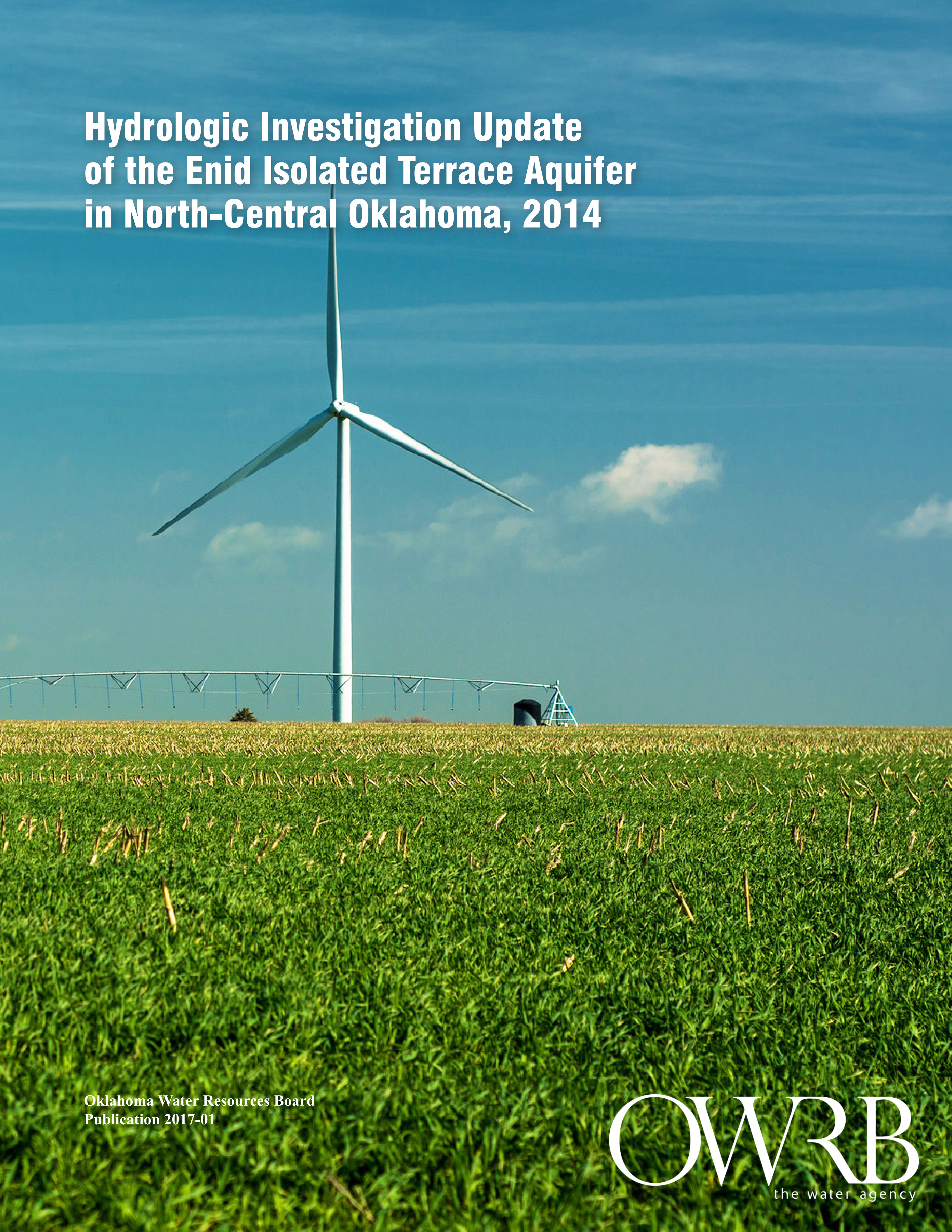
Hydrologic Investigation Update of the Enid Isolated Terrace Aquifer in North-Central Oklahoma, 2014



Oklahoma Water Resources Board
Publication 2017-01

OWRB
the water agency

Cover. Enid, Oklahoma, spring 2017. Photo by Christopher Neel

Hydrologic Investigation Update of the Enid Isolated Terrace Aquifer in North-Central Oklahoma, 2014

By Jessica S. Correll, R. Jacob Hernandez, Jon E. Sanford, and Kyle W. Spears

Oklahoma Water Resources Board
Publication 2017-01

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

Acknowledgments

The authors would like to thank the City of Enid Water Services, specifically Bruce Boyd, for providing access to wells and assisting in data collection for multiple pumping tests. Additionally, the authors would like to thank the many cooperative land and business owners who provided access to property. Recognition should be given to the following current and former OWRB employees who helped with data collection and maintenance: Christopher Neel, Derrick Wagner, Qualla Ketchum, Lauren Guidry, and Mary Niles.

Contents

Acknowledgments....iii
Abstract....1
Purpose and Scope....1
Introduction....2
Aquifer Extent....2
Climate....2
Geology....5
Hydrogeology....7
  Water Levels....7
    Potentiometric Surface....7
  Aquifer Characteristics....8
    Base and Saturated Thickness....8
    Single-well Pumping Tests....13
    Multi-well Pumping Tests....13
  Water Use....17
  Recharge....19
    RORA Computer Program....19
    Soil-Water Balance Model....19
Water Quality....21
Summary....24
Selected References....26

Figures

1. Enid Isolated Terrace aquifer and study area with locations of weather stations, continuous water-level recorder wells, and Mass Measurement Program wells 3
2. Annual precipitation, average precipitation, and 5-year weighted average precipitation, 1902–2013, at the Enid Cooperative Observer station 4
3. Average monthly precipitation for 1994–2013 at the Breckinridge Mesonet station 4
4. Surficial geologic units in the study area 6
5. Water levels from Mass Measurement Program wells showing long-term responses in the study area 7
6. Water levels from continuous water-level recorder wells and precipitation data from the Breckinridge Mesonet station showing short-term responses in the study area 8
7. Potentiometric-surface contours and synoptic well locations in the study area 9
8. Base of the terrace deposits in the study area 10
9. Saturated thickness of the study area with cross-sections A-A' and B-B' (Figure 10) 11
10. Cross-sections (A) A-A' and (B) B-B' showing geologic units, the potentiometric surface, and base of the study area 12
11. Hydraulic conductivity of the study area 14
12. Depth to water in the (A) Enid Monitoring 1 and (B) Enid Monitoring 3 wells during the pumping draw-down and recovery periods of multi-well aquifer tests in the study area 16
13. Recovery curve and derivative with best-fit Neuman method for the multi-well aquifer test at OWRB 157021 16
14. Drawdown and recovery curve and derivative with best-fit Neuman method for the multi-well aquifer test OWRB 102684 17
15. Average annual groundwater use by type from the study area for 1967–2013 17
16. Groundwater use reported to the OWRB from the study area for 1967–2013 18
17. Annual recharge to the study area in the Skeleton Creek drainage basin for 1997–2013, computed using the RORA computer program 19
18. Annual recharge to the study area for 1998–2013, computed using a soil-water balance model 19

19. Average annual recharge to the study area for 1998–2013, computed using a soil-water balance model 20
20. Total dissolved solids concentrations in groundwater samples collected from wells in the study area 23
21. Groundwater types determined from water quality samples collected from wells in the study area 24

Tables

1. Stratigraphic column of geologic and hydrogeologic units in the study area 5
2. Summary statistics for calculated hydraulic conductivity values from 392 single-well pumping tests in the study area 13
3. Well-site characteristics used to calculate aquifer characteristics from multi-well aquifer tests in the study area 15
4. AQTESOLV analysis results from multi-well aquifer tests in the study area 15
5. Annual reported groundwater use in the study area for 1967–2013 17
6. Average annual reported groundwater use in the study area by use type for 1967–2013 18
7. Monthly and annual total and average recharge from a soil-water balance model in the study area for 1998–2013 21
8. Summary statistics of constituent concentrations in groundwater samples collected from the study area for 2014 22

Hydrologic Investigation Update of the Enid Isolated Terrace Aquifer in North-Central Oklahoma, 2014

By Jessica S. Correll, R. Jacob Hernandez, Jon E. Sanford, and Kyle W. Spears

Abstract

The Oklahoma Water Resources Board (OWRB) conducts hydrologic investigations and twenty-year updates 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 review and update of the Enid Isolated Terrace hydrologic investigation completed in 1982 by the OWRB, which set the maximum annual yield for the aquifer at 19,000 acre-feet with an equal proportionate share of 0.5 acre-feet per acre.

The Enid Isolated Terrace aquifer is located in north-central Oklahoma in the western half of Garfield County with a small portion in Alfalfa County. The aquifer consists of Quaternary-age alluvial and terrace deposits that are underlain by Permian-age clays, shales, and sandstones. Updated maps published by the Oklahoma Geological Survey (OGS) in 2002 and 2006 were used to define a study area of 174 square miles. Climate data were analyzed from the Enid Cooperative Observer (COOP) station and the Oklahoma Mesonet station in Breckinridge with mean annual precipitation values of 30.73 inches and 31.23 inches, respectively. There were approximately 1,600 groundwater wells and 64 groundwater permits located within the study area in 2013. Depth to water was measured in 72 groundwater wells in March of 2014 to produce a potentiometric surface map, which indicated that groundwater generally flows to the east-southeast, where at least two streams receive discharge from the aquifer. The saturated thickness of the study area ranged from 0 to about 65 feet. Data from six monitoring wells were analyzed to show long-term water-level changes in the aquifer. Three wells were equipped with water-level recorders to characterize monthly trends and responses to precipitation. A mean hydraulic conductivity value of 50.16 feet per day was calculated for the study area using single-well pumping tests. Two multi-well pumping tests were conducted in January and February of 2013 on wells operated by the City of Enid. With the resultant data, the AQTESOLV modeling program estimated transmissivity values to range from 2,330 to 5,030 feet per day, hydraulic conductivity to range from 101 to 132 feet per day, and storativity values to range from 0.002 to 0.01.

Water use data for 1967–2013 were analyzed for the study area; the main uses for this time period were irrigation and public water supply with an average annual use of 3,243 acre-feet. Mean annual recharge was estimated to be 4.35 inches using climate data from the Breckinridge Mesonet station and the Enid COOP station using a soil-water balance model. Additionally, average annual recharge over the Skeleton Creek drainage basin was estimated to be 2.79 inches using the surface water analysis software RORA on streamflow data from Skeleton Creek (U.S. Geological Survey (USGS) 07160350). Groundwater wells were sampled for selected water quality parameters in 2014 as a part of the OWRB Groundwater Monitoring and Assessment Program (GMAP). Water type in the study area was not uniform and nitrates exceeded the U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL) for public water supply in 11 of the 19 wells sampled.

Purpose and Scope

In accordance with Oklahoma statutes, the OWRB performed a hydrologic survey of the Enid Isolated Terrace groundwater basin in 1982 (Kent and others, 1982) that investigated the Enid Isolated Terrace aquifer extent, recharge, climate, geology, and water quality, and subsequently produced a groundwater model. Utilizing this data, the MAY determination was reached in November 1982. The OWRB issued a Board order for the allocation of water rights, approving the MAY proportioned at 0.5 acre-feet per acre of land overlying the basin. Oklahoma statutes direct the OWRB to update hydrologic surveys at least every twenty years after issuance of the final order determining the MAY. The primary purpose of this study is to provide an update of the previous investigation, including the aquifer extent, geology, and hydrology. The objectives of this update are to (1) summarize hydrologic information about the study area from existing reports; (2) evaluate data and information for 1982–2014; and (3) determine which, if any, changes impacted the aquifer during this period.

Nomenclature and area descriptions are important to this study. The term "study area" is defined as the alluvium and terrace geology (Stanley and others, 2002; Stanley and others, 2008) and includes the aquifer boundary determined by the 1982 hydrologic survey (Kent and others, 1982). The term “aquifer extent” is the area defined as the Enid Isolated Terrace aquifer (Kent and others, 1982).

Introduction

Throughout the study area, water-level data were collected and analyzed along with existing OWRB well completion reports. A portion of the previously defined southwestern edge of the aquifer extent (Kent and others, 1982) was excluded during this investigation because updated maps and field observations showed a discontinuous alluvium deposit separated by Permian units.

The study area lies within the central red-bed plains geomorphic province (Johnson and Luza, 2008). The land surface over the aquifer is generally flat with rolling hills and sand dunes. Skeleton Creek is the main surface water feature in the study area; headwater tributaries of Turkey Creek and Black Bear Creek (elevations ranging from 1,100 to 1,400 feet above North American Vertical Datum of 1988 (NAVD 88)) are located within the study area.

The major land-use types in the study area are agriculture (mainly wheat), cattle ranching, and oil and gas production (Reely, 1992). The City of Enid is the principal populated area with smaller towns to the east and west. The majority of groundwater use was attributed to the city prior to 1995, at which time public water supply use was partially shifted from the Enid Isolated Terrace aquifer to the Cimarron Terrace aquifer. The 2010 population estimate for the City of Enid was about 50,000 (U.S. Census Bureau, 2010) compared to about 45,000 in 1982 (Kent and others, 1982).

Aquifer Extent

The Enid Isolated Terrace aquifer extent generally follows surficial geology. The study area defined in this report includes terrace deposits to the northwest, east, and south (Figure 1) that were not previously included (Kent and others, 1982), which followed the terrace deposits shown on 1980 OGS maps (Bingham and Bergman, 1980). Updated geologic maps published by the OGS (Stanley and others, 2002; Stanley and others, 2008) show a greater extent of terrace deposits than is shown by the 1980 maps (Bingham and Bergman, 1980). In an attempt to validate the current geologic area, older publications were referenced. In a 1924 USGS publication (Renick, 1924) an outline of tertiary water-bearing units closely resembles the study area more than the 1982 aquifer extent. OWRB staff field-verified the 2002 OGS maps and found them to be more accurate than the 1980 maps. The southeast area of the previously defined aquifer extent (Kent and others, 1982) was excluded from this study because maps and field investigations determined that this area was Permian bedrock with some discontinuous alluvium deposits.

Climate

The study area is located in a continental, temperate, and subhumid climate (Kent and others, 1982). The mean temperature for Garfield County is 53.8 degrees Fahrenheit; typically, highest temperatures occur in August, and lowest temperatures occur in January (Oklahoma Climatological Survey (OCS), 2014a).

