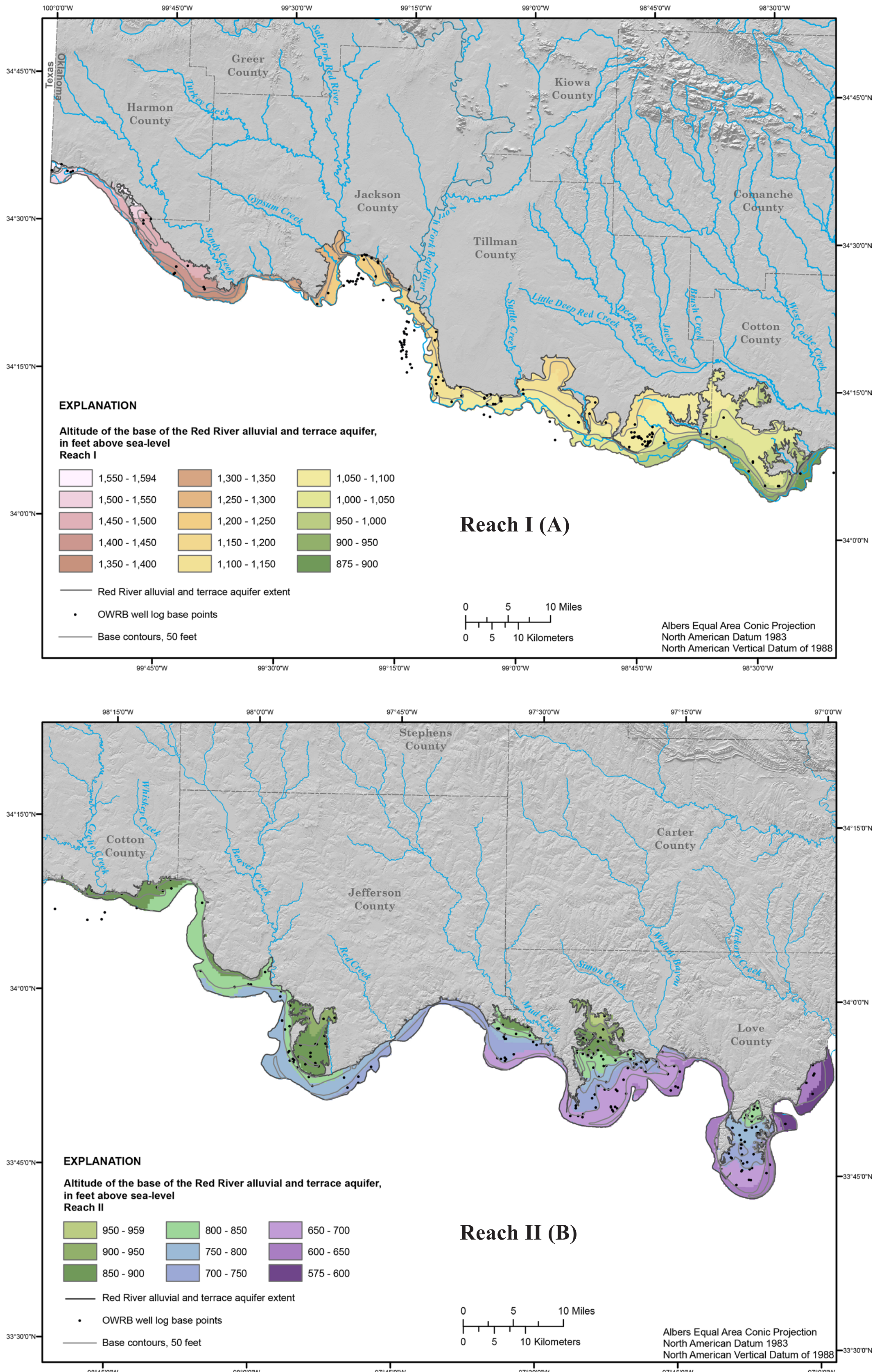


Figure 14. Raster map showing the altitude of the base of Reach I (A) and Reach II (B) of the Red River alluvial and terrace aquifer derived using lithologic logs submitted to the OWRB.

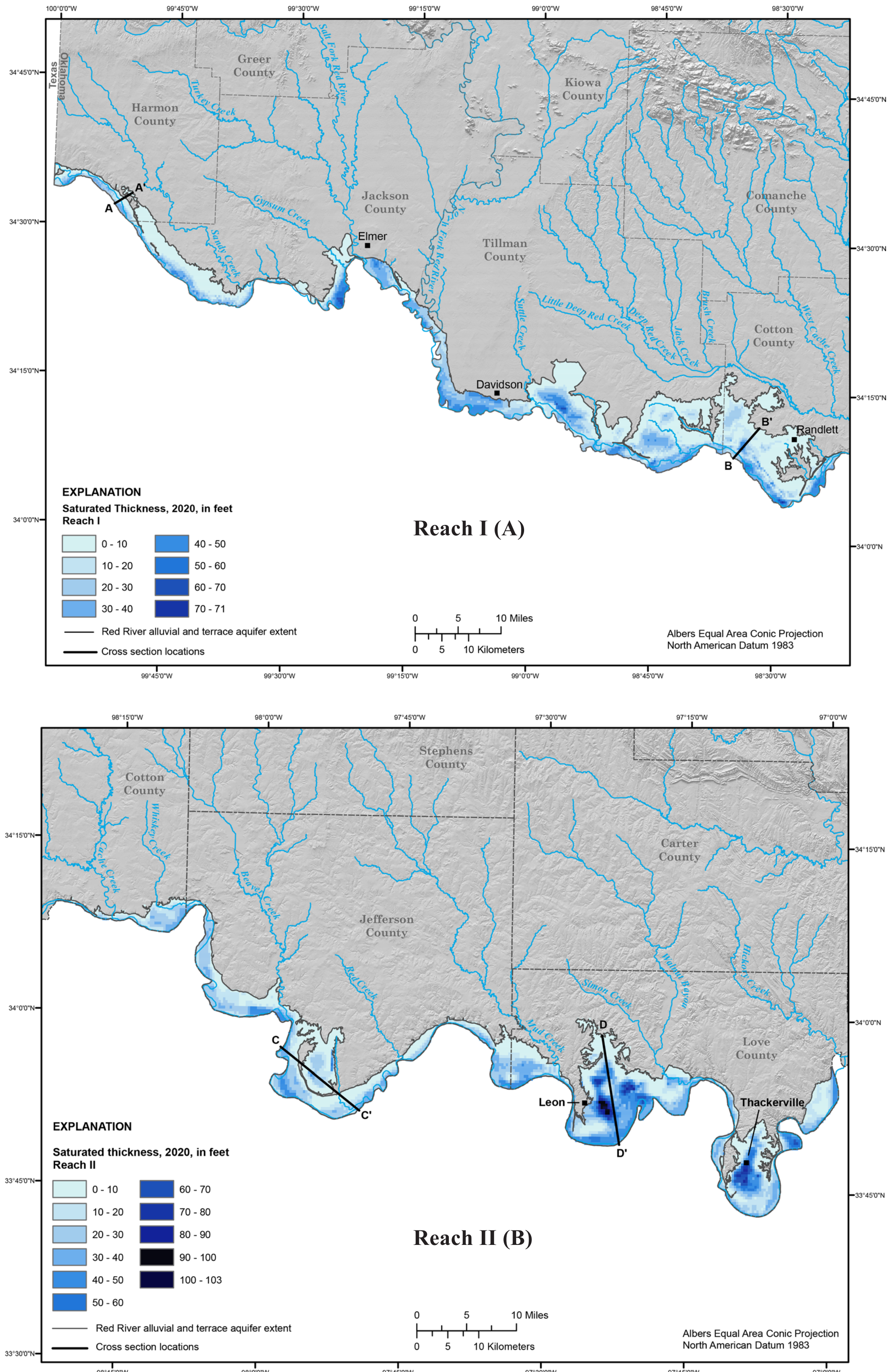


Figure 15. Saturated thickness (2020) and cross-section locations of Reach I (A) and Reach II (B) of the Red River alluvial and terrace aquifer.

the Red River in Love County about 11 miles northeast of Thackerville, Oklahoma (Figure 14).

Saturated Thickness of the Red River Alluvial and Terrace Aquifer

The saturated thickness of the Red River alluvial and terrace aquifer (Figure 15) was estimated by subtracting the base of the aquifer (Figure 14) from the 2020 potentiometric surface (Figure 10). The saturated thickness typically decreases to less than 10 feet where the alluvial and terrace deposits thin to the north. In Reach I, the mean saturated thickness within the aquifer boundary was 16 feet with a mean saturated thickness of 26 feet in areas in which the aquifer is saturated. The saturated thickness was generally greater near the Red River where wide floodplain deposits are present and in areas with thick terrace deposits (Figure 15). The thickest saturated portions were 60 to 71 feet and are located in three areas: seven miles southwest of Elmer, Oklahoma; eight miles southeast of Davidson, Oklahoma; and 7.5 miles southwest of Randlett, Oklahoma. In Reach II, the mean saturated thickness within the aquifer boundary was 22 feet with a mean saturated thickness of 27 feet in areas in which the aquifer is saturated. The saturated thickness was generally the greatest in the larger terrace deposits in Love County and in floodplains near the Red River (Figure 15). The thickest saturated portions were 100 to 103 feet, located about two miles east of Leon, Oklahoma and about one mile southwest of Thackerville, Oklahoma.