Precipitation data for the study area were retrieved from two sources: the Enid COOP station and the Breckinridge Mesonet station (Figure 1). COOP stations are part of a climate observation network of the National Weather Service (NWS) for which volunteers collect daily maximum and minimum temperatures, snowfall, and rainfall data (NWS, 2011). The Oklahoma Mesonet is a network of automated environmental monitoring stations, with at least one Mesonet station in each of Oklahoma’s 77 counties (OCS, 2014b). The Enid COOP station recorded daily precipitation data (OCS, 2014c) for 1894–2013, but the period of 1894–1901 was not used because those years did not meet the criteria of having at least 11 months of precipitation data. Mean annual precipitation for 1902–2013 at the Enid COOP station was 30.73 inches with a maximum annual precipitation value of 57.12 inches in 1973 and a minimum annual precipitation value of 13.42 inches in 1956. Figure 2 is a graph of the Enid COOP station’s annual precipitation data and a 5-year weighted average with above-average and below-average periods highlighted. A highlighted period of below-average precipitation occurred from the mid-1920s to 1960 with a brief above-average period during the 1940s. Annual precipitation remained above average for the majority of 1960–2013 with brief below-average periods.

Mean annual precipitation for 1994–2013 for the Breckinridge Mesonet station was 31.2 inches with a maximum value of 50.1 inches in 1999, and a minimum value of 17.5 inches in 2006 (OCS, 2013). The highest average monthly precipitation occurred in June with 4.5 inches. January had the lowest mean monthly precipitation of 1.0 inch (Figure 3). Breckinridge Mesonet station data were recorded during a period of above-average precipitation, and as a result, the estimated recharge may be high.

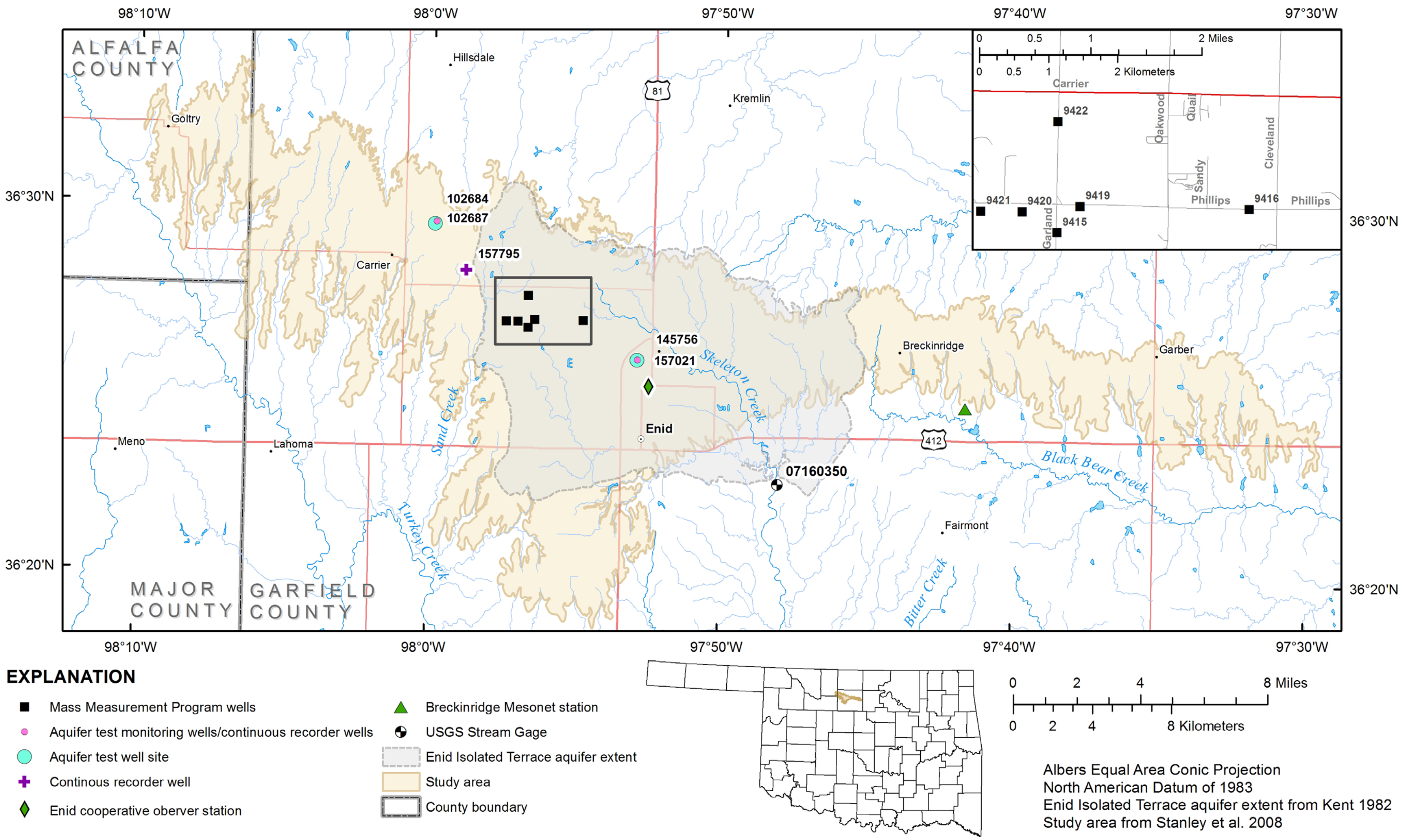


Figure 1. Enid Isolated Terrace aquifer and study area with locations of weather stations, continuous water-level recorder wells, and Mass Measurement Program wells.

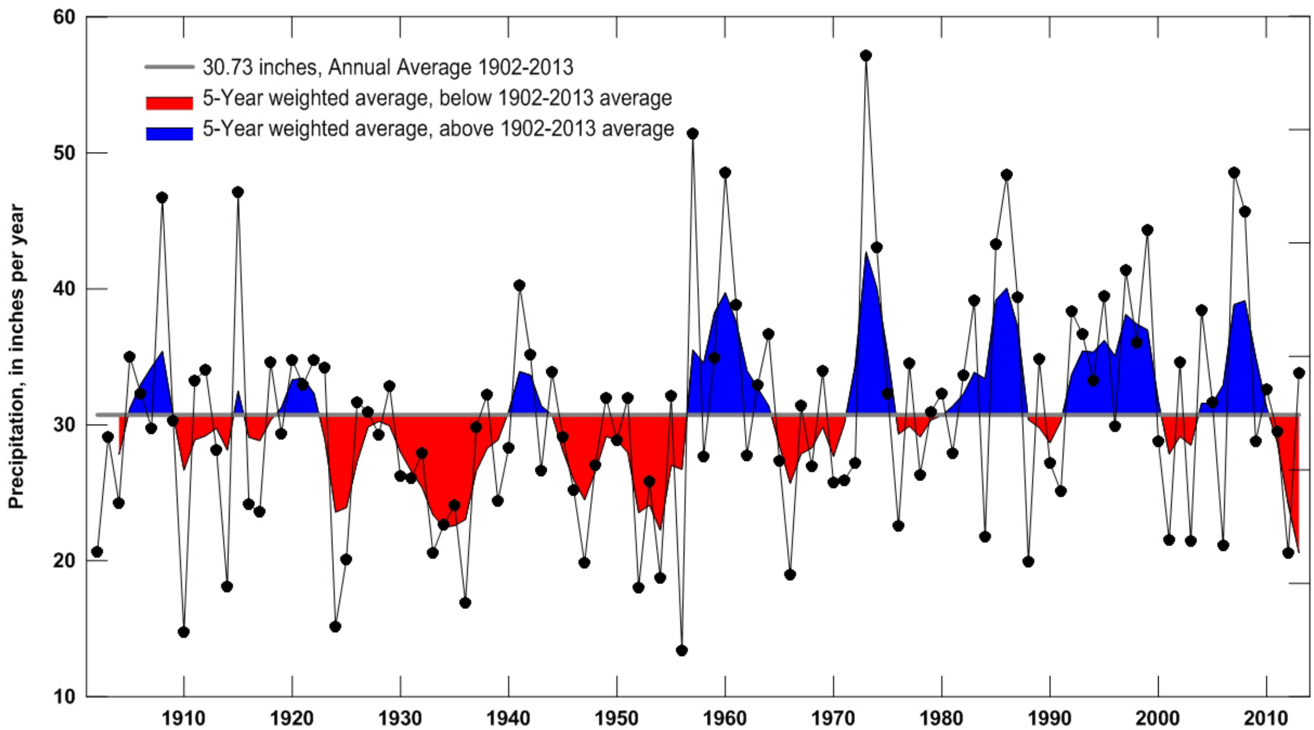


Figure 2. Annual precipitation, average precipitation, and 5-year weighted average precipitation for 1902–2013 at the Enid Cooperative Observer station.

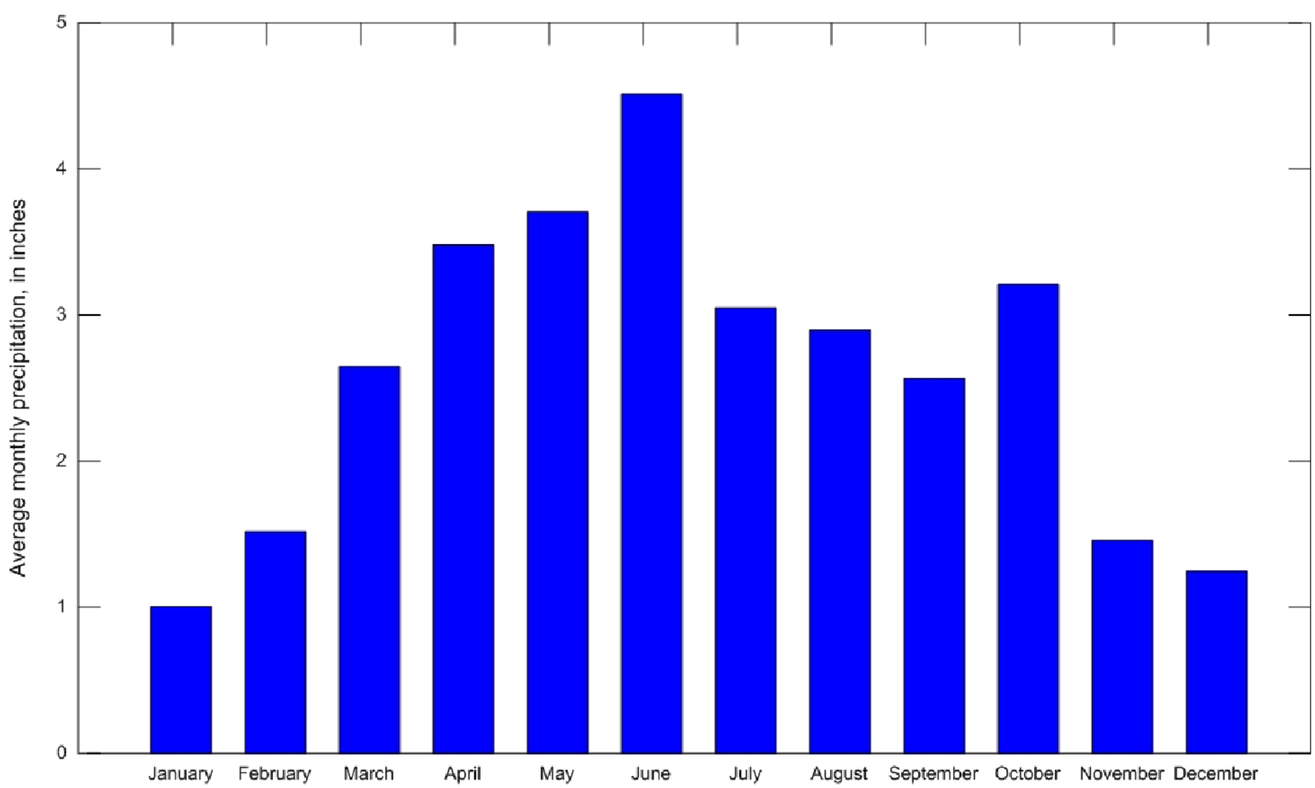


Figure 3. Average monthly precipitation for 1994–2013 at the Breckinridge Mesonet Station.

Geology

The Quaternary-age deposits that comprise the Enid Isolated Terrace aquifer are divided into two geologic units: alluvium and terrace (Figure 4) (Stanley and others, 2002; Stanley and others, 2008). Terrace in the area was deposited by the Cimarron River, which now occupies a valley at a lower elevation to the south because of its meandering nature. Fluvial processes during more recent times reworked the terrace deposits to form the alluvium deposits in and around stream beds. The alluvium deposits are described as unconsolidated clay, silt, sand, and gravel with a thickness of up to 80 feet (Stanley and others, 2002; Stanley and others, 2008). Some terrace deposits have been reworked into dune sand through eolian processes and consist of fine-grained to very fine-grained unconsolidated sand from older alluvium and terrace deposits (Stanley and others, 2002; Stanley and others, 2008). The terrace deposits are the oldest Quaternary-age deposits and are composed of silt, sand, and gravel with a maximum thickness of 75 feet along major streams (Bingham and Bergman, 1980).

Permian-age units surround and unconformably underlie the Quaternary-age deposits (Figure 4). The Permian-age units in the study area were deposited during the Leonardian epoch. During that time a shallow sea was retreating over western Oklahoma creating alluvial, deltaic, and nearshore-marine red sandstones and shales (Johnson and Luza, 2008). The red color that dominates the Permian-age units in Oklahoma is caused by an iron oxide coating on the grains of the sandstones and shales.

The Permian-age units in the study area are members of the El Reno Group, Hennessey Group, and a portion of the Sumner Group (Table 1). The Cedar Hills Sandstone of the El Reno Group is the youngest bedrock unit underlying the Quaternary units and is located on the western side of the study area. It has a mean thickness of 180 feet and is composed of orange-brown to greenish-grey fine-grained sandstone and siltstone with some red shale (Bingham and Bergman, 1980).

From youngest to oldest, the Hennessey Group consists of the Bison Formation, Salt Plains Formation, Kingman Siltstone, and Fairmont Shale. The Bison Formation consists of red-brown shale and greenish-grey/orange-brown calcitic siltstone with minor sandstones. Maximum thickness of the Bison Formation is 120 feet (Bingham and Bergman, 1980). The Salt Plains Formation, which has a maximum thickness of 160 feet, is described as red-brown shale with several thin beds of orange-brown fine-grained sandstone. The Kingman Siltstone has a maximum thickness of 70 feet and is composed of red-brown siltstone with layers of greenish-grey calcitic siltstone (Bingham and Bergman, 1980). The Fairmont Shale, the oldest formation in the Hennessey Group, has a maximum thickness of 150 feet and consists of red-brown shale with thin layers of siltstone (Bingham and Bergman, 1980).

The Sumner Group contains the Garber Sandstone and Wellington Formation. With a maximum thickness of 600 feet, the Garber Sandstone is described as orange-brown, fine- to medium-grained quartz sandstone with thin conglomerate beds grading into shales and siltstones to the north. The Wellington Formation is not easily distinguished from the Garber Sandstone because the two geologic units are similar in composition.

Table 1. Stratigraphic column of geologic and hydrogeologic units in the study area.

Period	Epoch	Group	Formation	Member	Maximum thickness, in feet	Aquifer
Quaternary	Holocene			Alluvium	80[a,b]	Enid Isolated Terrace
				Dune Sand	no data	
	Pleistocene			Terrace	75[c]	
Permian	Leonardian	El Reno Group	Cedar Hills Sandstone		180[c]	El Reno Minor
		Hennessey Group	Bison Formation		120[c]	
			Salt Plains Formation		160[c]	
			Kingman Siltstone		70[c]	
			Fairmont Shale		150[c]	
		Sumner Group	Garber Sandstone		600[c]	
			Wellington Formation		850[c]	

[a] Modified from Stanley and others, 2002
[b] Stanley and others, 2008
[c] Bingham and Bergman, 1980

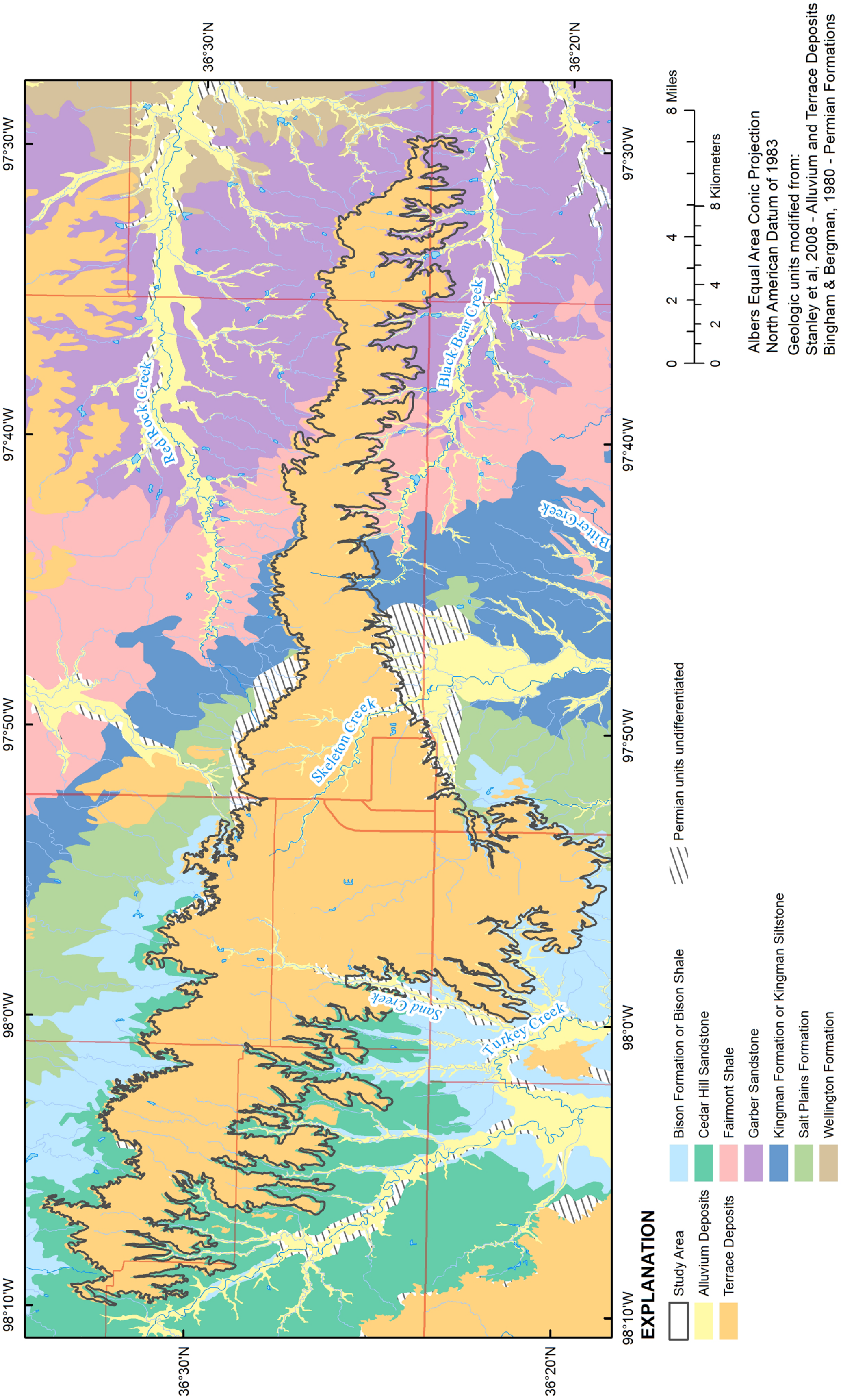


Figure 4. Surficial geologic units in the study area.

Hydrogeology

Groundwater in the terrace deposits is unconfined, flowing generally from northwest to southeast. The study area follows the alluvium and terrace deposits in the area with most of the Permian units contributing little to no water, which results in a lateral boundary. Vertical hydrologic connectivity between the groundwater in the terrace deposits and the underlying Permian-age units has not been defined. Well log data indicate Permian-age units located beneath the aquifer are not transmissive enough to contribute substantial volumes of water to the Enid Isolated Terrace aquifer. The thickest terrace deposits are 80 feet thick and occur in the center of the study area near the City of Enid.

Water Levels

Water levels collected during the winter months as part of the OWRB Mass Measurement Program were analyzed for long-term (greater than 10 years) water level trends in the aquifer (Figure 5) and to determine the types of long-term stresses. Following an extended drier-than-average period, 1924–1956 (see Climate section), groundwater level recovery occurred between 1974 and approximately 2000 (Figure 5). Decreases in water levels between 2000 and 2006 are indicative of a dry period and/or increased water use. Water levels increased again between 2007 and 2010 when the study area received above-average precipitation. Recent (2010–2014) decreases in water levels show the effects of drought conditions.

Water-level recorders were installed in three wells between late 2013 and early 2014 to observe the effects of precipitation events and pumping stresses (Figure 1). Two of the wells, OWRB 157021 (Enid Monitoring 1) and OWRB 102684 (Enid Monitoring 3), were also used to perform aquifer tests because of their proximity to municipal wells operated by the City of Enid. OWRB 157795 (P7-Carrier) illustrated a cyclic increase in groundwater levels during winter months. Water levels decreased slightly in the summer of 2014 and again in the winter of 2015 (Figure 6), which may have been caused by regional pumping and recovery or from seasonal variations.

Potentiometric Surface

A potentiometric surface map shows the level to which water will rise in tightly-cased wells. OWRB staff measured depth to water in 72 wells within the study area on March 14, 2014. Nearly half of the wells were used for domestic supply and the rest were for industrial use, irrigation, livestock, or public supply. The depth to water ranged from 2.58 to 66.45 feet below land surface with a median depth of 27.47 feet below land surface. The potentiometric surface altitude

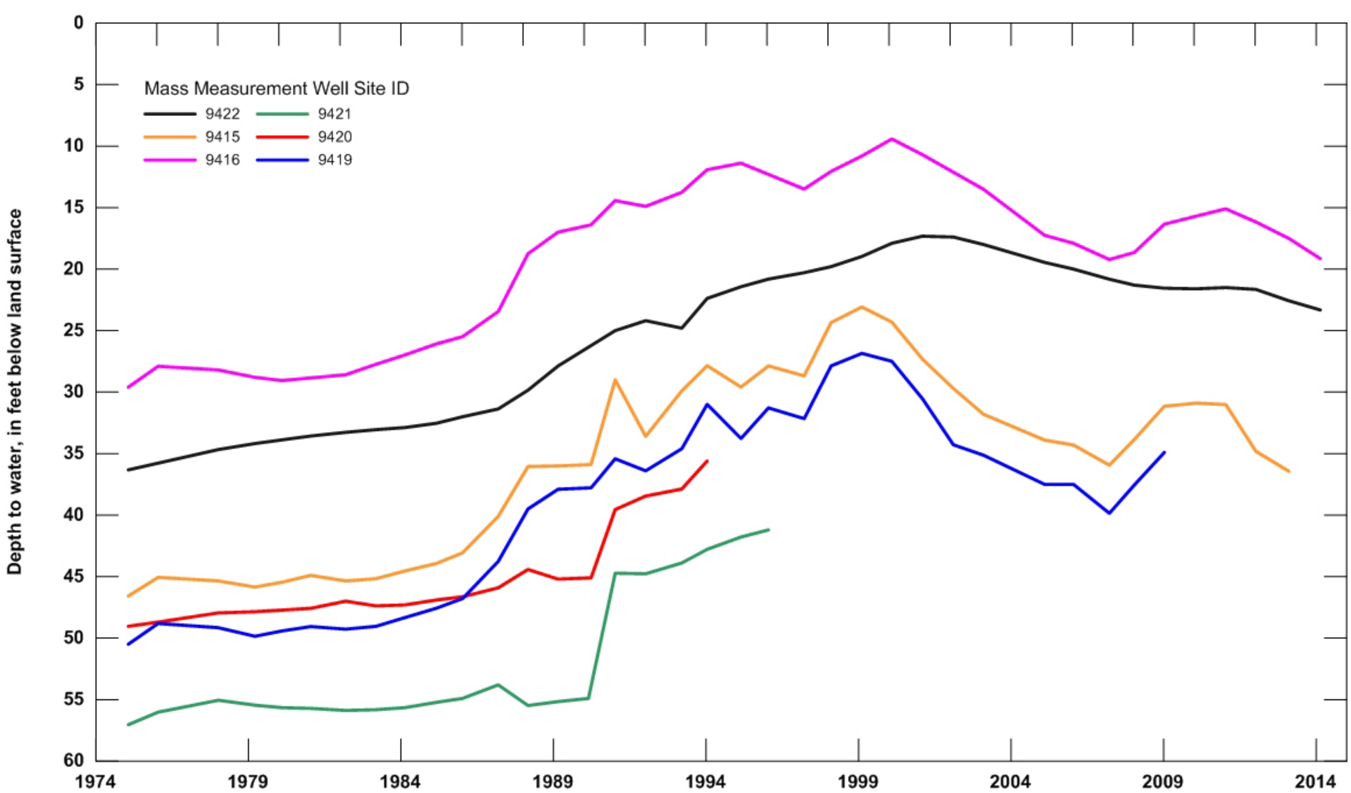


Figure 5. Water levels from Mass Measurement Program wells showing long-term responses in the study area.

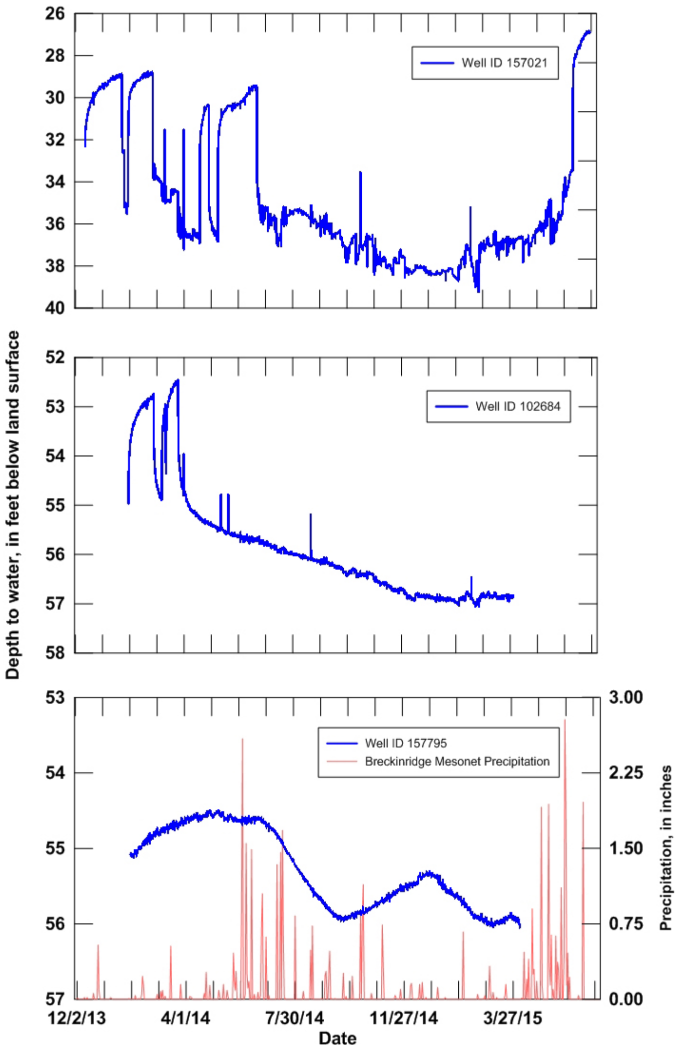


Figure 6. Water levels from continuous water-level recorder wells and precipitation data from the Breckinridge Mesonet station showing short-term responses in the study area.

was estimated by subtracting the depth to water from the land surface elevations collected using high-precision GPS instruments with decimeter accuracy (Figure 7). Contours were fitted to these data and illustrate groundwater flow toward perennial streams.

Groundwater flow in the aquifer is perpendicular to potentiometric contour lines from higher to lower water level altitudes or elevations. Groundwater flow direction is predominately east-southeast. A trough in the potentiometric surface is present in the southern area of the study area, south of the City of Enid, corresponding to the erosional feature in the surface of the underlying Permian units. Contours bow in a "V" pattern at perennial streams such as Skeleton Creek, Sand Creek, and other major streams (Figure 7), indicating groundwater from the Enid Isolated Terrace is discharging to these surface water features. Bowing of potentiometric contour lines is not seen around other creeks in the aquifer area, which may indicate the other creeks are (1) not in communication with the aquifer; (2) too small to be characterized on the scale of the potentiometric map; or (3) intermittent and dependent on the time of year, amount of rainfall, and rate of recharge.

Aquifer Characteristics

Base and Saturated Thickness

The base of the terrace deposits was interpolated using 1,738 well logs from the OWRB water well records database. The base of the terrace deposits was generally described as red shale, shale, red bed, red bedrock, or bedrock, and referenced to the NAVD 88 for elevation. The lithologic descriptions listed above are considered to describe the underlying Permian units acting as an aquitard (units that retard but do not prevent groundwater flow). The data show the base of the study area declining from 1,340 feet above sea level in the northwest to about 1,100 feet above sea level in the east and southeast (Figure 8). A depression was observed in the base elevation in the north-central part of the study area near the City of Enid, which may have formed by erosion from river channels prior to the deposition of terrace deposits.

Saturated thickness of the Enid Isolated Terrace was estimated by subtracting the base elevation from the potentiometric surface elevation (Figure 9). The mean saturated thickness within the study area was estimated to be 14.8 feet. The area of greatest saturated thickness was to the north and northwest of the City of Enid in the vicinity of U.S. Highway 81 (Figure 9) with a saturated thickness value of 65 feet. This corresponds to the thickest terrace deposits observed in lithologic descriptions from the OWRB water well records database. The Breckinridge and Carrier arms of the study area had lower saturated thicknesses due to thinning terrace deposits (Figure 9).