Cross Sections

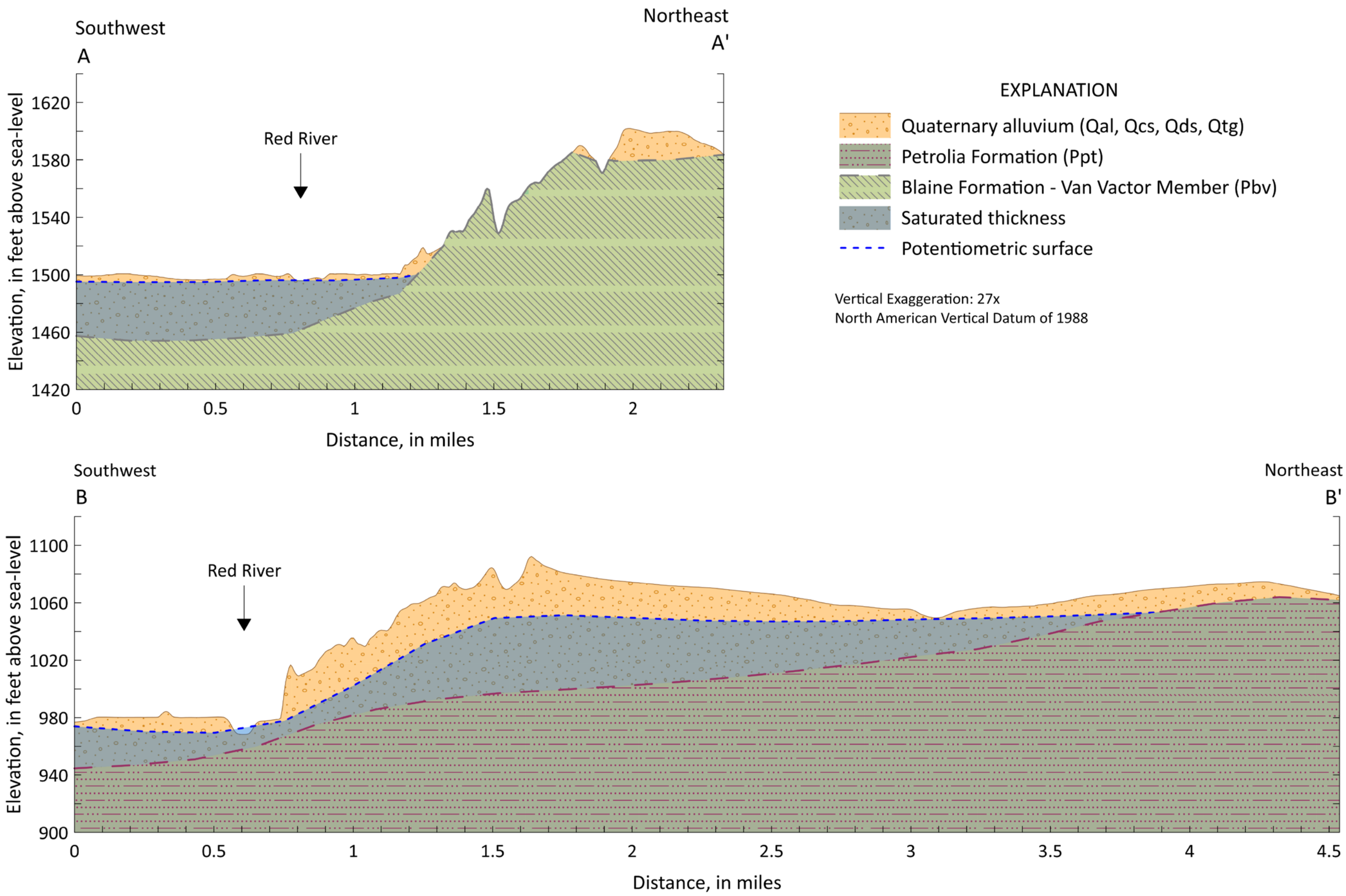
Four cross sections of the Red River alluvial and terrace aquifer (Figures 16, 17) were created showing the base of the aquifer (Figure 14) and the 2020 potentiometric surface datasets (Figure 10). Cross-section A-A' runs from southwest to northeast in the western part of Reach I in Harmon County and shows an area where the aquifer is located primarily in the current floodplain of the Red River (Figure 16). The underlying unit is the Van Vactor Member of the Blaine Formation. Terrace gravels are located about 90 feet above the current elevation of the Red River but are not saturated at this location. Cross-section B-B' runs from southwest to northeast in Cotton County and shows an area with about one mile of dune sand and an additional three miles of cover sand extending northeast of the Quaternary alluvial deposits (Figure 16). The aquifer is underlain by the Petrolia Formation at this location. Cross-section C-C' runs from northwest to southeast in Jefferson County showing terrace gravel and dune sand deposits located between a bend in the Red River (Figure 17). The terrace and dune deposits shown are up to 55 feet thick and thin outward from the thickest area in the middle of the terrace deposit. Cross-section D-D' runs from north to south in Love County and shows terrace sand and cover sand deposits extending more than 10.5 miles north of the Red River (Figure 17). The Antlers Formation underlies the aquifer at this location and is the primary source of groundwater for wells drilled in areas with thin terrace and cover sand deposits.

Recharge

Groundwater recharge is defined as the process of precipitation entering the groundwater flow system and is the primary means of inflow into the aquifer. The rate of recharge is controlled by various factors such as precipitation, soil type, aquifer lithology, vegetation, land use, and land-surface gradient. Recharge rates are often difficult to quantify because of high spatial and temporal variability. A code-based water-balance technique called the soil-water balance code (SWB), which uses precipitation and physical attributes to estimate recharge rates, was used to estimate recharge for the period of 1930-2022.

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

The SWB code only considers water input in the form of precipitation and runoff entering the grid cell from up-gradient. The daily precipitation value for a grid cell must exceed the interception and estimated potential evapotranspiration before water is assumed to contribute to soil moisture (Westenbroek and others, 2010). Once soil-moisture exceeds the maximum water capacity for the soil type, the grid cell is considered saturated and excess is converted to recharge (Westenbroek and others, 2010). 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 relationship. 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



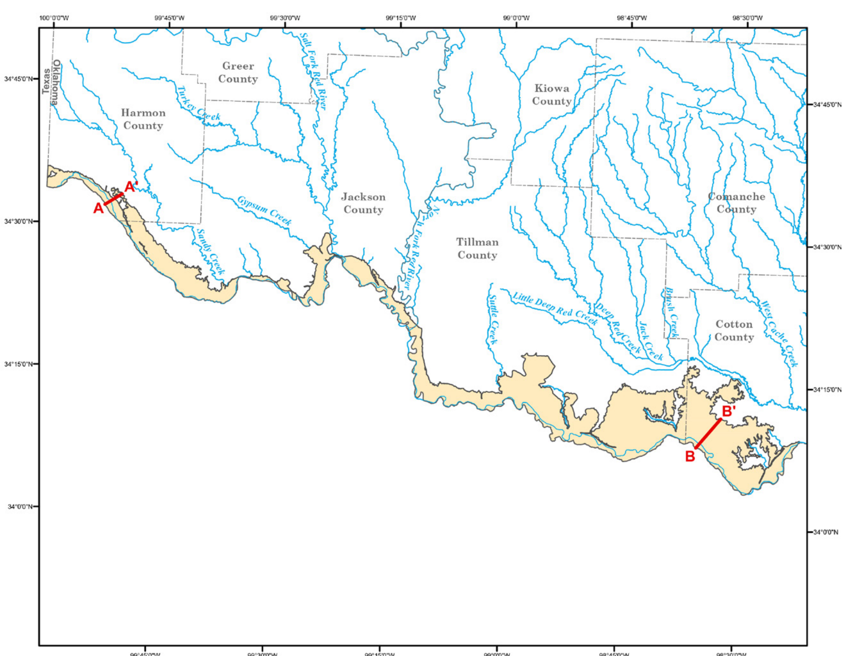


Figure 16. Cross-sections A-A' and B-B' and locations in Reach I of the Red River alluvial and terrace aquifer showing the geologic units, 2020 potentiometric surface, and saturated thickness.

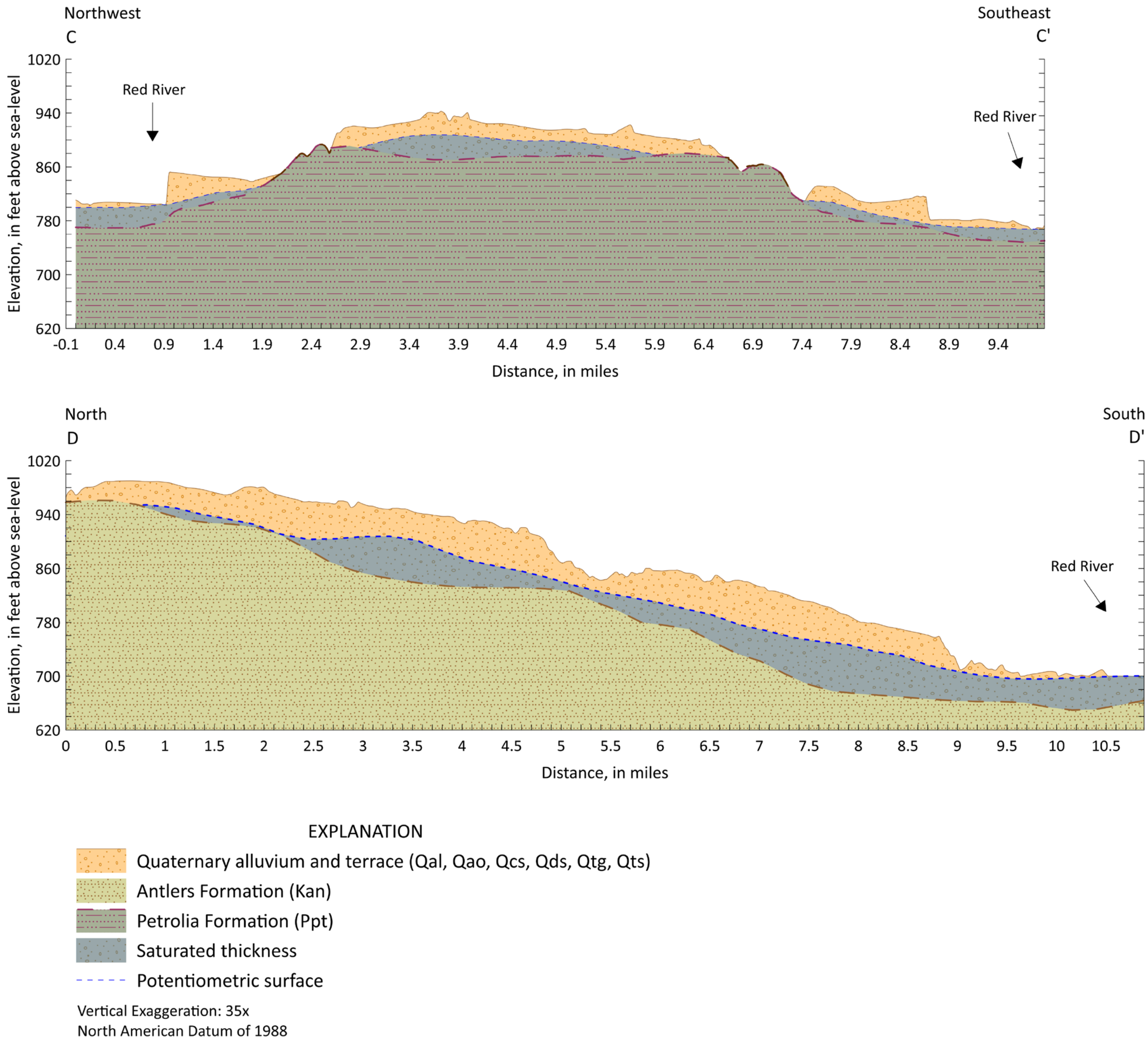
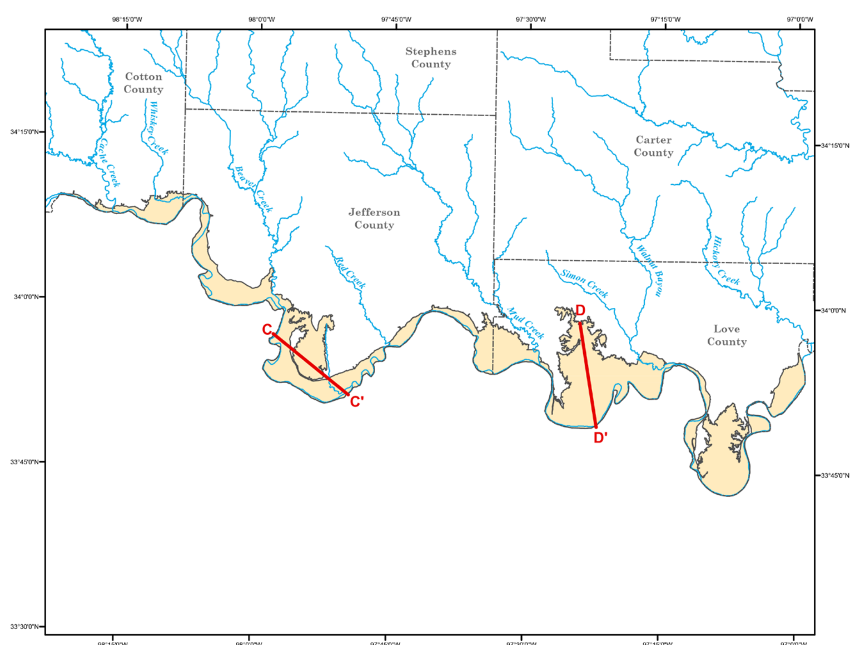


Figure 17. Cross-sections C-C’ and D-D’ and locations in Reach II of the Red River alluvial and terrace aquifer showing the geologic units, 2020 potentiometric surface, and saturated thickness.