Two cross-sections were drawn to illustrate features of the study area (Figure 9): one from north to south (A-A', Figure 10A) and another northwest to southeast (B-B', Figure 10B). The A-A' cross-section indicates a four mile wide trough in the Permian-age bedrock, which allowed the accumulation of terrace deposits up to 50 feet, and shows this area with a saturated thickness of 30 to 40 feet (Figure 10A). Cross-section B-B' shows the potentiometric surface intersecting the land surface at Sand Creek and Skeleton Creek, which indicates that groundwater is discharging to the surface (Figure 10B).

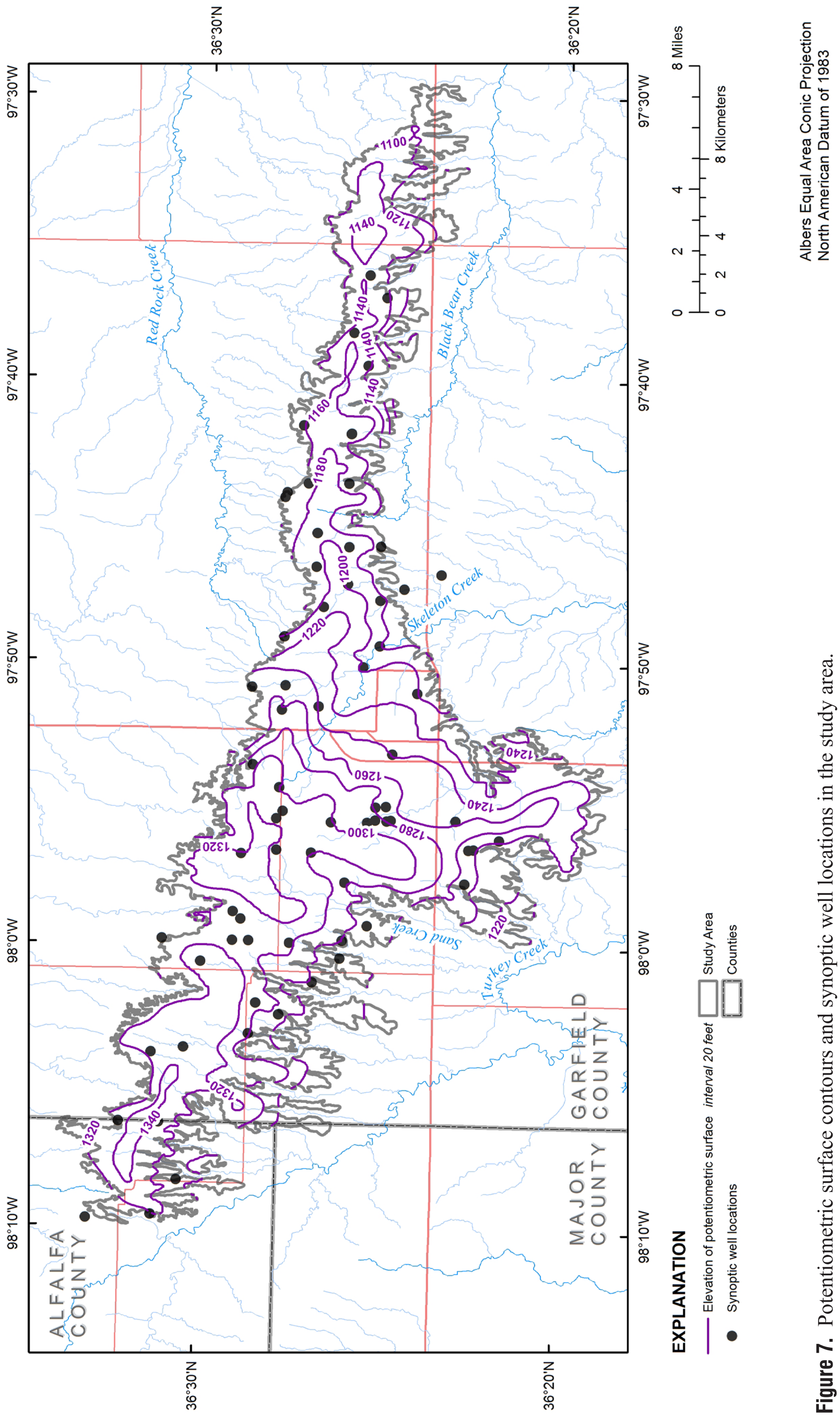


Figure 7. Potentiometric surface contours and synoptic well locations in the study area.

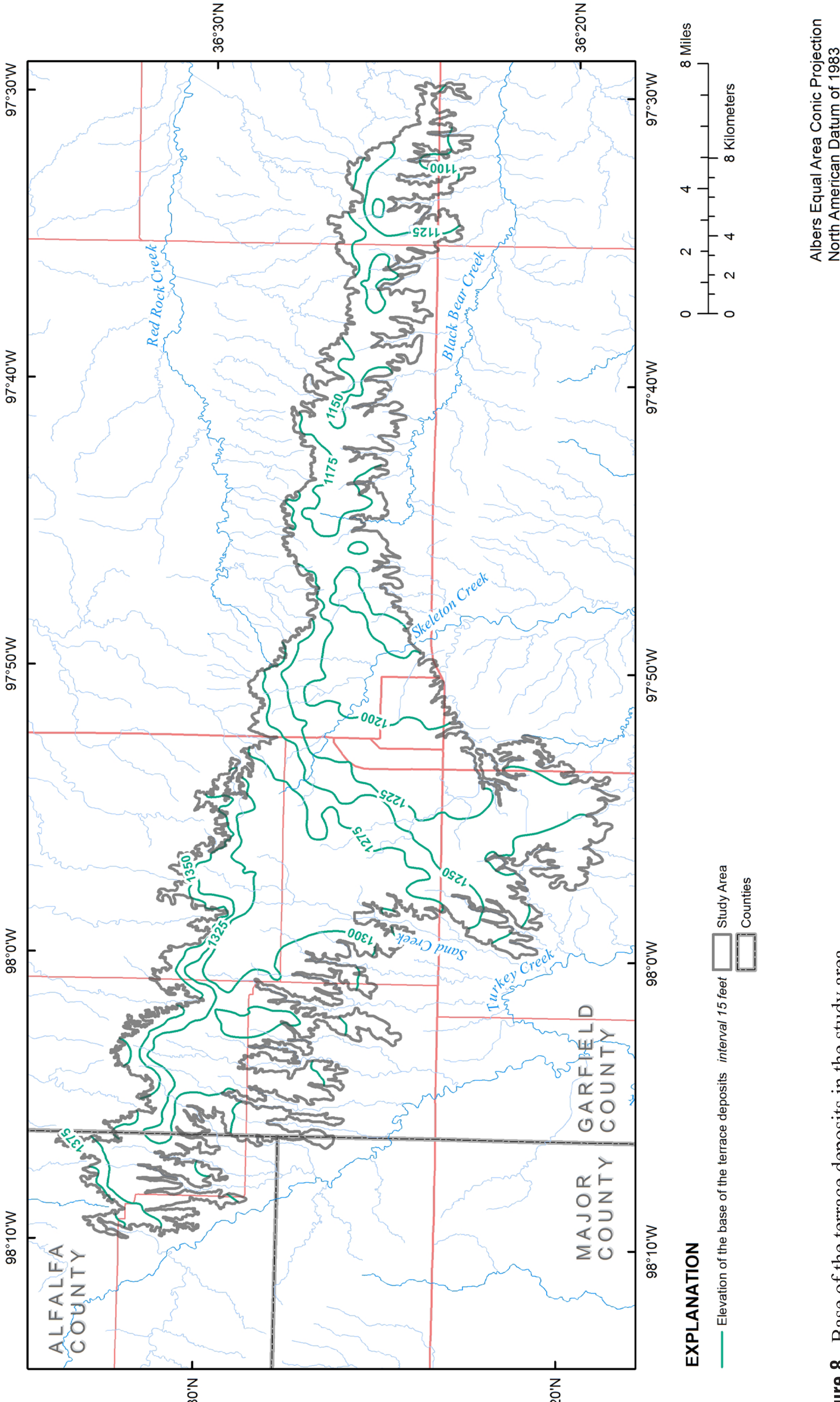


Figure 8. Base of the terrace deposits in the study area.

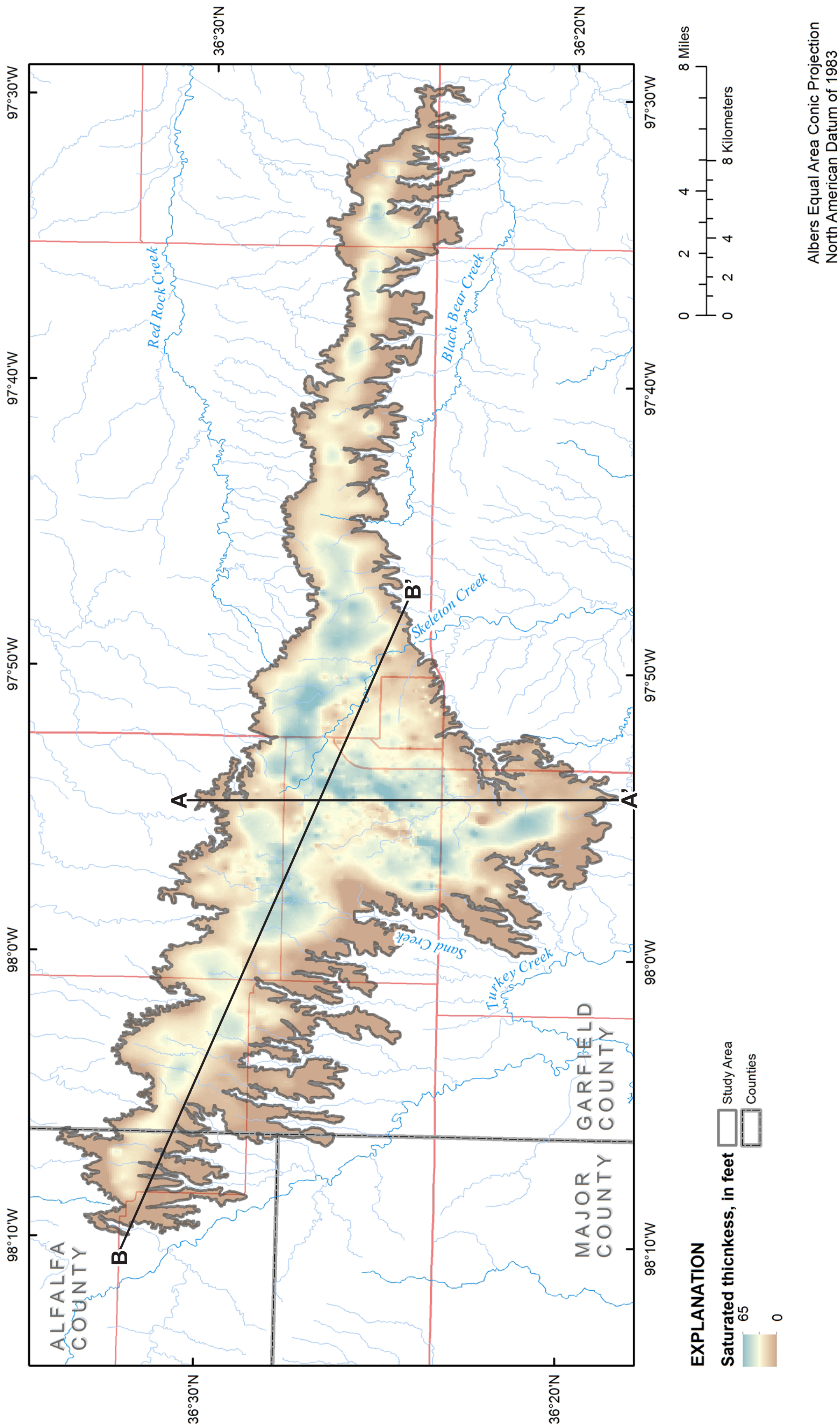


Figure 9. Saturated thickness of the study area with cross-sections A-A' and B-B' (Figure 10).

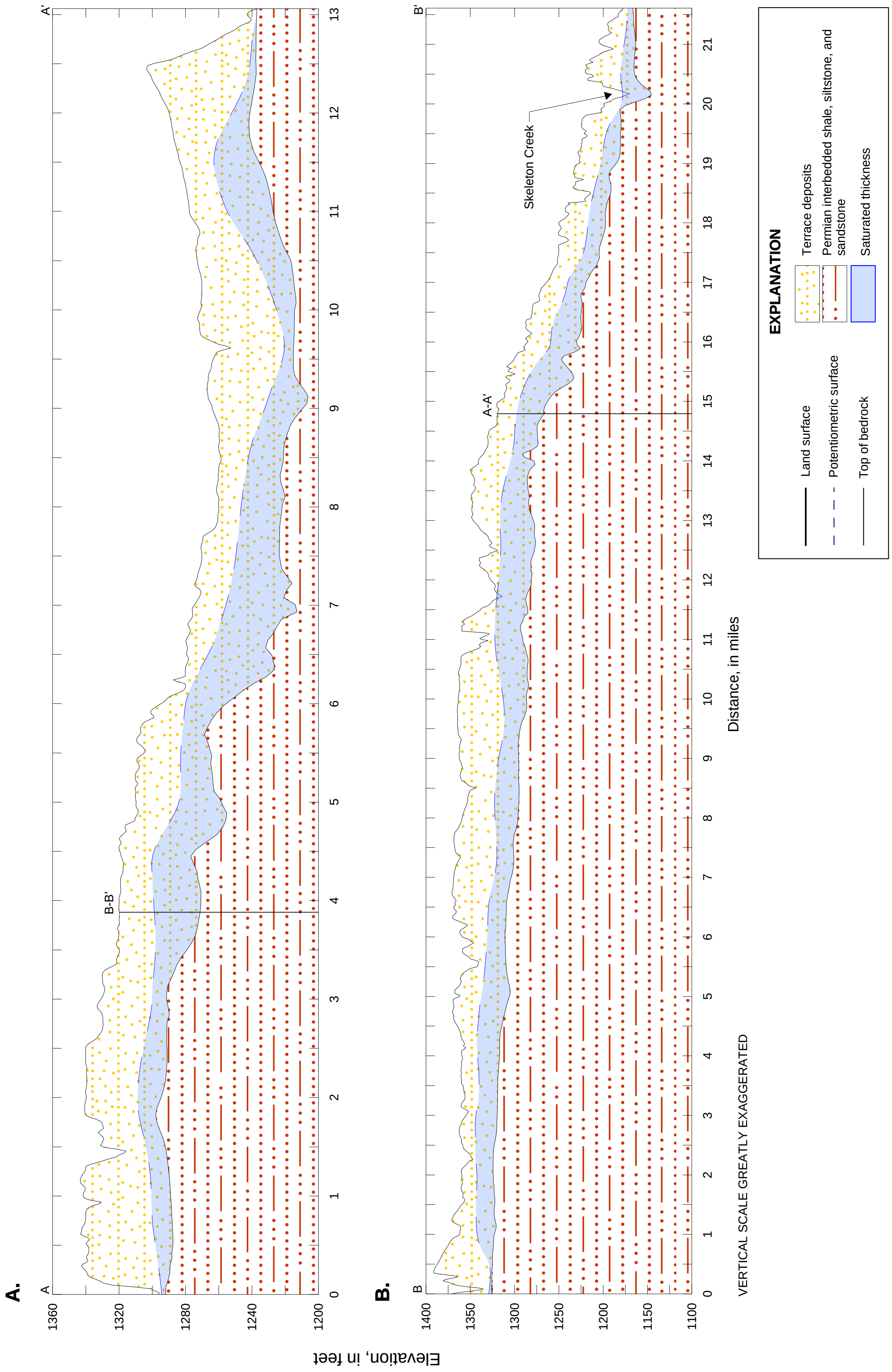


Figure 10. Cross-sections (A) A-A' and (B) B-B' showing geologic units, the potentiometric surface, and base of the study area.

Single-well Pumping Tests

Single-well pumping tests are performed by well drillers to determine specific capacity, which is the rate of discharge of water from the well divided by the draw-down of the water level within the well (Lohman, 1972) based on water-level response to the withdrawal of water. Single-well pumping test data, which includes pumping rate, test duration, and the draw-down depth to water, is submitted to the OWRB on well completion reports. Aquifer characteristics such as transmissivity, the rate at which water flows through a unit width of the aquifer under a hydraulic gradient (Lohman, 1972), and hydraulic conductivity, the column of water that will move in unit time under a unit hydraulic gradient, measured perpendicular to flow direction (Lohman, 1972), at the well location can be estimated using data gathered from the tests. Transmissivity was estimated by inputting this data into an online calculator (HydroSOLVE, Inc., 2014), which uses a modified version of the Cooper and Jacob solution for flow into a well in a confined aquifer (Cooper and Jacob, 1946):

$$(1)\ T = 0.183 \frac{Q}{S_W} \log \left(\frac{2.25Tt}{r_W^2 S}\right)$$

In this equation, T is the transmissivity of the aquifer at the well location in square feet per day, Q is the constant pumping rate in cubic feet per day, S_W is the draw-down depth to water in the pumping well in feet, r_w is the well radius in feet, S is the storativity, which is dimensionless and assumed to be 0.07 (Reely, 1992), and t is the duration of the pumping test in days. Since T appears in the logarithm term, techniques such as successive approximation can be used to solve for T (HydroSOLVE, Inc., 2014).

Transmissivity, estimated using the above equation, was divided by the saturated thickness at the well site to calculate hydraulic conductivity. Since groundwater wells are not typically over-drilled in terrace aquifers, saturated thickness was assumed to be the depth to the bottom of the well minus the initial depth to water in the well at the beginning of the pumping test. The first water zone or the first saturated layer in the lithology description of driller logs was used when an initial depth to water was not reported.

In the study area, 392 single-well pumping tests were reported. The ranges of estimated hydraulic conductivities from this dataset were 0.32 to 289.69 feet per day (Table 2). Most of the estimated hydraulic conductivities were within the range of a medium-sand-dominated aquifer (0.26 to 141.73 feet per day) (Schwartz and Zhang, 2003) and were consistent with observed and reported lithologies. Fifteen wells had an estimated hydraulic conductivity above 141.7 feet per day and were likely influenced by coarser sediments such as sand or gravel.

Single-well tests are only able to measure properties within the immediate vicinity of the well and typically for short amounts of time, which can result in variability. The spatial distribution of wells with reported pumping test data were biased to the Enid municipal area (Figure 11). Using the results of the draw-down tests, the hydraulic conductivities for the aquifer were interpolated in Figure 11 and show variable values. The western and eastern arms of the study area lack data to estimate hydraulic conductivity for those areas. A section of the study area northwest of Enid has higher hydraulic conductivity values where well log data showed higher pumping rates, exceeding 100 gallons per minute, but relatively little draw-down. Some lower hydraulic conductivity values were present in this area where wells have been partially screened into the Permian units below the terrace deposits resulting in slower flow into the well. The high density of draw-down data in the central portion of the study area created a localized area of data saturation resulting in the spotted pattern seen in Figure 11. This may reflect a more heterogeneous geology than expected.

Table 2. Summary statistics for calculated hydraulic conductivity values from 392 single-well pumping tests in the study area.

Statistic	Value, in feet per day
Mean	50.16
Median	39.22
Minimum	.32
Maximum	289.69

Multi-well Pumping Tests

Multi-well pumping tests were performed at two sites to estimate transmissivity, storage coefficient, specific yield, and hydraulic conductivity. This type of pumping test is typically done on wells in areas that have higher hydraulic conductivity (such as public water supply wells), which means they tend to be at the upper end of the calculated range. Both test sites were public water supply wells owned and maintained by the City of Enid. Each test site had a monitoring well within 30 feet of the pumping well, which typically results in greater data reliability compared to single-well pumping tests. Unconfined pumping tests should have monitoring wells relatively close (less than 320 feet) to the pumping wells and pump for at least 24 hours as a result of slow propagation of head loss (Kruseman and others, 1994). The first aquifer test was located on the northwest side of the City of Enid with pumping well OWRB 145756 (Van Buren) and monitoring well OWRB 157021 (Enid Monitoring 1). OWRB 145756 had a total depth of 63 feet below land surface and OWRB 157021 had a total depth of 55 feet below land surface. The second aquifer test was performed at the corner of Robertson Road and Boomer Road on pumping well OWRB 102687 (Carrier #6) and monitoring well OWRB 102684 (Enid Monitoring 3). OWRB 102687 had a total depth of 76 feet below land surface and OWRB 102684 had a total depth of 82 feet below land surface.

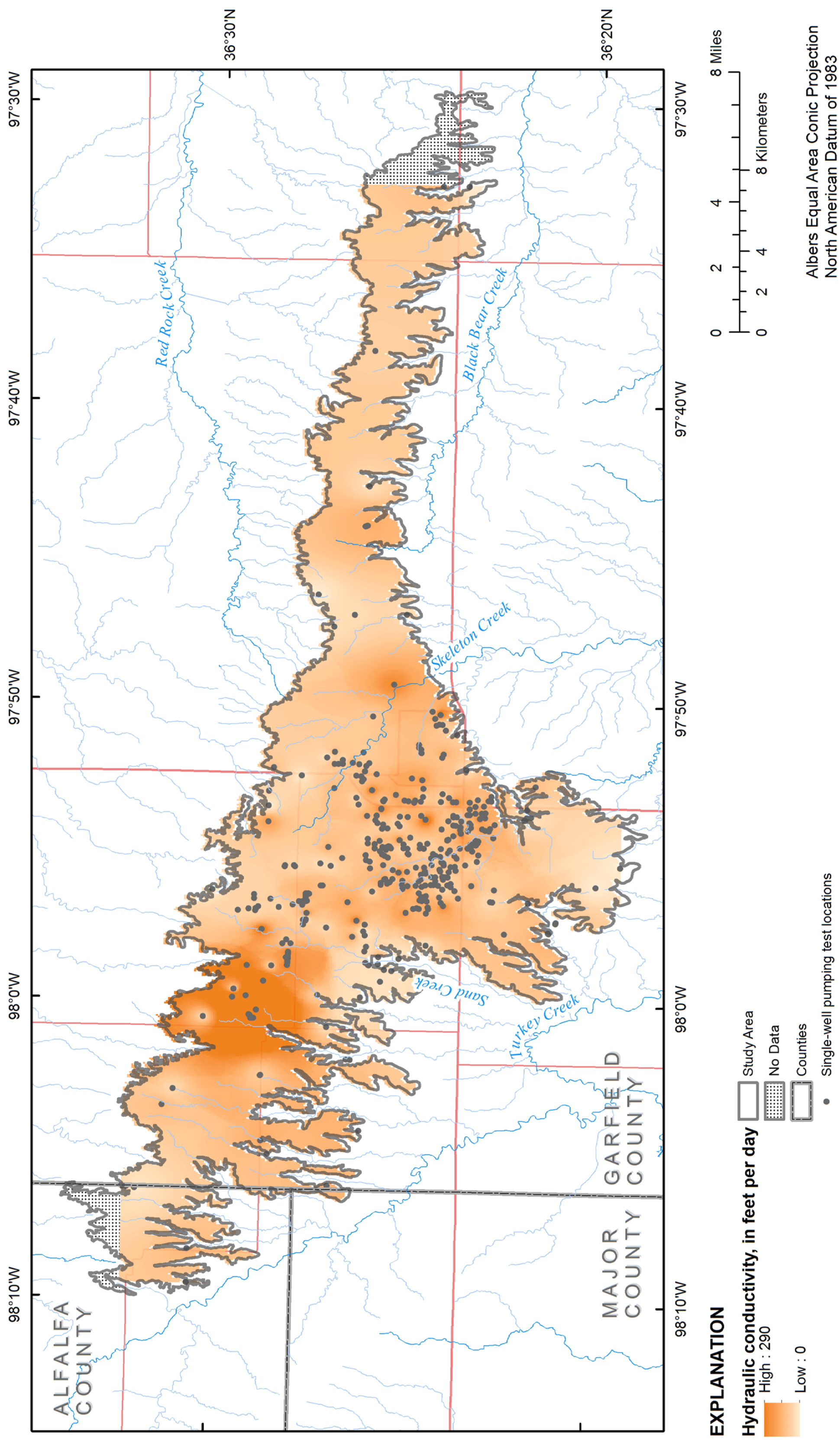


Figure 11. Hydraulic conductivity of the study area.

Pressure transducers were installed in both monitoring wells, and pumping wells were shut down for approximately 30 days prior to the pumping test to obtain a baseline measurement of the aquifer at equilibrium. The pumping test for OWRB 145756 began recording water levels at one-minute intervals at 11:26 a.m. on April 28, 2014, with a mean pumping rate of 150 gallons per minute (the rate started at 130 gallons per minute and ended at 170 gallons per minute) and ran until 11:05 a.m. on May 8, 2014 (Figure 12A). The pumping test for well 102687 began recording water levels at one-minute intervals at 12:33 p.m. on February 26, 2014, and ran until 12:05 p.m. on March 7, 2014 (Figure 12B). City of Enid officials stated that the pumping rate for well 102687 was 120 gallons per minute (City of Enid, oral communication, 2014). When the pumping ceased, water levels were recorded for a one-week recovery period at both sites.

Measurement dates were converted to elapsed time in minutes and water-level measurements were converted to change in water level (draw-down) from the first water level measurement. The converted pumping test data were imported into the program AQTESOLV (HydroSOLVE, Inc., 2014) along with well casing size, aquifer saturated thickness, and pumping rate or field observations (Table 3). The pumping data analysis from monitoring well OWRB 157021 was not included as a result of possible inconsistent pumping rates and the close proximity to the pumping well, which caused calculation difficulties during analysis, resulting in unrealistic values.

The Neuman solution (Neuman, 1972) provided a best fit for the pumping as well as the recovery data at OWRB 102684 and for the recovery data only at OWRB 157021 (Figures 13 and 14). These solutions are appropriate for unconfined aquifers with a delayed gravity response, variable rate, and partial penetration. To analyze only recovery data with type curves developed for draw-down analysis, an Agarwal method (Agarwal, 1980) was applied to transform the time scale for OWRB 157021. The combined pumping and recovery data for OWRB 102684 indicated a transmissivity of 5,611.3 square feet per day, a storage coefficient of 0.016, a specific yield of 0.22, and a hydrologic conductivity of 140.3 feet per day (Table 4). The estimated hydraulic conductivity values fall into the range of fine sand to gravel (Dominico and Schwartz, 1998), while the specific yield values indicate materials ranging from silt to gravel (Morris and Johnson, 1967).

Table 3. Well-site characteristics used to calculate aquifer characteristics from multi-well aquifer tests in the study area.

Pumping test site	Saturated thickness, in feet	Anisotropy	Distance from pumping well, in feet	Radius of pumping well, in feet	Radius of observation well, in feet	Pumping rate, in gallons per minute
Pumping well OWRB 145756 Van Buren, observation well OWRB 157021 Enid Monitoring 1	23	1	10	0.83	0.5	150
Pumping well OWRB 102687 Carrier #6, observation well OWRB 102684 Enid Monitoring 3	40	1	25.5	1.3	0.5	120

Table 4. AQTESOLV analysis results from multi-well aquifer tests in the study area.

Site ID	Test Status	Method	Transmissivity, in square feet per day	Storage Coefficient	Hydraulic Conductivity, in feet per day
157021	Pumping	Moench (1993)	3,039.90	0.002	132.2
157021	Recovery	Neuman (1972)	2,333.10	0.006	101.4
102684	Recovery	Neuman (1972)	5,031.30	0.01	125.8

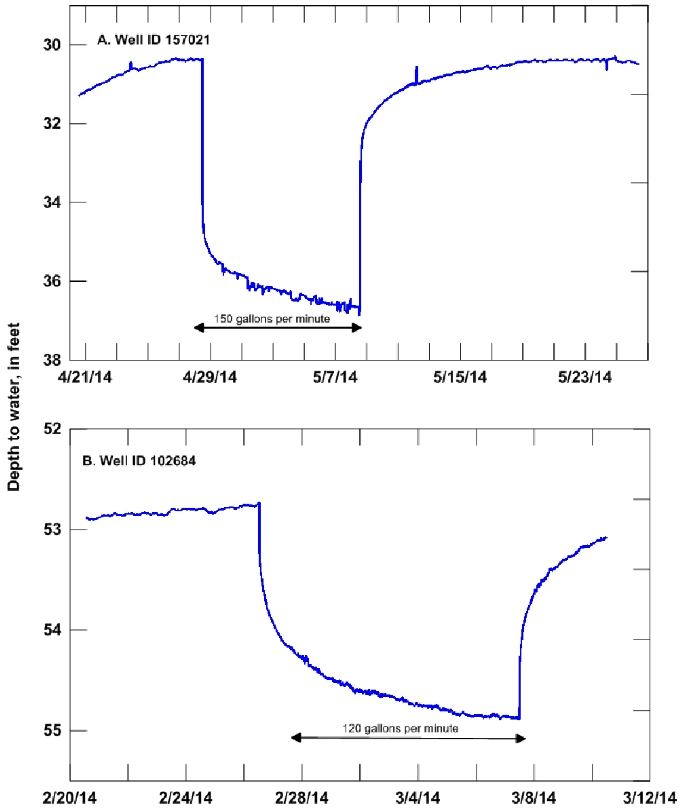


Figure 12. Depth to water in the (A) Enid Monitoring 1 and (B) Enid Monitoring 3 wells during the pumping draw-down and recovery periods of multi-well aquifer tests in the study area.