(Westenbroek and others, 2010). The slope of the land surface is used only to direct estimated runoff to adjacent cells (Westenbroek and others, 2010).

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

Soil data were derived from the National Resources Conservation Service (NRCS) SSURGO dataset (National Resources Conservation Service, 2014). Soils are represented by four hydrologic soil groups (A-D) and are categorized based on infiltration capacity, with ‘A’ soils having the highest infiltration capacity and ‘D’ soils having very low infiltration capacity (Westenbroek and others, 2010). Each soil type must be assigned an available soil-water capacity (Westenbroek and others, 2010). The values for available soil-water capacity were assigned based on soil texture (Westenbroek and others 2010). Available water capacities range from 1.20 to 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, 2019). Land-use data, in conjunction with available soil-water capacity, were used to calculate surface run-off and maximum soil-moisture holding capacity (Westenbroek and others, 2010). The SWB model uses a land-use lookup table containing NRCS curve numbers, precipitation interception, maximum daily recharge values, and root-zone depths specific to each land-use type (Westenbroek and others, 2010). The data contained in the lookup table are provided by the NRCS (Westenbroek and others, 2010). Characteristics such as available water capacities, infiltration rates, root-zone depth, maximum soil recharge, interception, and curve numbers are based on the mean for each land and soil type. A flow direction grid 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 code was used to estimate spatially distributed groundwater recharge between 1930-2022 over the Red River alluvial and terrace aquifer. This 93-year time period was chosen based on the availability of precipitation data from multiple stations. The model requires tabular climate data and four gridded datasets: (1) soil-water capacity, (2) land-use classification, (3) hydrologic soil group, and (4) flow direction (Westenbroek and others, 2010). Climate data consisting of daily precipitation, daily minimum temperature, and daily maximum temperature were obtained from 16 COOP stations and six Oklahoma Mesonet stations located in the study area (National Oceanic and Atmospheric Administration, 2023; Oklahoma Climatological Survey, 2023c; Oklahoma Mesonet, 2023a). Each dataset was sampled to a 250 square-meter grid covering the extent of the aquifer.

The outputs of the SWB code were monthly and annual recharge grids that were clipped to the boundary of the Red River alluvial and terrace aquifer. Figure 18 shows the spatial variability in estimated mean annual recharge for 1930-2022. Estimated mean annual recharge in the aquifer during this period was 1.18 inches per year in Reach I and 3.57 inches per year in Reach II (Figure 19). Recharge is generally highest in areas near the Red River and in some of the larger terrace deposits likely caused by greater infiltration rates due to larger amounts of coarse-grained sand and gravel deposits. Mean annual recharge is greater in Reach II due to precipitation differences with mean annual precipitation in Reach II of 33.40 compared to 25.14 inches in Reach I.

Four time periods were selected based on trends of below or above mean recharge estimates: (1) 1930-80, (2) 1981-2001, (3) 2002-14, and (4) 2015-22 (Table 5). A prolonged period of below mean recharge occurred during the period 1930-80, with below mean recharge for 42 years (Reach I) and 40 years (Reach II) out of 51 years. A period of above mean recharge occurred during the period 1981-2001, with above mean recharge for 15 of the 21 years in each reach. This was followed by a period of below mean recharge between 2002-14 and a period of above mean recharge between 2015-22. The highest SWB-estimated annual recharge for both reaches occurred in 2015, with 5.57 inches in Reach I and 20.44 inches in Reach II (Figure 20). The lowest SWB-estimated annual recharge was 0.15 inches in 2012 in Reach I and 0.30 inches in 1963 in Reach II. Figure 21 shows the SWB-estimated recharge for 2011, a year with very low recharge in both reaches. Monthly recharge trends are similar for both reaches (Figure 22). The highest mean monthly recharge occurs in May with a mean of 0.21 inches in Reach I and 0.48 inches in Reach II. The lowest mean monthly recharge occurs in July with 0.03 inches in Reach I and 0.07 inches in Reach II.

Hydraulic Properties

Characteristics of an aquifer that affect groundwater flow and storage are referred to as hydraulic properties. The principle hydraulic properties estimated in this study to describe the Red River alluvial and terrace aquifer are hydraulic conductivity (K), transmissivity (T), and storativity (S). Hydraulic conductivity of the aquifer is defined as the rate of flow through a unit cross-sectional area under a unit hydraulic gradient (Lohman, 1972). Units for hydraulic conductivity are expressed in units of feet per day for this

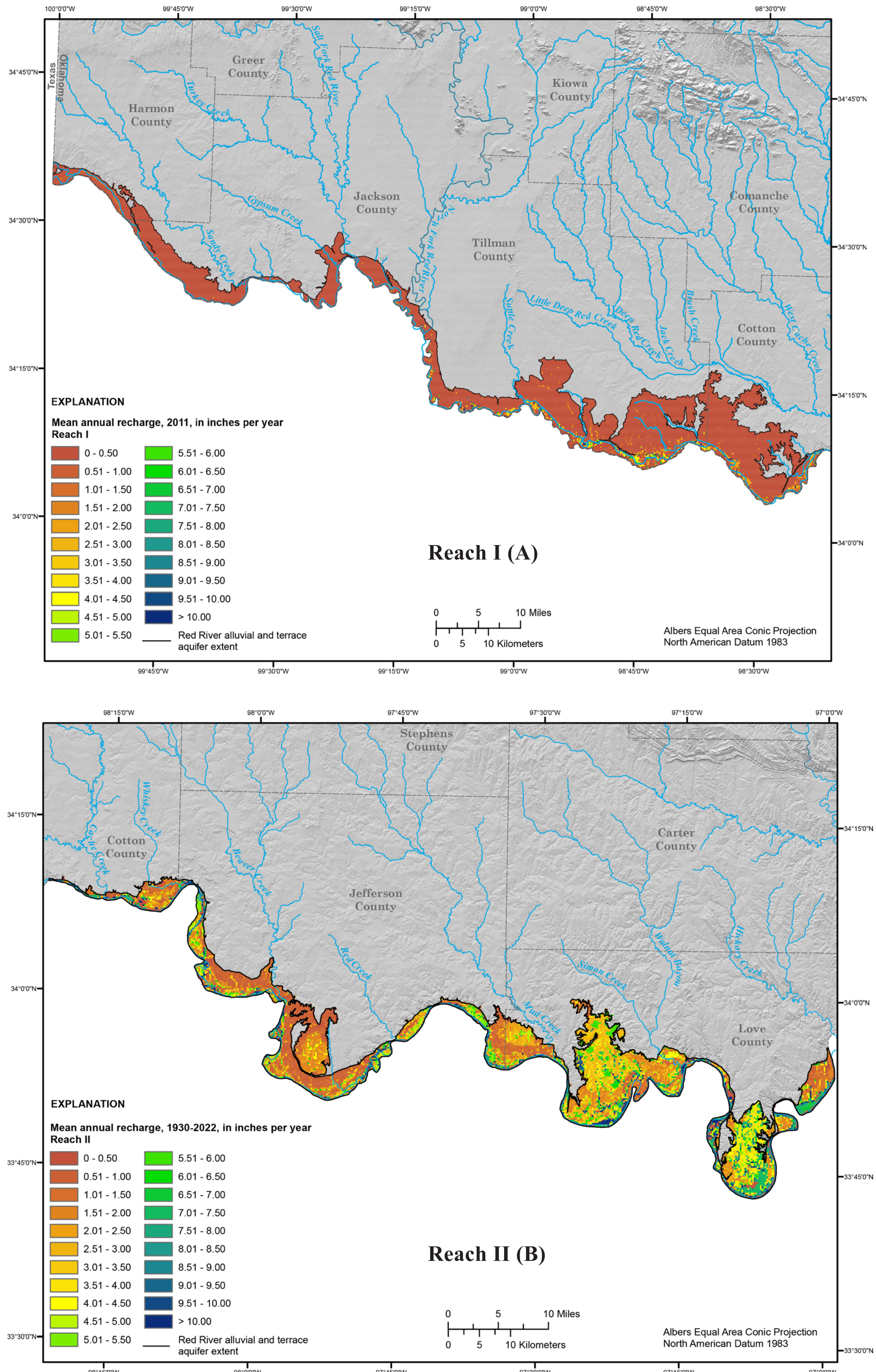


Figure 18. Spatial distribution of mean annual recharge to Reach I (A) and Reach II (B) of the Red River alluvial and terrace aquifer calculated using the SWB code, 1930-2022.