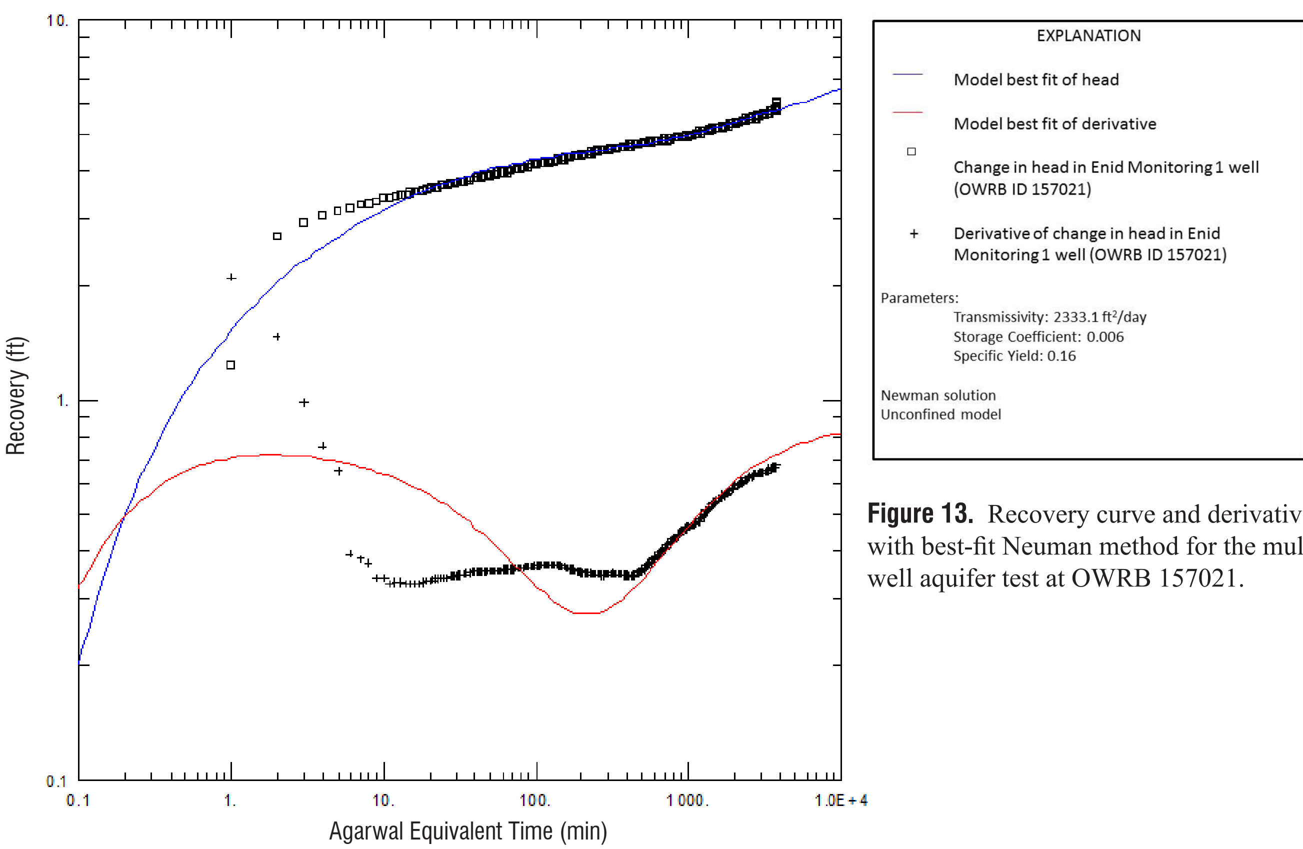


Figure 13. Recovery curve and derivative with best-fit Neuman method for the multi-well aquifer test at OWRB 157021.

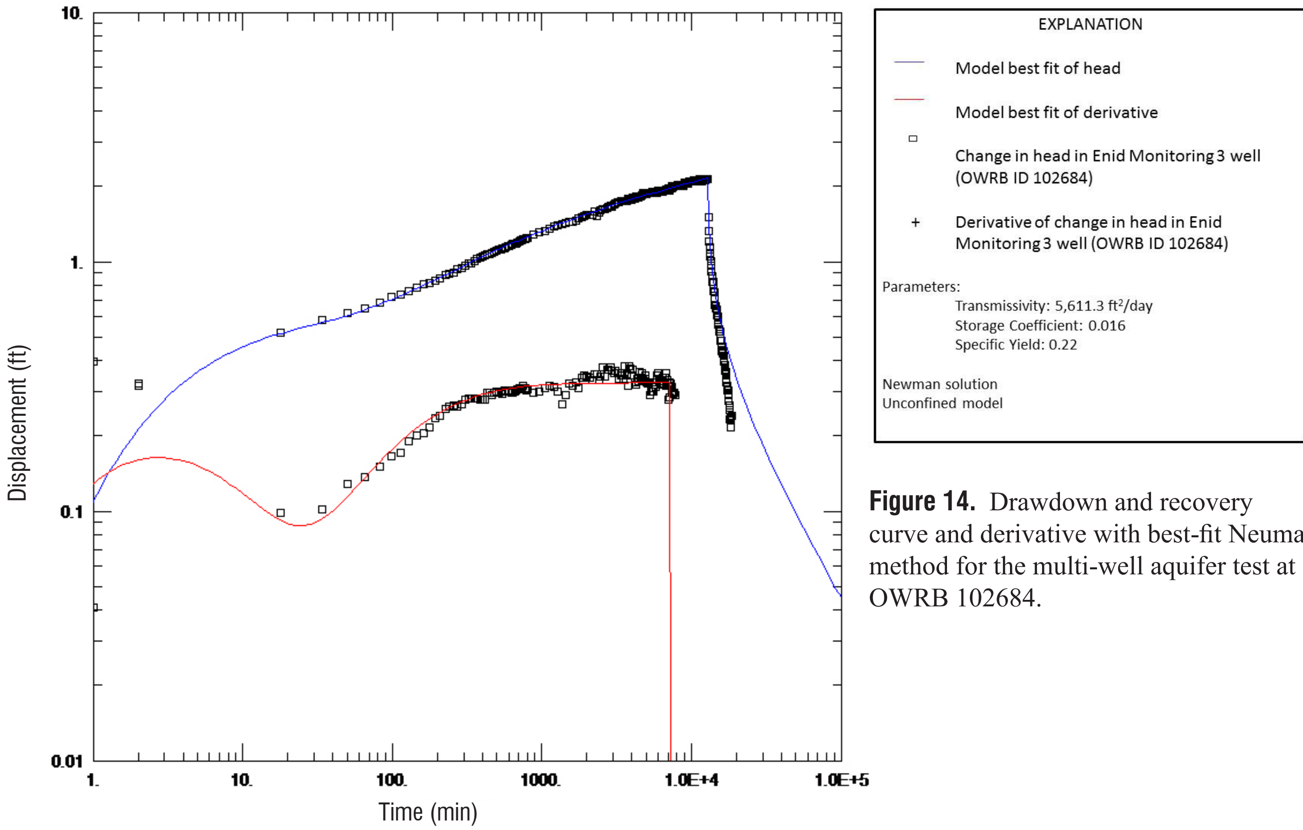


Figure 14. Drawdown and recovery curve and derivative with best-fit Neuman method for the multi-well aquifer test at OWRB 102684.

Table 5. Annual reported groundwater use in the study area for 1967–2013.

	Annual reported water use in acre-feet*		
	1967-2013	1967-1997	1998-2013
Average	3,243	3,095	3,520
Median	3,301	3,284	3,402
Minimum	1,434	1,434	2,106
Maximum	4,882	4,246	4,882

*The year 1992 was excluded from this analysis.

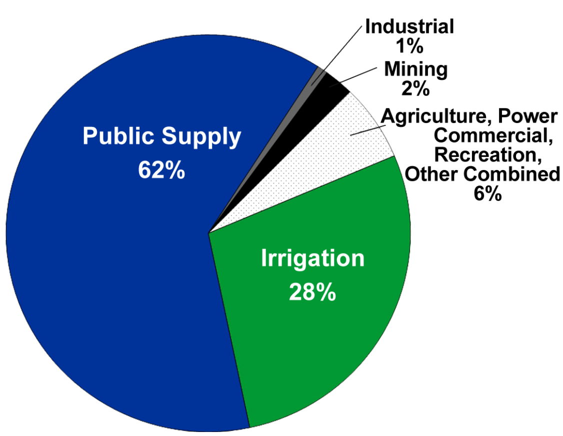


Figure 15. Average annual groundwater use by type from the study area for 1967–2013.

Water Use

Permitted water users are required to report their groundwater use annually to the OWRB for industrial, commercial, agricultural, irrigation, power, mining, recreation, or public supply use. Comprehensive water use record-keeping began around 1967. The OWRB does not require annual reporting for domestic groundwater use less than five acre-feet for self-supplied and agriculture purposes or groundwater use for irrigation of less than three acres (OWRB, 2014). Prior to 1980, inches applied during irrigation were not required to be reported. As a result, the OWRB adopted rules to estimate the number of inches applied for pre-1980 data based on the number of applications (OWRB, 2014), which provided a method to calculate groundwater use.

Annual groundwater use data were reported by 64 permitted users of water from the study area for the period of record, 1967–2013. Mean annual groundwater use for the period of record was 3,243 acre-feet per year with a maximum annual groundwater use of 4,882 acre-feet in 2011 and a minimum annual groundwater use of 1,434 acre-feet in 1996 (Table 5). Groundwater use records for 1992 were periodically missing, resulting in a skewed minimum value; therefore, that year was removed from analysis. The majority (62 percent) of mean annual groundwater use for the period of record was for public supply; 28 percent was for irrigation (Figure 15).

Two time periods, 1967–1997 and 1998–2013, are shown in Table 5. Average reported groundwater use for 1967–1997 was 3,095 acre-feet with a minimum of 1,434 acre-feet in

1996 and a maximum of 4,246 acre-feet in 1968 (Table 5). Similar groundwater use is shown for 1998–2013 with a mean of 3,520 acre-feet, a minimum of 2,106 acre-feet in 1998, and a maximum of 4,882 acre-feet in 2011 (Table 5). Public water supply and irrigation categories were the highest use types throughout all of the time periods analyzed (Table 6). The primary difference between the two time frames is a shift in the principal groundwater use from public supply to irrigation (Figure 16). The shift was caused when the City of Enid began utilizing the Cimarron River Alluvium and Terrace aquifer for water supply and creating more efficient city water plans. The increased groundwater use for mining during 1986–1995 reflects long-term permits that were obtained for railroad construction. A small decrease in irrigation and public water supply during the late 1980s into the 1990s is the result of increased rainfall during that period.

Table 6. Average annual reported groundwater use in the study area by use type for 1967–2013.

	Average annual reported water use in acre-feet*									
	Irrigation	Public Supply	Industrial	Power	Mining	Commercial	Recreation	Agriculture	Other	Total
1967-2013	901	2,046	28	0	71	62	113	6	16	3,243
1967-1997	436	2,318	44	0	108	95	71	9	13	3,095
1998-2013	1,772	1,535	0	0	0	0	191	1	22	3,520

*The year 1992 was excluded from this analysis.

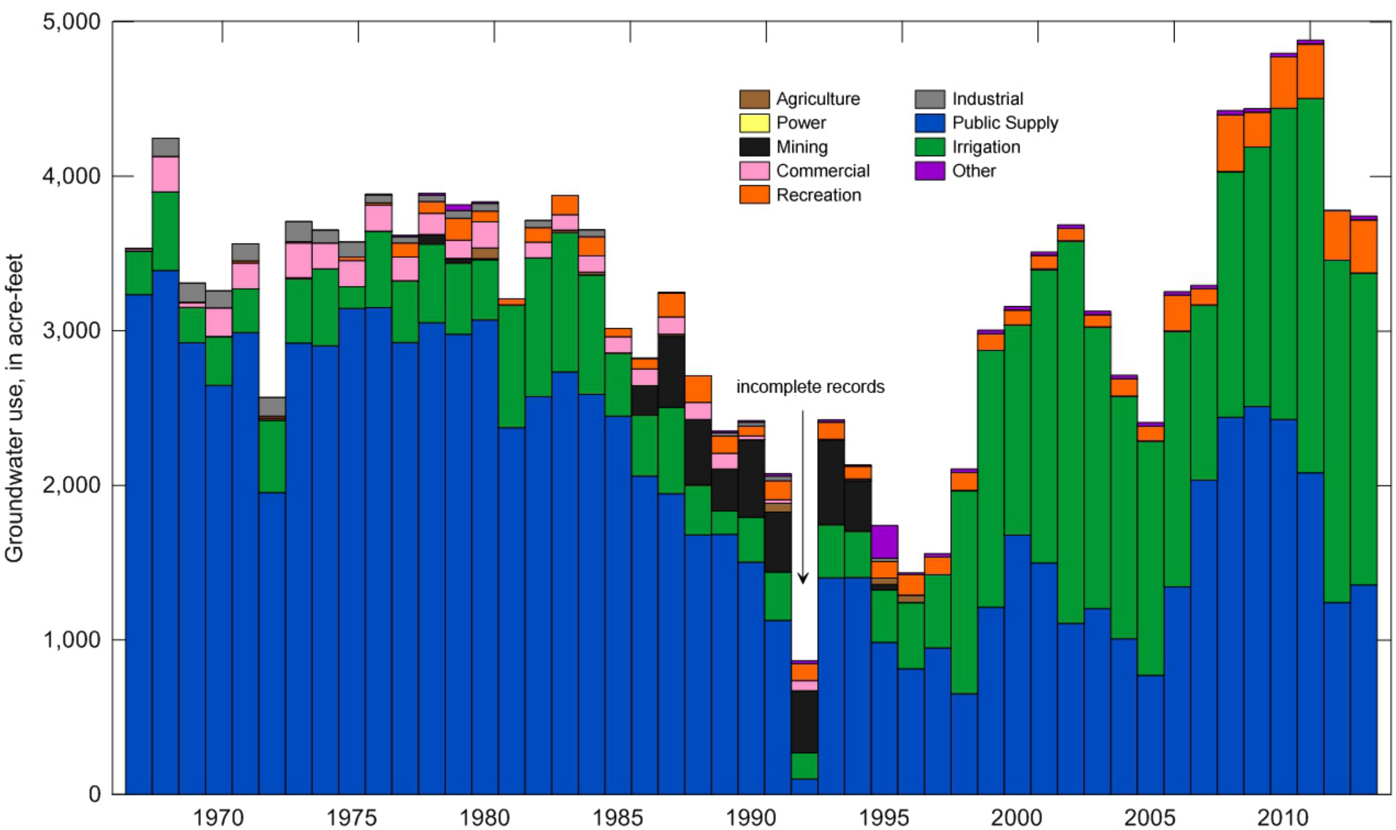


Figure 16. Groundwater use reported to the OWRB from the study area for 1967–2013.