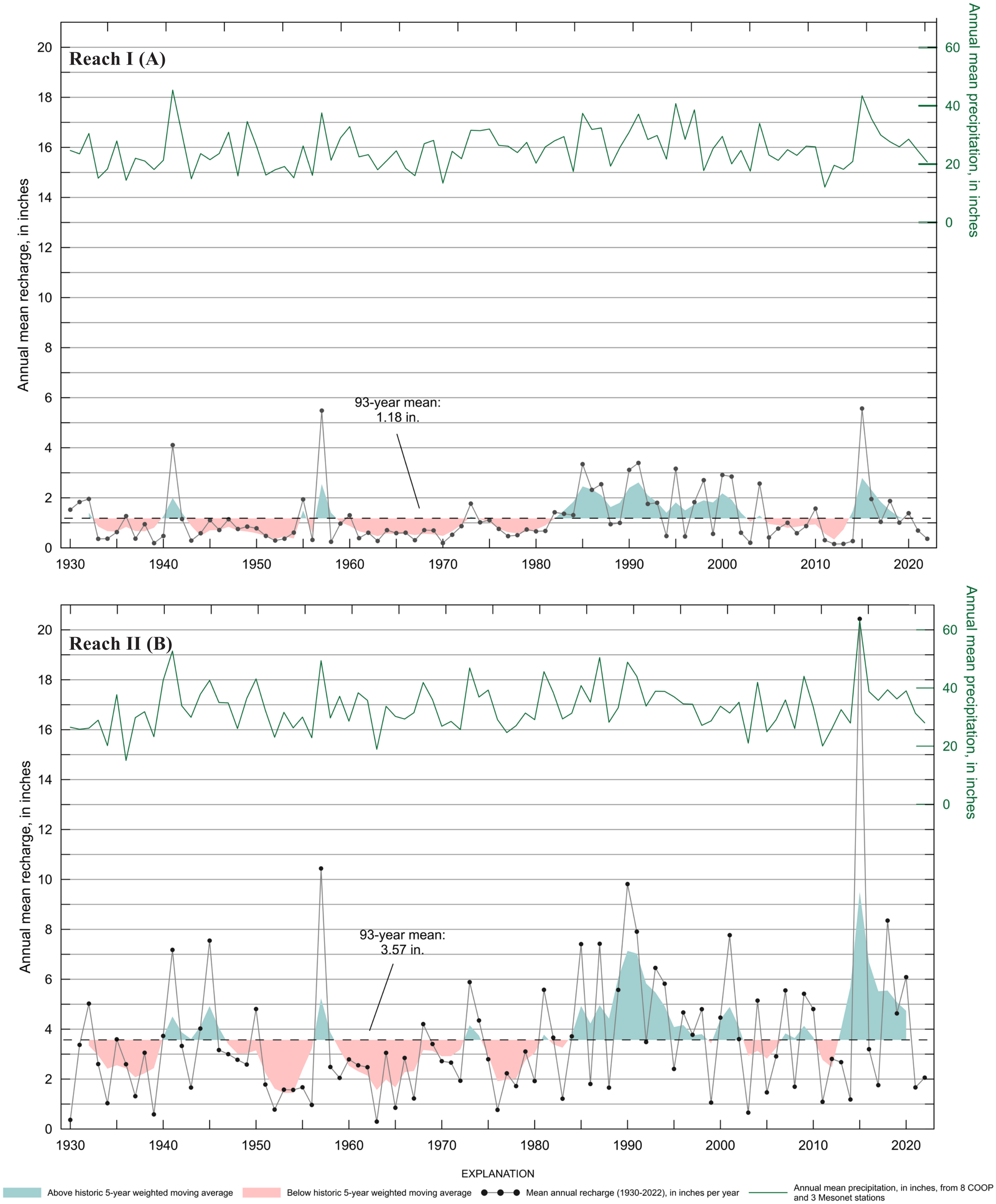


Figure 19. Mean annual recharge to Reach I (A) and Reach II (B) of the Red River alluvial and terrace aquifer using the SWB code, with historic 5-year moving average and mean annual precipitation, 1930-2022.

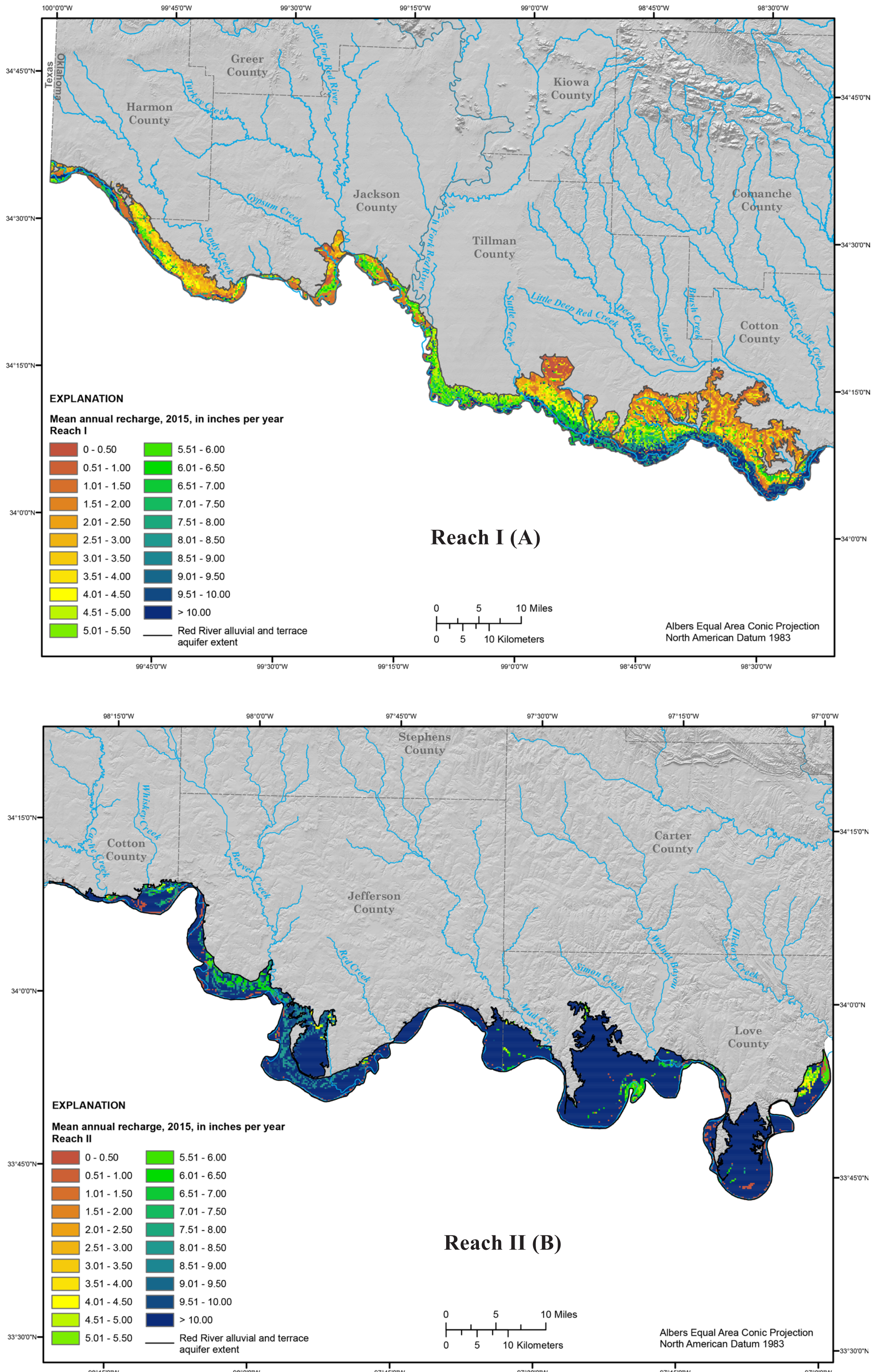


Figure 20. Mean annual recharge estimated by using the SWB code in Reach I (A) and Reach II (B) of the Red River alluvial and terrace aquifer in 2015, a year of above mean recharge.

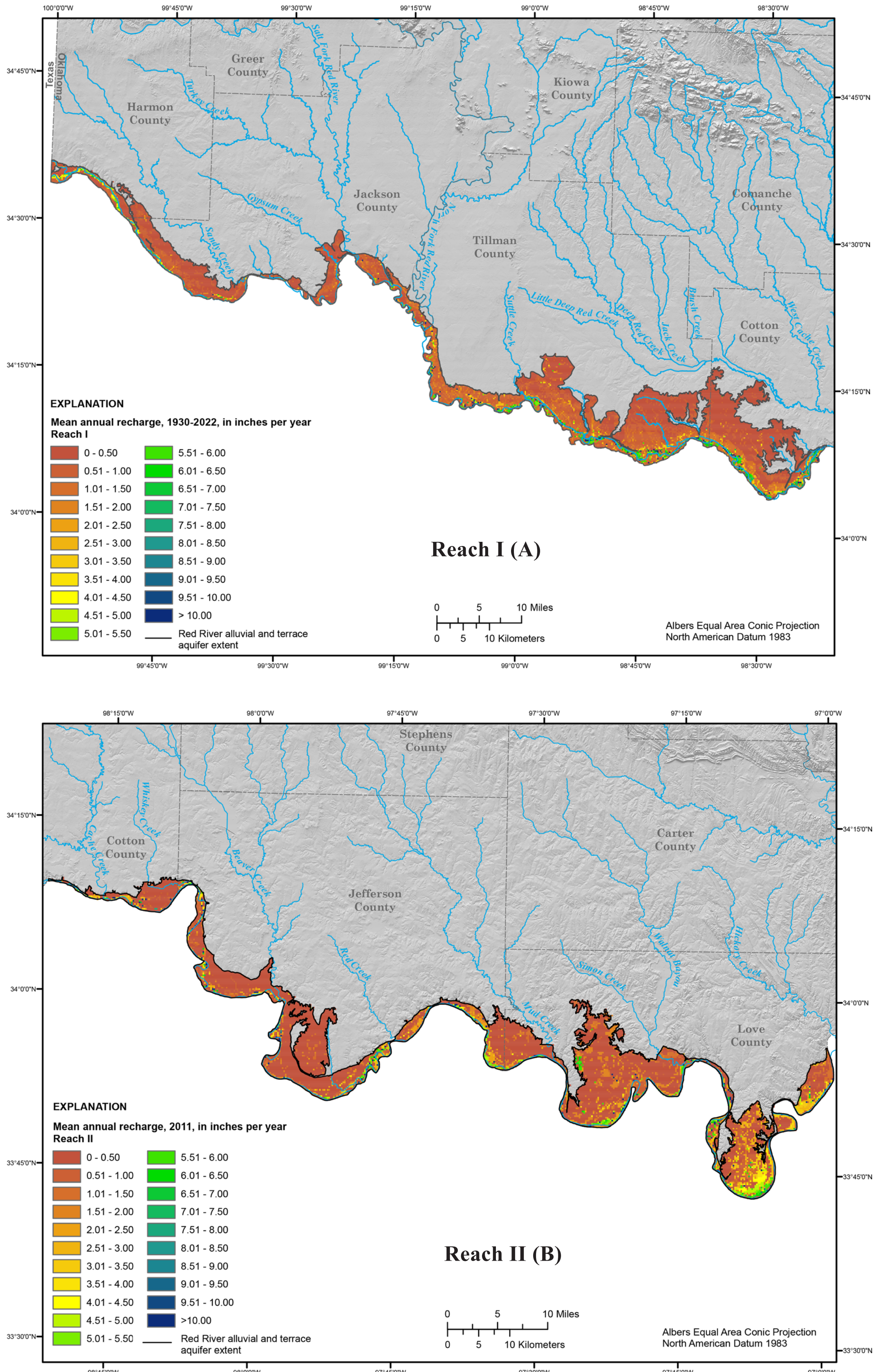


Figure 21. Mean annual recharge estimated by using the SWB code in Reach I (A) and Reach II (B) of the Red River alluvial and terrace aquifer in 2011, a year of below mean recharge.

Table 5. Summary statistics for SWB estimated recharge for Reach I and Reach II from 1930-2022, 1930-80, 1981-2001, 2002-14, and 2015-22.

Statistic	Reach I - Mean annual SWB recharge, in inches				
	1930-2022	1930-1980	1981-2001	2002-2014	2015-2022
Minimum	0.15	0.19	0.46	0.15	0.36
Maximum	5.57	5.48	3.39	2.57	5.57
Mean	1.18	0.92	1.90	0.73	1.73
Median	0.77	0.70	1.80	0.58	1.21

Statistic	Reach II - Mean annual SWB recharge, in inches				
	1930-2022	1930-1980	1981-2001	2002-2014	2015-2022
Minimum	0.30	0.30	1.06	0.66	1.67
Maximum	20.44	10.44	9.82	5.55	20.44
Mean	3.57	2.83	4.78	3.00	6.02
Median	2.85	2.60	4.67	2.81	3.92

report. Transmissivity is the rate that water flows through a unit width of aquifer thickness under a unit hydraulic gradient (Lohman, 1972). Storativity is a dimensionless volume of water released from or taken into storage per unit aquifer surface area per unit change in head (Sayre, 1955). Storativity in the Red River alluvial and terrace aquifer is released under unconfined conditions as water drains from pore spaces. This is defined as specific yield and is also sometimes referred to as effective porosity (Lohman, 1972). Hydraulic conductivity and transmissivity were estimated using well-drawdown data, slug tests, percent-coarse analysis, and a multi-well aquifer test (Figure 23). Specific yield was estimated by conducting percent-coarse analysis (Figure 24) and a multi-well aquifer test.

Slug Tests and Well-Drawdown Data

Slug tests are a useful method of aquifer testing to determine the hydraulic conductivity of the aquifer near the well and the connectivity of the well to the aquifer. The slug tests were completed by initiating an instantaneous water-level change by introducing a solid PVC cylinder into the well to displace the water and observing the water-level response. A total of 10 slug tests were performed at three wells throughout the aquifer (Figure 23). At least two slug tests were completed at each well: 1) a falling-head slug test, begins when the slug is fully submerged into the water column, which displaces water upward, causing the water to disperse into the formation, resulting in water levels returning to static conditions; 2) a rising-head slug test begins when the slug is removed from the water column, causing the water column to fall and water from the formation to enter the well, resulting in water levels returning to static conditions. Slug tests were analyzed using the AQTESOLV software package (Duffield, 2007). The Bouwer-Rice unconfined model provided the best match to the data and was used for slug test analyses (Bouwer and Rice, 1976). Analyses of slug test data indicated a hydraulic conductivity of 95.7 feet per day and transmissivity of 3,828 square feet per day at well 198259 in Reach I (Table 6, Figure 24). The mean hydraulic conductivity was 111.1 feet per day and mean transmissivity was 3,988 square feet per day in Reach II (Table 6, Figure 24).

Drawdown tests, also known as specific capacity tests, are performed by well drillers during the time of drilling. Data submitted on well completion reports to the OWRB include pumping rate, pumping duration, well diameter, and drawdown depth to water (Oklahoma Water Resources Board, 2020). Data from 26 wells in Reach I and 6 wells in Reach II in which saturated thickness could be determined and the test had a pumping duration of at least 6 hours to ensure maximum drawdown were utilized. Transmissivity at each location was estimated using an equation based on the Cooper and Jacob (1946) solution (Duffield, 2021):

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

where,

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

Sw is the total length of equilibrated drawdown in feet

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

t is time in days

S is the storativity of the aquifer (dimensionless)

The Cooper and Jacob (1946) equation can also be written to solve for transmissivity:

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

Transmissivity may be used to determine hydraulic conductivity:

$$T = Kb$$

where,

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

b is the saturated thickness of the aquifer in feet

Using a storativity value of 0.23, which was derived from the multi-well aquifer test performed in this study, the mean hydraulic conductivity in Reach I was 83.0 square feet per day in Reach I and 105.1 square feet per day in Reach II

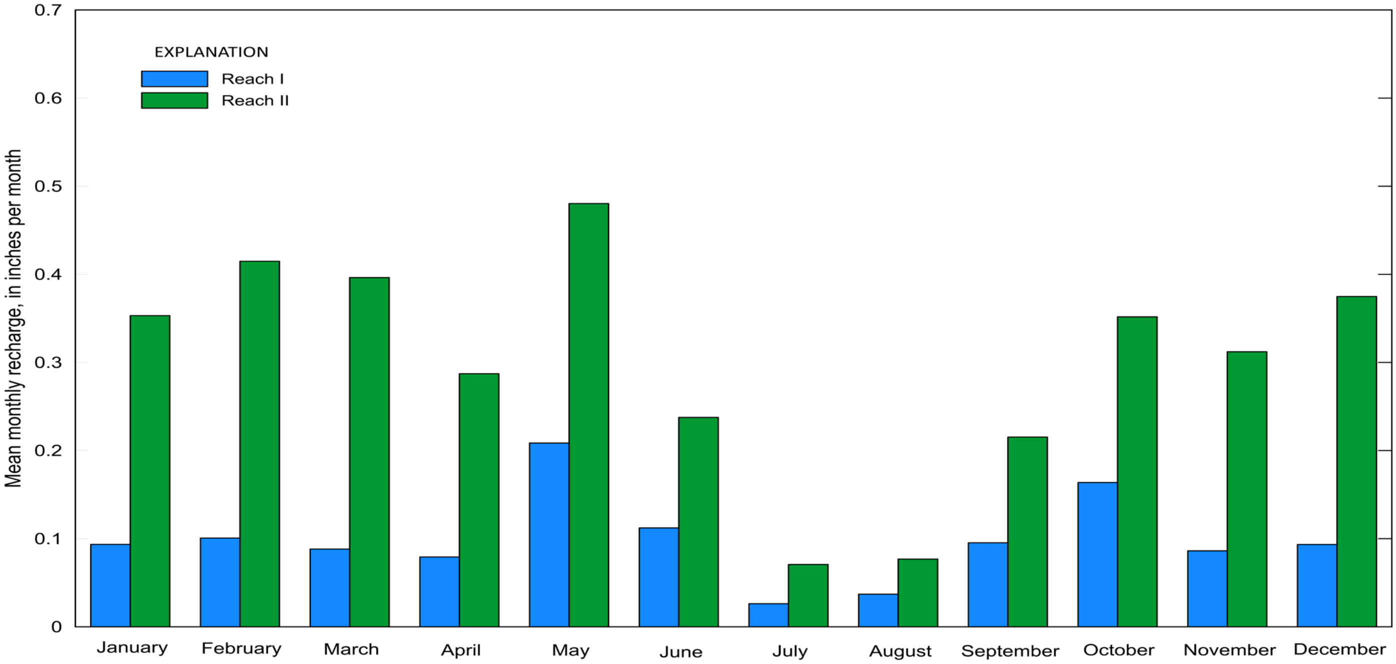


Figure 22. Mean monthly recharge to the Red River alluvial and terrace aquifer, calculated using the SWB code, 1930-2022.

(Table 6, Figure 24). The mean transmissivity was 2,956 square feet per day in Reach I and 2,153 square feet per day in Reach II (Table 6).

Multi-Well Aquifer Test

A multi-well aquifer test was completed as part of this investigation to determine transmissivity, hydraulic conductivity, and specific yield. A multi-well aquifer test includes a pumping or production well and at least one nearby observation well, with water levels being measured continuously during two distinct phases: 1) a pumping phase in which the production well is turned on and runs until water levels stabilize, and 2) a recovery phase in which the production well is turned off and data is collected until water levels return to pre-disturbance levels. The production well (OWRB 27035) is located 6.5 miles southwest of Grandfield, Oklahoma and 3.2 miles north of the vegetation line comprising the Oklahoma-Texas boundary along the southern bank of the Red River. A single observation well (OWRB 164991) was used for the test and is located 42.6 feet west of the pumping well; both are owned and operated by Tillman County Rural Water District #1.

The pumping well and a nearby well (OWRB 27036) were turned off 24 hours prior to the multi-well aquifer test to allow groundwater levels to return to static conditions. The Grandfield Mesonet station recorded 1.8 inches of rain between six and three days prior to the test (Oklahoma Mesonet, 2023a). No rain occurred during the three days leading up to and during the pumping phase, but there was trace precipitation (0.03 inches) during the recovery phase (Oklahoma Mesonet, 2023a). Analysis of continuous water levels in OWRB 198259, which is 7.6 miles east of and 29 feet shallower than the pumping well, did not show a substantial spike in water level until after the recovery phase was completed; therefore, this precipitation was considered negligible. Both the pumping and recovery data were analyzed using the AQTESOLV software package (Duffield, 2007) using several curve-matching solutions.

The production well (OWRB 27035) was completed to a depth of 64 feet below ground surface; the base of the Red River alluvial and terrace aquifer was observed in the lithologic log at 67 feet. The 10.75-inch diameter casing was screened from 54-64 feet below land surface. The observation well (OWRB 164991) had a total depth of 69 feet below land surface at the time of the test and the lithologic log indicated that the base of the Red River alluvial and terrace aquifer was 63 feet below land surface. The observation well had an eight-inch casing, screened from 49-64 feet below land surface, and was located two feet lower in elevation than the production well.

After the 24-hour equilibration period, the production well began pumping at 9:20 AM on May 17, 2023, to start the pumping phase of the test. Total volume pumped was recorded every minute until 10:00 AM, every two minutes until 1:20 PM, and every five minutes after that until 6:00 PM. A final volume pumped was recorded immediately before the well was shut off at 7:40 AM on May 18, 2023. Converting these volume observations into flow rate yielded a mean flow rate of 31.2 gallons per minute. Small variations in flow rate were evident in the derivative of observed displacement (Figure 25); therefore, three pumping phases were input into the model with mean flow rates ranging