Recharge

For this investigation, recharge is described as the process by which water infiltrates the subsurface and becomes part of the groundwater-flow system. Recharge for the Enid Isolated Terrace primarily occurs from infiltration of precipitation. Recharge can be influenced by precipitation, hydraulic conductivity of the substrate, soil type, seasonal climate variability, land use, and topography. Recharge was estimated using two methods: (1) recession-curve displacement (RORA) and (2) soil-water balance (SWB). The RORA method is more basin-specific and utilizes streamflow data, which shows the effects of recharge, whereas SWB covers an aquifer-wide area employing different datasets, including soil characteristics and climate data, resulting in a more predictive method of estimation.

RORA Computer Program

The RORA computer program uses a base-flow recession-curve displacement method (Rorabaugh, 1964) to estimate groundwater recharge from streamflow discharge data and summarize quarterly and annual recharge (Christenson and others, 2011). Base-flow is defined as the part of streamflow that is not from runoff. The USGS operated a streamflow gauge on Skeleton Creek at Enid (USGS 07160350) from February 1996 to present. Historical streamflow data were retrieved from the NWIS (USGS, 2014) and analyzed using the RORA computer program (Rutledge, 1998). The year 1996 was not analyzed because the data did not encompass the entire year. Controlling components of groundwater discharge to streams include evaporation, plant transpiration, and groundwater withdrawal.

Mean annual recharge to the Enid Isolated Terrace aquifer in the Skeleton Creek drainage basin was 2.79 inches for 1997–2013. Within that period, the minimum annual recharge was 1.1 inches in 2006, and the maximum annual recharge was 4.9 inches in 1999 (Figure 17). The range in annual recharge corresponds to extremes in annual precipitation (17.5 inches in 2006, and 50.1 inches in 1999) reported at the Breckinridge Mesonet station for the same period.

Soil-Water Balance Model

A soil-water balance (SWB) model (Westenbroek and others, 2010) was used to estimate monthly and annual recharge to the Enid Isolated Terrace aquifer for 1998–2013. A SWB model estimates spatial and temporal variations in recharge using datasets describing soil characteristics (soil-water capacity and hydrologic soil group), climate (daily temperature and precipitation), and land cover (Westenbroek and others, 2010). The available soil-water capacity and hydrologic soil group data were derived from the Gridded Soil Survey Geographic Database (gSSURGO) (National Resources Conservation Service (NRCS), 2014). Soils were categorized into four hydrologic soil groups (A-D) on the basis of infiltration capacity, with "A" soils having the highest infiltration capacity and "D" soils having the lowest infiltration capacity (Westenbroek and others, 2010). Available soil-water capacity values ranging from 1.20-3.60 inches per foot of thickness were assigned based on soil texture (Westenbroek and others, 2010). Climate data, obtained for the Breckinridge Mesonet station, included the daily minimum, maximum, and mean temperatures as well as the daily precipitation for 1998–2013. The Hargreaves-Samani method was used to estimate the potential evapotranspiration in the SWB model because more site-specific calculations can be made without requiring additional climate data that is needed when using other methods (Westenbroek and others, 2010).

Land cover data were derived from the 2011 National Land Cover Database (NLCD), which provides 16 classes for land cover (Multi-Resolution Land Characteristics Consortium, 2011). Land-use data and available soil-water capacity were used in the SWB model to estimate surface runoff and maximum soil-moisture holding capacity (Westenbroek and others, 2010). The SWB model uses a land-use lookup table

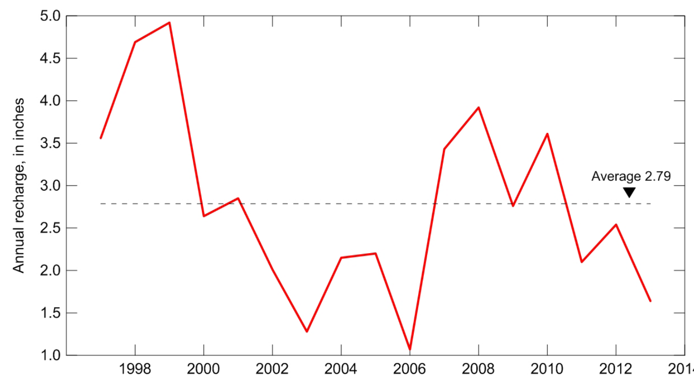


Figure 17. Annual recharge to the study area in the Skeleton Creek drainage basin for 1997–2013, computed using the RORA computer program.

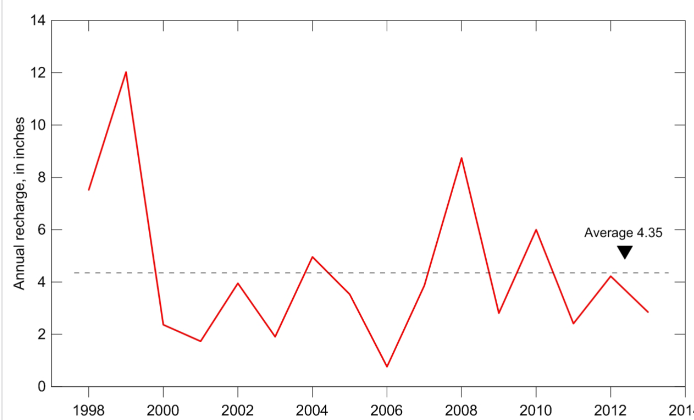


Figure 18. Annual recharge to the study area for 1998–2013, computed using a soil-water balance model.

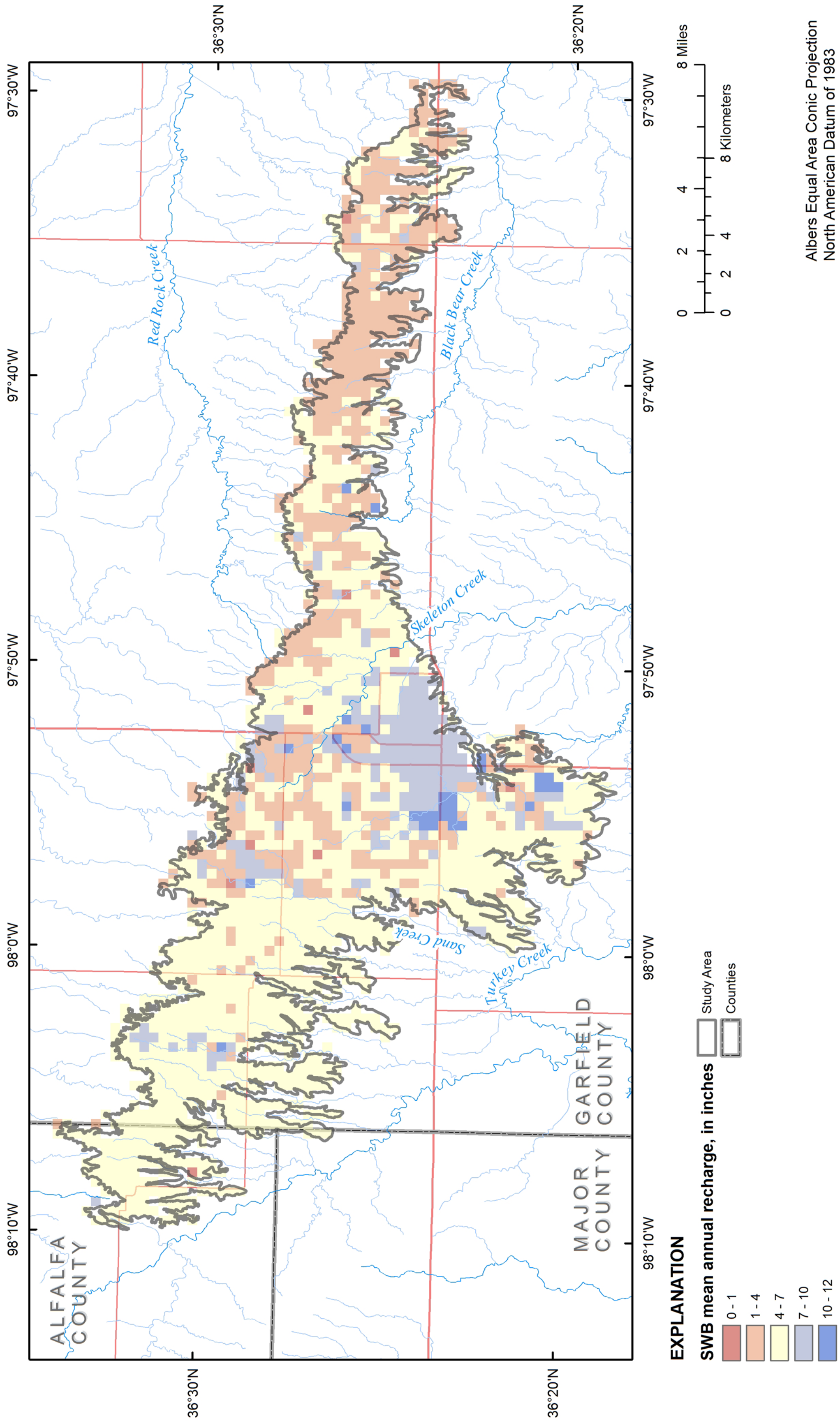


Figure 19. Average annual recharge to the study area for 1998–2013, computed using a soil-water balance model.

Table 7. Monthly and annual total and average recharge from a soil-water balance model in the study area for 1998–2013.

	Monthly and annual average recharge (in inches) from Soil Water Balance model												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2013	0.002	0.215	0.092	0.307	0.000	0.000	0.048	0.175	0.012	0.733	0.766	0.504	2.852
2012	0.522	1.343	1.115	1.240	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.221
2011	0.013	0.038	0.520	0.000	0.026	0.000	0.000	0.000	0.000	0.059	0.616	1.137	2.408
2010	0.090	1.680	0.673	1.617	0.885	0.000	0.000	0.000	0.001	0.150	0.900	0.000	5.997
2009	0.000	0.452	0.077	0.575	0.013	0.000	0.000	0.103	0.001	0.960	0.624	0.007	2.811
2008	0.483	1.339	1.766	0.989	1.082	0.658	0.058	0.000	0.095	1.651	0.206	0.418	8.745
2007	0.002	0.013	0.408	0.411	0.147	1.302	0.035	0.000	0.035	1.322	0.000	0.189	3.864
2006	0.000	0.000	0.096	0.665	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.762
2005	1.602	0.607	0.000	0.000	0.000	0.002	0.000	0.536	0.002	0.780	0.000	0.000	3.529
2004	0.234	0.437	1.350	0.564	0.000	0.000	0.000	0.075	0.000	0.226	1.738	0.341	4.966
2003	0.030	0.467	1.122	0.081	0.000	0.000	0.000	0.000	0.001	0.082	0.011	0.112	1.905
2002	0.002	0.157	0.011	0.102	0.000	0.000	0.000	0.006	0.282	2.358	0.118	0.917	3.952
2001	0.291	1.001	0.410	0.000	0.027	0.000	0.000	0.000	0.000	0.000	0.004	0.000	1.733
2000	0.005	0.680	1.488	0.180	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.014	2.367
1999	1.434	0.974	1.843	2.221	0.000	0.966	0.000	0.000	1.950	0.731	0.105	1.810	12.033
1998	1.500	0.000	2.075	0.599	0.035	0.000	0.000	0.000	0.000	0.872	1.392	1.053	7.525
Average	0.388	0.588	0.815	0.597	0.138	0.183	0.009	0.056	0.149	0.620	0.405	0.406	4.354

containing NRCS curve numbers, precipitation interception, maximum recharge rates, and root zone depths for each soil type (Westenbroek and others, 2010). Root zone depth values for small grains (land-use code 83) were changed to reflect typical root depths of winter wheat in each soil type: MED/CRS (soil A) = 5 feet; loamy till (soil B) = 6.2 feet; clay till (soil C) = 4.1 feet; and fine (soil D) = 4.7 feet (Weaver, 1926). The values for grasslands, pasture, and urban/recreational grasses (land-use codes 71, 81, and 85, respectively) were increased by 20 percent to reflect higher root zone values for Bermuda grass and other native grasses (Wu, 1985; Duble, 2016).

The SWB model produced monthly and annual recharge grids of 500 meters by 500 meters. Mean annual recharge for the gridded study area was 4.35 inches for 1998–2013 (Figure 18). The maximum annual recharge was 12.03 inches in 1999 and the minimum annual recharge was 0.76 inches in 2006 (Figure 18). Mean monthly recharge for 1998–2013 was greatest during March, with a mean recharge of 0.82 inches (Table 7). The lowest amount of monthly recharge occurred during July with a mean of 0.01 inches. The mean annual recharge was greatest in the portions of the aquifer near the City of Enid and was least in the far northeast portion of the aquifer (Figure 19).

Water Quality

In 2014, the OWRB GMAP collected water quality samples from nine wells within the Enid Isolated Terrace aquifer extent (OWRB, 2015). Water quality samples were collected from ten additional wells as part of this investigation to achieve a better distribution across the study area (see the 2015 Beneficial Use Monitoring Program Report for a map of wells sampled).

The water produced from the study area is described as fair to good in quality, very hard, and moderately alkaline (OWRB, 2015). The total dissolved solids concentrations in water produced from the study area ranged from 145 to 1,880 milligrams per liter with a mean of 684 milligrams per liter and a median of 660 milligrams per liter (Table 8).

A noticeable trend of higher total dissolved solids concentrations occurs toward the south-southeastern portion of the study area (Figure 20). Total dissolved solids concentrations tend to be lower where recharge is likely occurring and higher near discharge areas.

The dominant cation in water produced from the study area is sodium plus potassium; concentrations ranged from 22

Table 8. Summary statistics of constituent concentrations in groundwater samples collected from the study area for 2014.