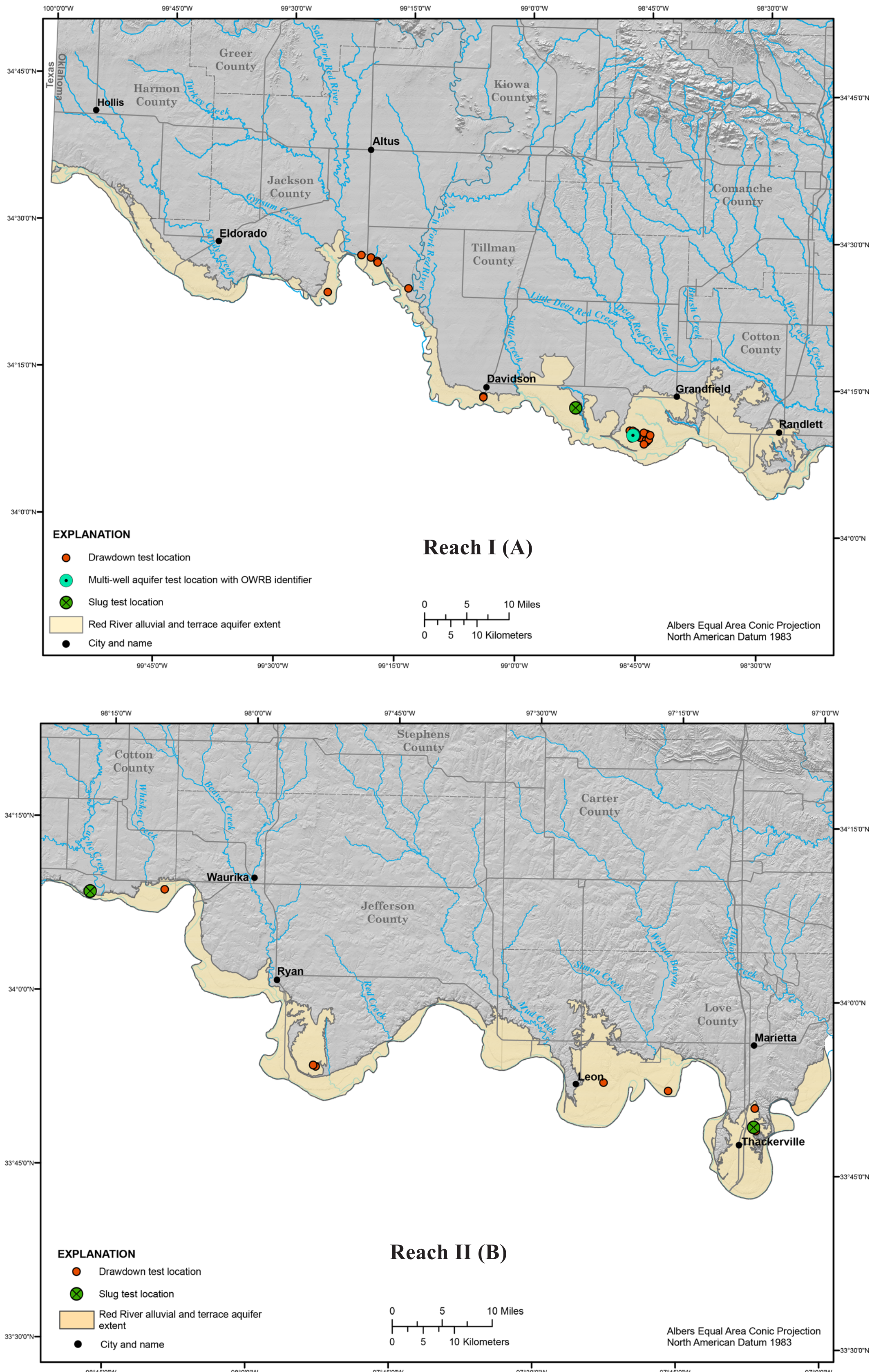


Figure 23. Map showing locations of multi-well pumping test, drawdown tests, and slug tests in Reach I (A) and Reach II (B) the Red River alluvial and terrace aquifer as part of this study.

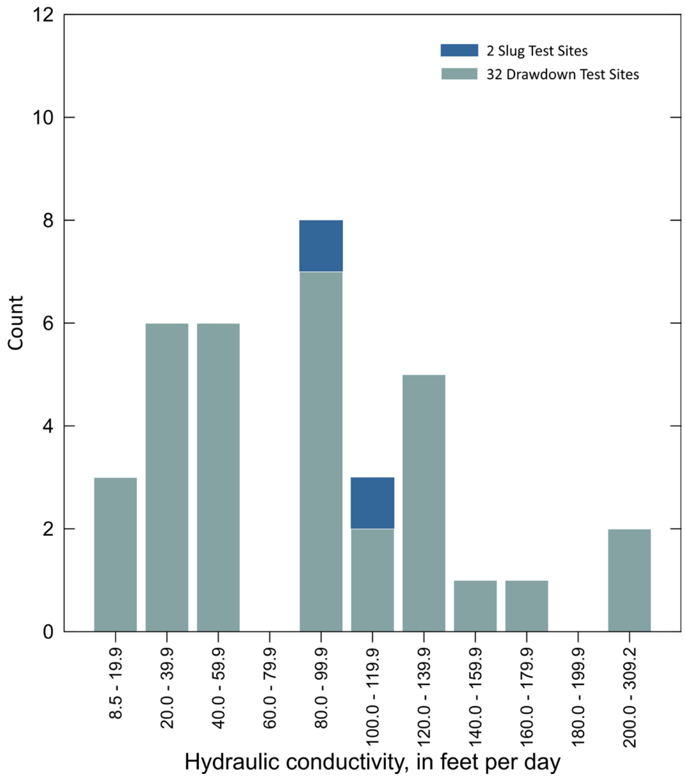


Figure 24. Histogram showing the hydraulic conductivity distribution of slug tests and drawdown data.

from 31.1 to 35.0 gallons per minute. Water levels were measured by hand using the same intervals, except that the initial measurements were recorded every 15 seconds until 10:00 AM. Water levels were also continuously collected electronically every minute, but due to equipment failure, these were only collected after 12:47 PM on May 17, 2023. On May 18, 2023, at 7:40 AM, the pump was shut off and the recovery phase began. Measurements were continuously recorded electronically every half-second until 9:12 AM, when the electronic measurement interval was switched to once per minute. Manual measurements were also recorded with diminishing frequency, similar to the schedule used for the pumping phase. The recovery phase was concluded at 10:40 AM on May 19, 2023, when the recording equipment was collected, and the nearby wells were returned to automatic schedules.

Both the pumping phase (Figure 25) and the recovery phase (Figure 26) of the multi-well pumping test were analyzed concurrently in AQTESOLV with possible unconfined aquifer solutions. The Moench (1997) solution for unconfined aquifers produced the best overall fit between the phases. There was an acceleration in water-level recovery after approximately 30 minutes that could not be reconciled with early recovery observations; therefore, the early-time and late-time recovery data were analyzed as two separate solutions (Figure 26). Of the model parameters, the anisotropy ratio, the constant for non-instantaneous water table drainage, and the specific yield were held constant due to insensitivity in at least one of the model solutions. The well construction parameters were also held constant and were consistent with the gathered well dimensions. All of the model parameters were sensitive in at least one model solution.

Transmissivity ranged from 2,377 square feet per day in the late-time recovery phase solution to 4,573 square feet per day in the early-time recovery phase solution, with a mean of 3,699 square feet per day between the three solutions (Table 6, Figure 25). Dividing by the aquifer thickness produces a mean hydraulic conductivity of 99.4 feet per day. The elastic storage coefficient, or the proportion of water which can be removed from a confined or unconfined aquifer due to decompression, varied from 0.000225 in the pump phase solution to 0.00440 in late-time recovery phase solution, with a mean of 0.00170. Specific yield was 0.23, the ratio of vertical to horizontal anisotropy was 0.334, and the coefficient for non-instantaneous drainage at the water table was 3.0E-6 inverse minutes across the model solutions.

Table 6. Summary of estimated hydraulic property statistics from different methods used in this study.

	Method	Mean Transmissivity, square feet per day	Mean Specific Yield	Mean Hydraulic Conductivity, feet per day	Count
Reach I	**Multi-well Aquifer Test**	3,699	0.23	99.4	1
	Percent Coarse	1,342	0.24	49.3	217
	Slug Tests	3,828	--	95.7	1
	Drawdown Tests	2,956	--	83.0	26
Reach II	**Multi-well Aquifer Test**	--	--	--	0
	Percent Coarse	1,651	0.22	44.2	92
	Slug Tests	3,988	--	111.1	2
	Drawdown Tests	2,153	--	105.1	6

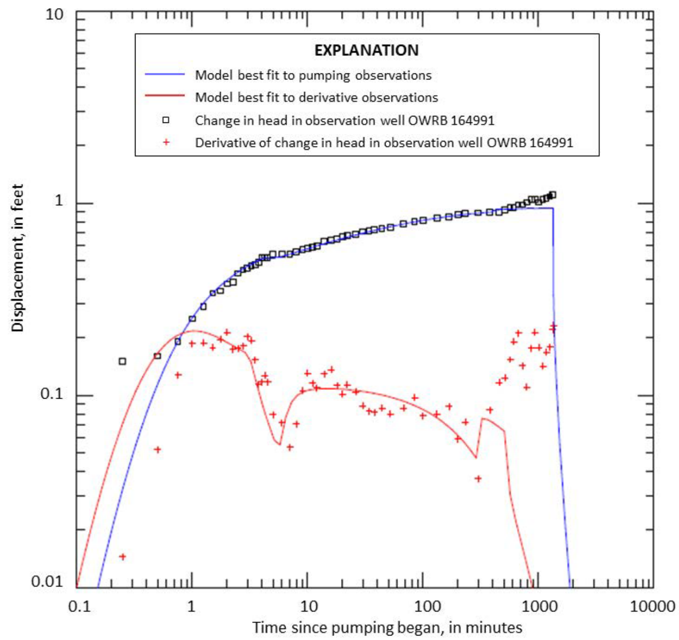


Figure 25. Drawdown and recovery curve and derivative with best-fit Moench method for the multi-well aquifer test in the Red River alluvial and terrace aquifer.

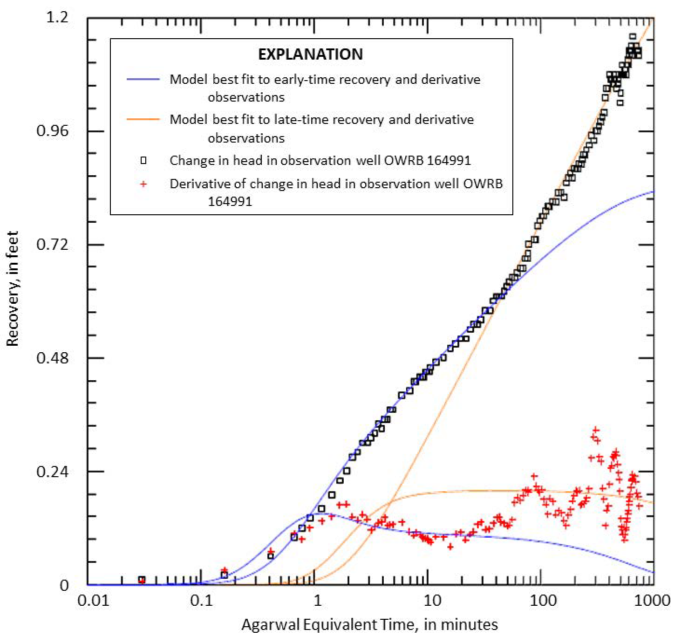


Figure 26. Recovery curve data and derivative with best-fit Moench method for the multi-well aquifer test in the Red River alluvial and terrace aquifer.

Percent-Coarse Analysis

Percent-coarse analysis using lithologic logs was used to determine the theoretical horizontal hydraulic conductivity of the aquifer, which uses lithologic descriptions. This method has given reasonable estimates of hydraulic conductivity and storage for other bedrock and unconsolidated aquifers in Oklahoma (Ellis and others, 2017; Neel and others, 2018). Lithologic descriptions were determined from 309 groundwater water well logs (217 in Reach I and 92 in Reach II) submitted to the OWRB by groundwater well drillers (Oklahoma Water Resources Board, 2020). To simplify and standardize lithologic descriptions, the descriptions were reclassified into five categories: sandstone, gravel, sand, coarse sand, fine sand, and clay. Hydraulic conductivity and specific yield values were assigned to each lithologic interval based on previously published values (Heath, 1983) for each type of material as well as slug and single-well drawdown tests performed in the aquifer. The assigned values were then used to calculate hydraulic conductivity and specific yield for each well weighted by the thickness of each lithologic interval. The estimated mean hydraulic conductivity was 49.3 feet per day in Reach I and 44.2 feet per day in Reach II (Table 6, Figure 27). Transmissivity values were estimated using saturated thickness values derived from this study (Figure 15). The mean transmissivity was 1,342 square feet per day in Reach I and 1,651 square feet per day in Reach II. The estimated specific yield values were 0.24 (Reach I) and 0.22 (Reach II).

Groundwater Quality

Groundwater samples were collected and analyzed by the OWRB in five wells in Reach I in 2015 (Oklahoma Water Resources Board, 2018) with additional samples collected at four wells in Reach I and eight wells in Reach II in 2020 (Figure 28). Samples were analyzed for physical properties and for concentrations of major ions, trace metals, and nutrients (Table 7). Bicarbonate is the most prevalent anion ranging from 78 to 505 milligrams per liter with a mean concentration of 289 milligrams per liter. Sulfate and chloride had mean concentrations of 127 and 181 milligrams per liter, respectively. Cations present include sodium, potassium, calcium, and magnesium with mean concentrations of 109, 3, 84, and 30 milligrams per liter, respectively (Table 7). The water type was bicarbonate for 14 of the 16 samples collected as shown in relative concentrations in milliequivalents per liter on Stiff (1951) diagrams (Figure 28) and a Piper (1944) plot (Figure 29).

Total dissolved solid values ranged from 128 to 4,340 milligrams per liter at 18 wells across the aquifer, with a mean of 698 milligrams per liter and a median of 399 milligrams per liter. Reach I had a mean total dissolved solids value of 1,069 milligrams per liter with a median of 403 milligrams per liter. Reach II had a mean total dissolved solids value of 326 milligrams per liter with a median of 244 milligrams per liter. Four wells exceeded secondary drinking water guidelines for total dissolved solids with concentrations greater than 500 milligrams per liter. The samples with the highest total dissolved solids values (881, 2,170, 4,340 milligrams per liter) were from three locations in Reach I (Figure 28). Wells at those three locations were drilled and screened 1-4 feet into the bedrock underlying the Red River

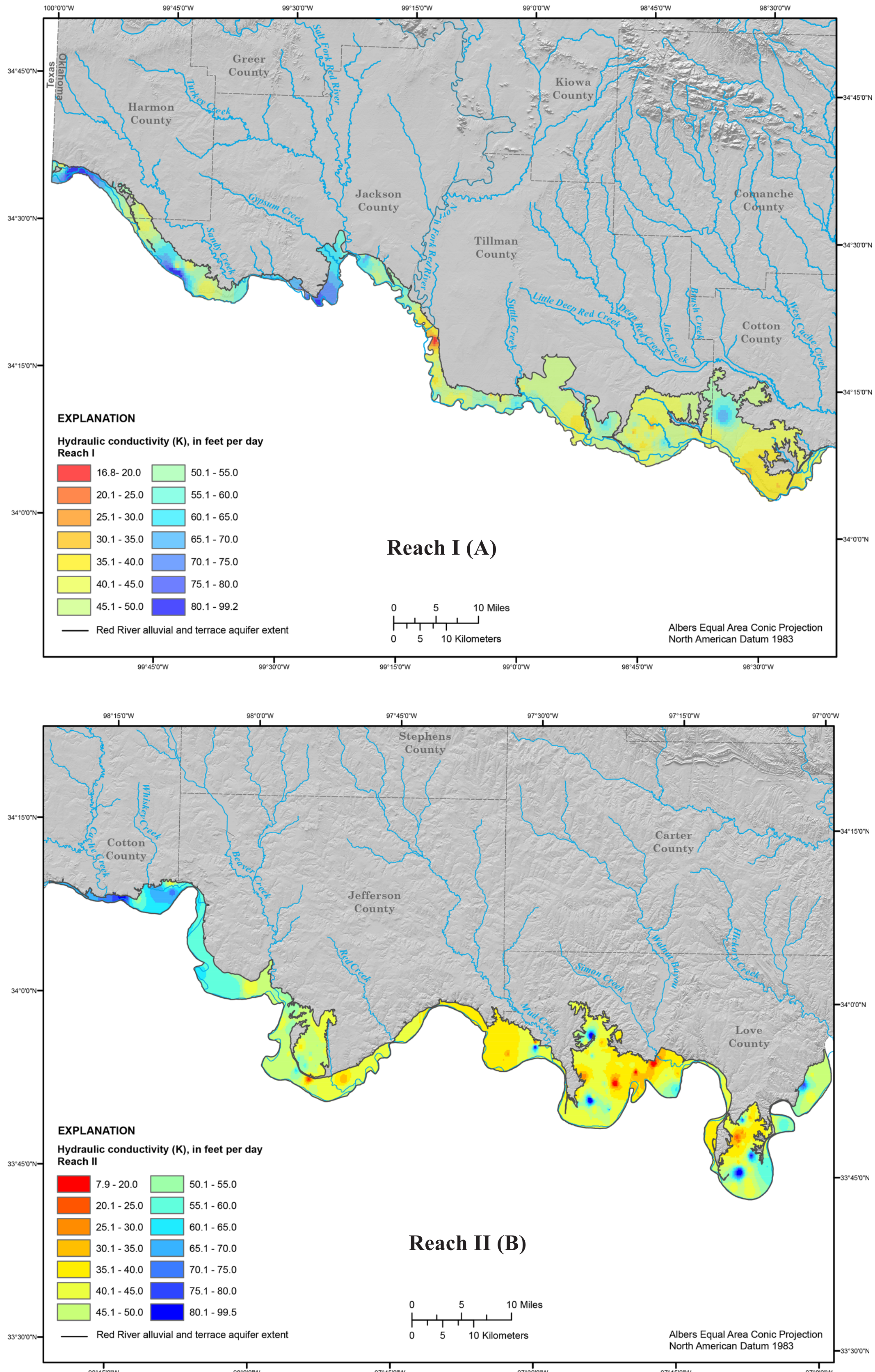


Figure 27. Estimated horizontal hydraulic conductivity using percent-coarse analysis in Reach I (A) and Reach II (B) of the Red River alluvial and terrace aquifer.

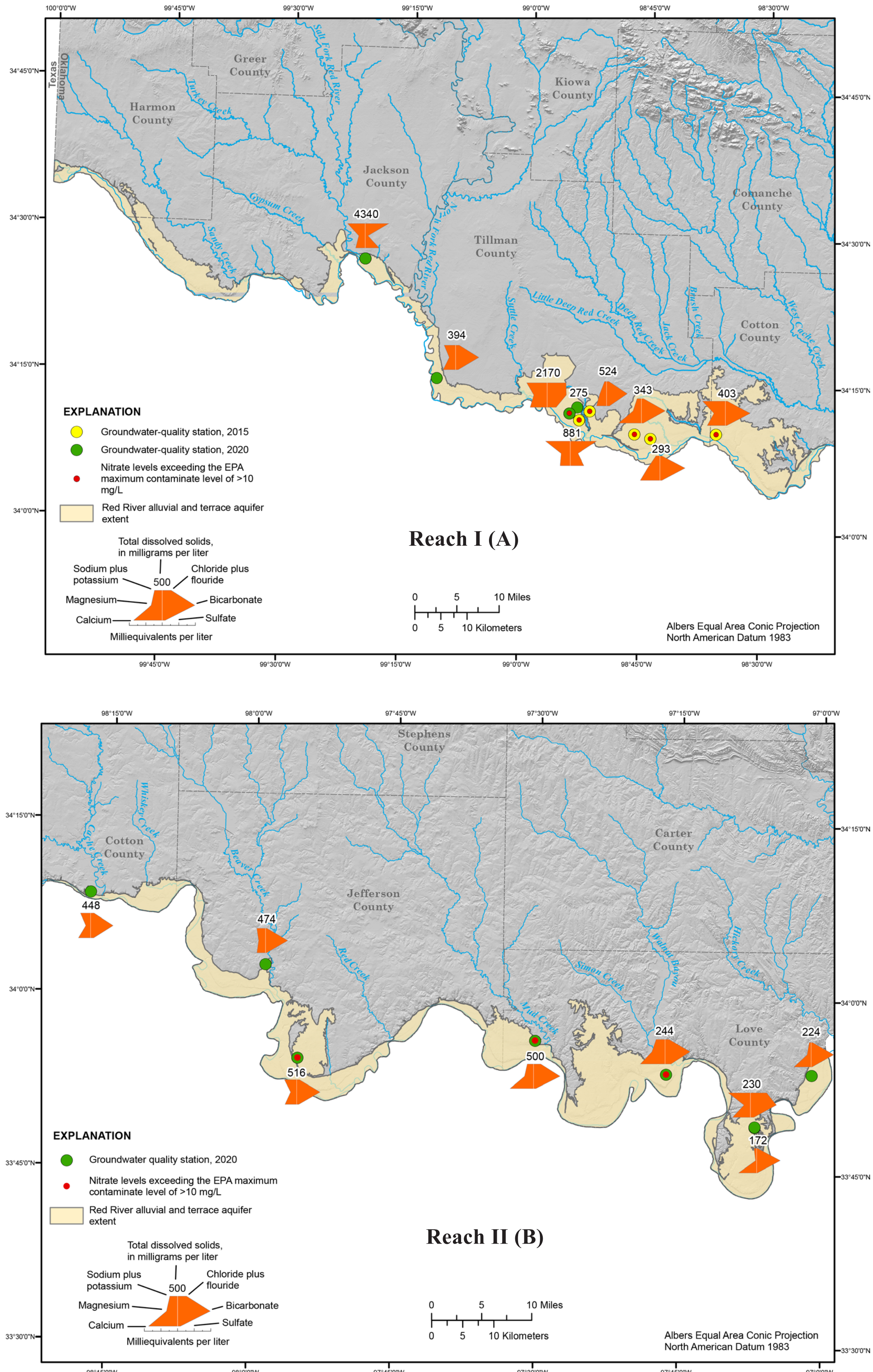


Figure 28. Groundwater quality stations in Reach I (A) and Reach II (B) of the Red River alluvial and terrace aquifer, 2015 and 2020.

Table 7. Summary statistics of constituent concentrations in groundwater samples collected in the Red River alluvial and terrace aquifer, 2015 and 2020.

Constituent	Samples analyzed	Mean Detected	Minimum	Maximum	Samples below detection limit	Percentile of Detected Concentrations		
						25	50	75
specific conductance^	17	1,197.4	191.0	6,962.0	0	391.3	705.4	886.7
Temperature(°C)^	17	21.2	19.0	25.0	0	19.9	20.6	22.5
pH	17	7.0	6.6	7.5	0	6.7	7.1	7.2
total dissolved solids*^	18	697.7	128.0	4,340.0	0	240.5	398.5	518.0
Hardness*	17	369.0	53.0	1,900.0	0	170.0	234.0	347.5
Calcium*	17	83.9	16.5	355.0	0	54.8	64.2	86.7
Magnesium*	17	29.6	2.0	144.0	0	10.4	21.6	28.3
Sodium*	17	109.2	5.6	747.0	0	13.7	36.5	90.3
Potassium*	17	2.8	0.9	16.4	1	1.2	1.6	2.7
Bicarbonate*	17	289.3	78.1	505.1	0	215.3	317.2	369.1
Sulfate*	17	127.0	4.9	1,250.0	0	13.7	20.9	43.0
Chloride*	17	181.2	3.5	1,550.0	2	11.2	27.2	55.9
Fluoride*	17	0.4	0.1	0.7	5	0.2	0.4	0.6
Silica*	17	19.6	11.6	26.9	0	17.2	19.4	22.4
Nitrate as N*	17	9.7	0.1	21.0	0	1.4	11.2	15.8
Bromide**	17	486.9	110.0	1,530.0	3	167.5	287.0	704.8
Phosphorous**	17	0.04	0.01	0.11	1	0.02	0.04	0.07
Aluminum**	17	++	++	++	17	++	++	++
Arsenic**	17	2.8	1.0	7.6	13	1.0	1.2	6.1
Barium**	17	203.6	21.8	509	1	120.5	202.0	262.5
Boron**	17	161.5	29.8	597	4	37.5	141.0	229.5
Cadmium**	17	++	++	++	17	++	++	++
Chromium**	17	4.6	1.0	10.8	14	++	++	++
Copper**	17	4.9	1.2	10.6	6	2.1	3.8	7.5
Iron**	17	403.7	24.3	1,150.0	14	++	++	++
Lead**	17	1.0	1.0	1.1	15	++	++	++
Manganese**	17	125.3	3.3	753.0	10	5.1	7.3	81.2
Molybdenum**	17	2.7	1.2	4.1	15	++	++	++
Uranium**	17	5.8	1.0	13.7	4	2.5	4.5	8.9
Vanadium**	17	7.3	1.6	20.7	7	2.7	4.3	11.4
Zinc**	17	23.9	10.0	49.3	8	10.9	14.7	42.3

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

Specific conductance is in microseimens per centimeter at 25° C

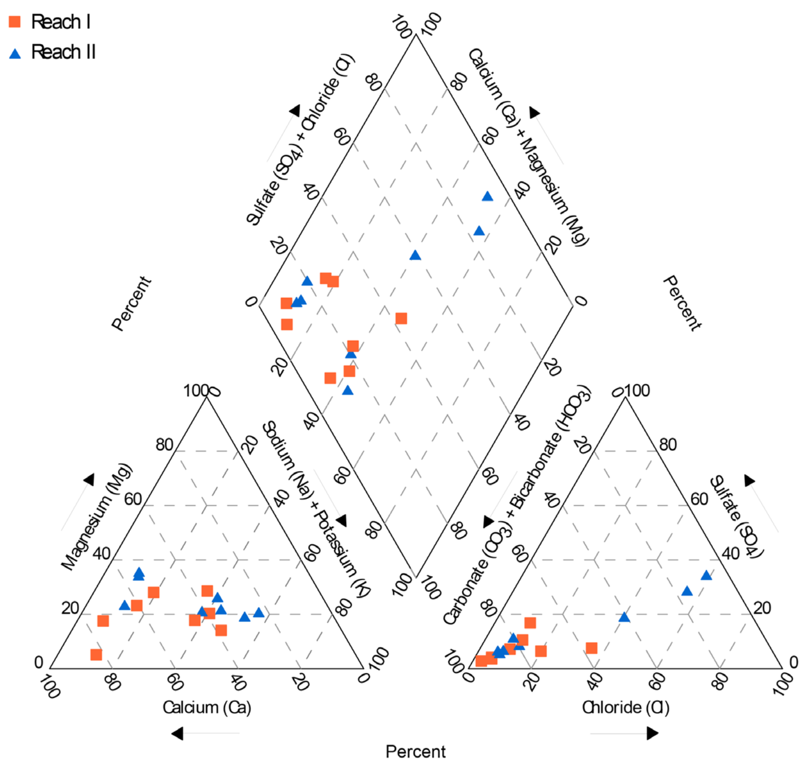
*, presented in milligrams per liter

**, presented in micrograms per liter

^, includes analysis of samples from 2013 and 2017

alluvial and terrace aquifer. This, along with the increase in salinity associated with water flowing over the gypsum units of the Blaine formation to the west, may explain the high total dissolved solids values compared to the rest of the aquifer.

Some of the constituents sampled exceeded the U.S. Environmental Protection Agency's (USEPA) maximum contaminant levels and secondary drinking water standards (U.S. Environmental Protection Agency, 2018). Maximum contaminant levels are established for contaminants which may pose a risk to humans at excessive levels in drinking water (U.S. Environmental Protection Agency, 2018). Secondary standards are guidelines regarding the aesthetic and cosmetic effects of drinking water without posing a health risk (U.S. Environmental Protection Agency, 2018). Six wells in Reach I and three wells in Reach II, had samples which exceeded the 10 milligrams per liter maximum contaminant



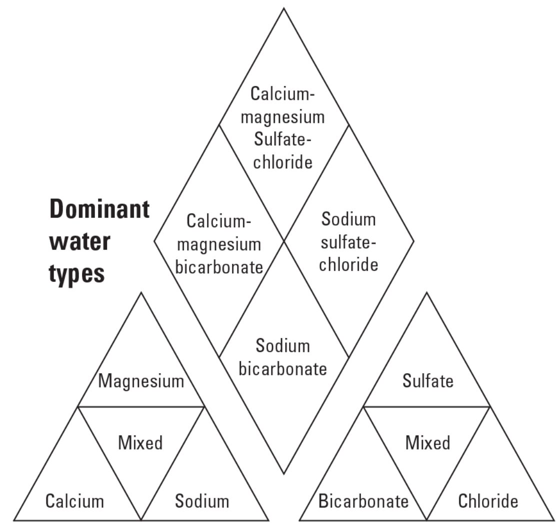


Figure 29. Piper plot from groundwater samples collected in the Red River alluvial and terrace aquifer, 2015 and 2020.

level for nitrate, which could be the result of runoff from agricultural activity (Figure 28). Possible sources for high concentrations of total dissolved solids include upward movement of saline water from lower geologic units.

Summary

The Red River alluvial and terrace aquifer consists of Quaternary-age deposits composed of sand, silt, clay, and gravel. The deposits unconformably overlie sedimentary bedrock units of Permian-age bedrock in Reach I and Permian- and Cretaceous- age bedrock in Reach II. The aquifer underlies 336 square miles in southwest Oklahoma (Reach I) and 286 square miles in south-central Oklahoma (Reach II). Groundwater from the aquifer is used primarily for irrigation and public water supply.

The study area received mean annual precipitation of 25.35 inches in Reach I and 32.68 inches in Reach II from 1930-2022. Recharge to the aquifer was estimated using the soil water balance code with estimated recharge of 1.18 inches per year in Reach I and 3.57 inches per year in Reach II. Mean annual recharge is greater in Reach II due primarily to the greater amounts of precipitation. The highest SWB-estimated annual recharge for both reaches occurred in 2015, with 5.57 inches in Reach I and 20.44 inches in Reach II. The lowest SWB-estimated annual recharge was 0.15 inches in 2012 for Reach I and 0.30 inches in 1963 for Reach II.

The mean reported groundwater use from the Red River alluvial and terrace aquifer from 1967 to 2022 was 1,487 acre-feet per year in Reach I and 1,062 acre-feet per year in Reach II. In Reach I, irrigation accounted for 84.0 percent of groundwater use and public water supply accounted for 16.0 percent, with other use accounting for less than 0.1 percent. In Reach II, irrigation accounted for 87.1 percent and public water supply accounted for 9.3 percent. Recreation, fish, and wildlife accounted for 3.5 percent of use with less than 0.1 percent for other uses. The lowest reported use in each reach was 562 acre-feet (Reach I) in 1992 and 334 acre-feet (Reach II) in 2005. The highest reported use in each reach was 2,538 acre-feet (Reach I) in 1999 and 2,221 acre-feet (Reach II) in 1974. Water use trends generally correspond with precipitation patterns, with higher reported water use during drought years and lower reported water use in wetter years.

The aquifer base altitude was determined from 358 well driller logs from the OWRB groundwater well records database lithologic descriptions in groundwater well completion reports. A potentiometric surface map was created from 31 groundwater well measurements in 2020 along with the depth to water recorded in groundwater well completion reports. Saturated thickness of the Red River alluvial and terrace aquifer was estimated by subtracting the base elevation of the alluvial and terrace deposits from the 2020 potentiometric surface. Mean saturated thickness in Reach I is 26 feet in areas in which the aquifer is saturated, with a maximum thickness of 71 feet. Mean saturated thickness in Reach II is 27 feet in areas in which the aquifer is saturated, with a maximum thickness of 103 feet. The saturated thickness is typically greatest in thick floodplain deposits near the Red River and in some of the thicker terrace deposits.

Horizontal hydraulic conductivity was estimated from drawdown tests analysis, slug tests, a multi-well aquifer test, and a percent-coarse analysis from lithologic logs. Mean hydraulic conductivity estimated from drawdown test analysis is 83.0 feet per day in Reach I and 105.1 feet per day in Reach II. Slug test hydraulic conductivity was 95.7 feet per day in Reach I and 111.1 feet per day in Reach II. Hydraulic conductivity estimated from a multi-well aquifer test was 135 feet per day. The percent-coarse analysis used lithologic logs and assigned hydraulic conductivity to lithologic descriptions, which resulted in a mean hydraulic conductivity of 49.3 feet per day in Reach I and 44.2 feet per day in Reach II. Transmissivity estimated from the multi-well aquifer test in Reach I was 5,011 square feet per day. Specific yield for the aquifer was estimated from a multi-well aquifer test and percent-coarse analysis from lithologic logs. Specific yield estimated from the multi-well aquifer test in Reach I was 0.23 The estimated specific yield from the percent-coarse analysis was 0.24 in Reach I and 0.22 in Reach II.

Water quality samples were collected from 16 wells throughout the aquifer in 2015 and 2020. Bicarbonate is the most prevalent anion in the sampled waters. The mean total dissolved solids in Reach I was 1,069 milligrams per liter with a median of 403 milligrams per liter. The mean total dissolved solids in Reach II was 326 milligrams per liter with a mean of 244. Six wells in Reach I and three wells in Reach II had samples with nitrates exceeding the USEPA 10 milligrams per liter MCL for public water supply.

Horizontal hydraulic conductivity was estimated from drawdown tests analysis, slug tests, a multi-well aquifer test, and a percent-coarse analysis from lithologic logs. Mean hydraulic conductivity estimated from drawdown test analysis is 83.0 feet per day in Reach I and 105.1 feet per day in Reach II. Slug test hydraulic conductivity was 95.7 feet per day in Reach I and 111.1 feet per day in Reach II. Hydraulic conductivity estimated from a multi-well aquifer test was 135 feet per day. The percent-coarse analysis used lithologic logs and assigned hydraulic conductivity to lithologic descriptions, which resulted in a mean hydraulic conductivity of 49.3 feet per day in Reach I and 44.2 feet per day in Reach II. Transmissivity estimated from the multi-well aquifer test in Reach I was 5,011 square feet per day. Specific yield for the aquifer was estimated from a multi-well aquifer test and percent-coarse analysis from lithologic logs. Specific yield estimated from the multi-well aquifer test in Reach I was 0.23 The estimated specific yield from the percent-coarse analysis was 0.24 in Reach I and 0.22 in Reach II.

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