Constituent	Mean	Minimum	Maximum	Number of samples below detection limit	Percentile		
					25	50	75
specific conductance	1247	305	3240	0	860.0	1240.0	1600.0
Temperature	20.0	17.6	27.2	0	18.8	19.5	20.4
pH	6.9	6.4	7.4	0	6.7	6.9	7.0
total dissolved solids*	683.6	145.00	1880.00	0	480.5	660.0	908.0
Hardness*	331.7	109.0	864.0	0	235.0	329.0	370.5
Calcium*	91.4	25.2	218.0	0	64.5	87.5	111.0
Magnesium*	23.3	8.1	50.3	0	15.4	22.1	25.7
Sodium*	147.6	18.9	372.0	0	60.7	153.0	185.5
Potassium*	2.4	1.2	3.5	0	2.0	2.6	2.9
Bicarbonate*	346	111	517	0	248.3	376.0	428.3
Sulfate*	90.3	20.5	216.0	0	33.6	75.8	124.5
Chloride*	159.2	12.1	784.0	0	45.9	116.0	201.0
Fluoride*	++	<0.2	0.5	10	++	++	0.2
Bromide**	553.9	110.0	2340.0	0	352.5	464.0	644.5
Silica**	22,326	2,400	35,500	0	20500.0	23600.0	25150.0
Nitrate as N*	10.8	2.1	29.0	0	5.1	11.3	14.2
Phosphorous**	0.071	<0.005	0.214	7	++	0.0	0.1
Aluminum**	++	++	++	19			
Arsenic**	3.7	<1	15.0	1	2.0	2.5	3.5
Barium**	185.5	64.7	496.0	0	90.2	181.0	255.0
Boron**	117.0	30.2	310.0	0	61.3	91.4	153.5
Cadmium**	++	++	++	19			
Chromium**	++	++	++	19			
Copper**	5.3	<5	20.0	14	++	++	5.7
Iron**	++	++	++	19			
Lead**+	++	++	++	19			
Manganese**	++	<5	17.8	17	++	++	++
Molybdenum**	++	<5	5.6	18	++	++	++
Uranium**	4.1	<1	16.9	2	1.7	3.3	5.1
Vanadium**	10.7	<5	26.2	1	7.5	9.0	11.7
Zinc**	47.2	<5	324.0	6	++	12.6	34.7

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

+, includes analysis of samples with different detection limits

Specific conductance is in microseimens per centimeter at 25° C

*, presented in milligrams per liter

**, presented in micrograms per liter

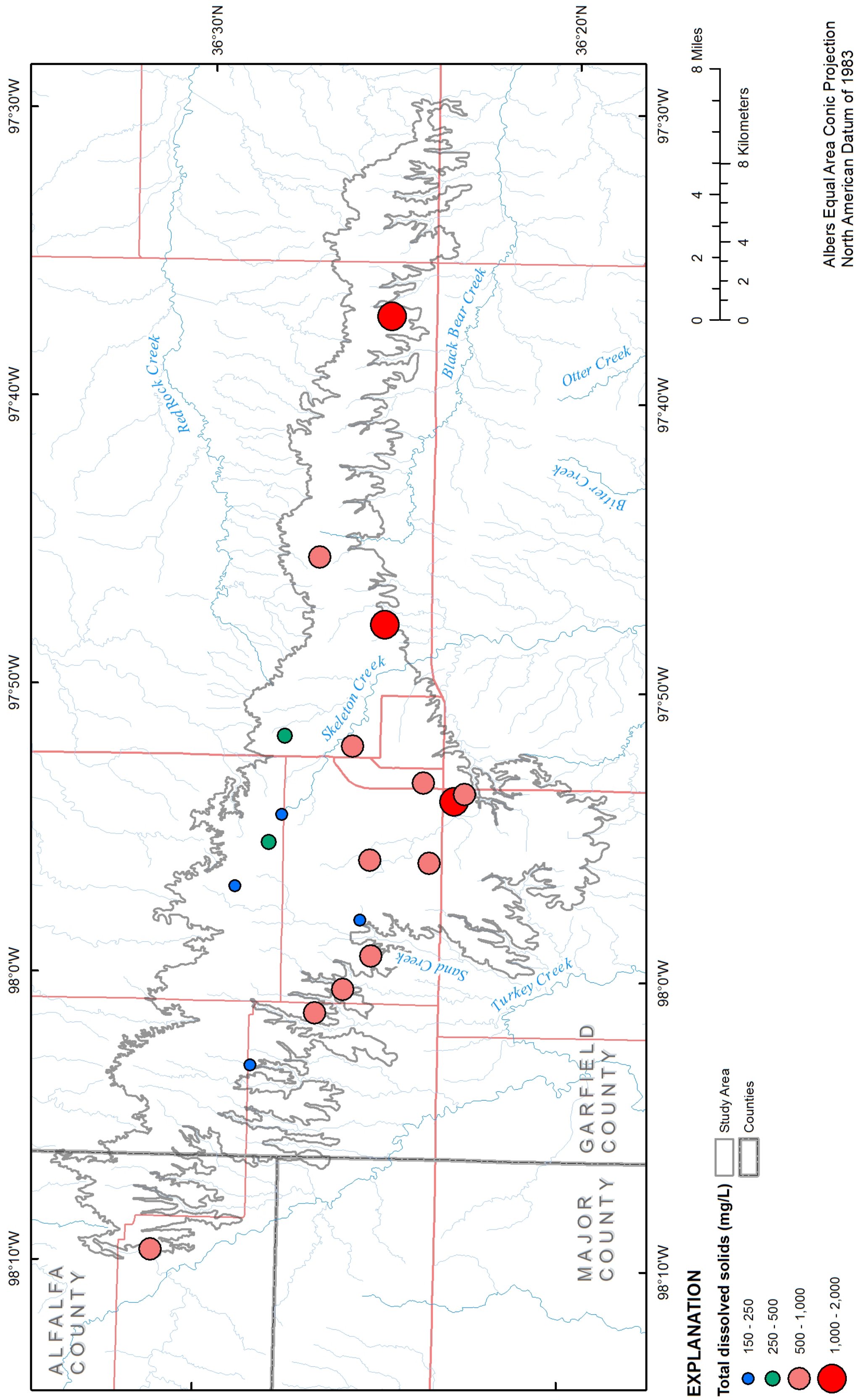


Figure 20. Total dissolved solids concentrations in groundwater samples collected from wells in the study area.

to 375 milligrams per liter with mean and median concentration of 156 and 150 milligrams per liter, respectively. The dominant anion type is variable, though sulfate is consistently low due to a lack of geologic source material. Sulfate concentrations ranged from 21 to 216 milligrams per liter with mean and median concentrations of 90 milligrams per liter and 124 milligrams per liter, respectively. Chloride concentrations ranged from 12 to 784 milligrams per liter with a mean concentration of 159 milligrams per liter. Carbonate plus bicarbonate concentrations ranged from 27 to 83 milligrams per liter with a mean concentration of 61 milligrams per liter (Table 8). Figure 21 is a Piper diagram in milliequivalents of water quality data from 19 well sites, which represents five water types (Deutsch and Siegel, 1997).

Some of the water samples from the study area had constituent concentrations that exceeded USEPA maximum contaminant levels for drinking water (USEPA, 2012). One of the water samples exceeded the maximum contaminant level for arsenic of 10 micrograms per liter with a concentration of 15 micrograms per liter. Eleven of the water samples had nitrate (reported as nitrogen) concentrations exceeding the maximum contaminant level of 10 milligrams per liter. The median and mean nitrate (reported as nitrogen) concentration from samples reported in this investigation is 11 milligrams per liter with and a maximum nitrate (reported as nitrogen) concentration of 29 milligrams per liter.

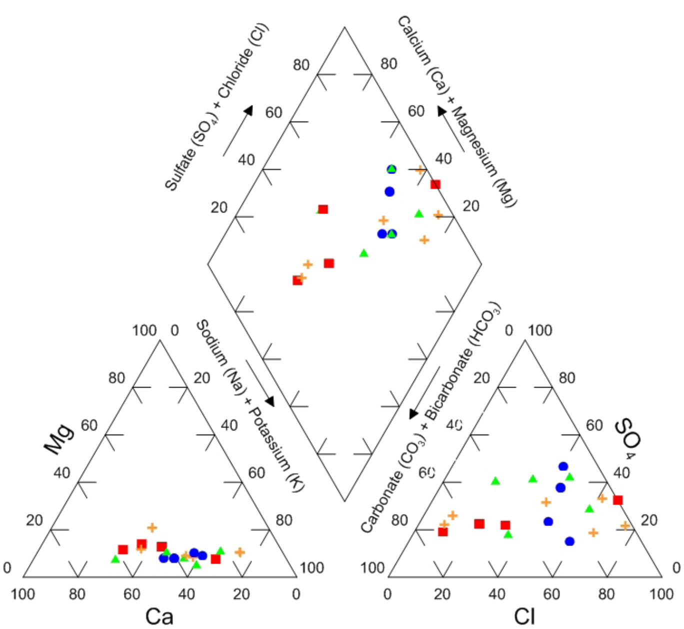


Figure 21. Groundwater types determined from water quality samples collected from wells in the study area.

Summary

The Enid Isolated Terrace aquifer consists of Quaternary-age terrace deposits underlain by Permian-aged clays, shales, and sandstones in Garfield and Alfalfa counties. The study area covers 174 square miles and receives 30.73 inches of precipitation annually on average. Groundwater flows from the east to the southeast with groundwater altitudes ranging from 1,350 to 1,133 feet. Recharge occurs mainly through precipitation; Skeleton Creek is the primary groundwater discharge feature within the study area. The most productive portion of the study area occurs in the central section where saturated thicknesses range from 30 to 60 feet. The aquifer is used mainly for public water supply and irrigation with total use averaging 3,243 acre-feet per year for 1967–2013. Water quality in the Enid Isolated Terrace is good with varying water types, although localized high concentrations of nitrates (as nitrogen) and arsenic do occur.

Since the completion of the previous study on the Enid Isolated Terrace in 1982 (Kent and others, 1982), the following changes to the area, population, and data have occurred:

1. Terrace deposits to the east and west of the previous study area were identified in recent geological maps. As a result, the aquifer study area has increased from 81 square miles to 174 square miles.

2. Population of the City of Enid increased from about 45,000 in 1982 (Kent and others, 1982) to about 50,000 in 2010 (U.S. Census Bureau, 2010).

3. The City of Enid significantly decreased the amount of municipal groundwater use from the Enid Isolated Terrace aquifer.

4. Recharge was 2.3 inches in the previous study, but estimates in this investigation ranged from 2.79 inches using the RORA method to 4.35 inches using a soil-water balance model. Since precipitation averages have stayed steady over the years, the differences may be attributed to the use of more advanced recharge estimation methods.

5. Data yielded the greatest saturated thicknesses near the center of the study area, north of the City of Enid, thinning towards the east and west.

6. The mean value for hydraulic conductivity was estimated to be 50.16 feet per day utilizing data from single-well pumping tests with a range of 0.32-289.7 feet per day.

7. Multi-well aquifer tests estimated transmissivity to range from 2,333 to 5,031 square feet per day, storativity to range from 0.01-0.006, and hydraulic conductivity to range from 101 to 132 feet per day.

Selected References

Agarwal, R.G., 1980, A new method to account for producing time effects when drawdown type curves are used to analyze pressure buildup and other test data: SPE Paper 9289, presented at the 55th SPE Annual Technical Conference and Exhibition, Dallas, TX, Sept. 21-24, 1980.

Bingham R.H., and Bergman, D.L., 1980, Reconnaissance of the water resources of the Enid quadrangle, north-central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 7, 4 plates.

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.

Cooper, H. H., Jr., and Jacob, C. E., 1946, A generalized graphical method for evaluating formation constants and summarizing well-field history: Am. Geophys. Union Trans., v. 27, no. 4, p. 526-534

Deutsch, W.J., and Siegel, R., 1997, Groundwater chemistry: Fundamentals and applications to contamination: CRC press, 232 p.

Duble, R. L., 2016, Bermudagrass – The sports turf of the south: Texas AgriLife Extension Service, Texas A&M, accessed April 20, 2016 at *http://aggie-horticulture.tamu.edu/archives/parsons/turf/publications/Bermuda.html*.

HydroSOLVE, Inc., 2014, “Transmissivity from Specific Capacity.” Transmissivity From Specific Capacity Calculator (Exact Forumula): Aquifer Test Forum, accessed August 01, 2014, at *http://www.aqtesolv.com/forum/transcap2.asp*.

Johnson, K.S., and Luza, K.V., 2008, Earth sciences and mineral resources of Oklahoma: Oklahoma Geological Survey Educational Publication 9, 4 p.

Kent, D.C., Beausoleil, Y.J. and Witz, F.E., 1982, Evaluation of aquifer performance and water supply capabilities of the Enid isolated terrace aquifer in Garfield County, Oklahoma: Stillwater, OK, Department of Geology, Oklahoma State University report, 58 Master’s Thesis, 84 p.

Kruseman, G.P., de Ridder, N.A., and Verweij, J.M., 1994, Analysis and evaluation of pumping test data: ILRI Publication, 377 p.

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

Moench, A.F., 1993, Computation of type curves for flow to partially penetrating wells in water-table aquifers: Ground Water, v. 31, no. 6, p. 966-971.

Multi-Resolution Land Characteristics Consortium (MLRC), 2011, National Land Cover Database: U.S. Geological Survey: accessed April, 2014, at *http://www.mrlc.gov/nlcd11_data.php*.

National Resources Conservation Service, 2014, Gridded soil survey geographic map, accessed July 21: 2014, at *http://datagateway.nrcs.usda.gov*.

National Weather Service, 2011, What is the Coop Program?: accessed August 30, 2011, at *http://www.weather.gov/om/coop/what-is-coop.html*.

Neuman, S.P., 1972, Theory of flow in unconfined aquifers considering delayed gravity response of the water table: Water Resources Research, v. 8, no. 4, p. 1031-1045.

Oklahoma Climatological Survey, 2013, Daily data retrieval: accessed October 2013, at *http://www.mesonet.org/index.php/weather/daily_data_retrieval*.

Oklahoma Climatological Survey, 2014a, The climate of Garfield County: accessed October 2014, at *http://climate.ok.gov/county_climate/Products/County_Climatologies/county_climate_garfield.pdf*.

Oklahoma Climatological Survey, 2014b, About the Mesonet: accessed August 2014, at *http://www.mesonet.org/index.php/site/about*.

Oklahoma Climatological Survey, 2014c, Daily time series using cooperative observer (COOP) data: accessed March 1, 2014, at *http://xocs.mesonet.org/index.php/climate/category/my_county_or_town*.

Oklahoma Water Resources Board, 2014, Taking and use of groundwater, Title 785, Chapter 30: accessed November 20, 2014, at *http://www.owrb.ok.gov/util/rules/pdf_rul/current/Ch30.pdf*.

Oklahoma Water Resources Board, 2015, Oklahoma Groundwater Report: Beneficial Use Monitoring Program, 61 p.

Reely, B.T., 1992, A linked optimization-simulation aquifer management model: Stillwater, OK, Oklahoma State University, PhD dissertation, 170 p.

Renick, B.C., 1924, Additional Ground-Water Supplies for the City of Enid, Oklahoma: U.S. Geological Survey Water Supply Paper 520-B.

Rorabaugh, M.I., 1964, Estimating changes in bank storage and groundwater contribution to streamflow: International Association of Scientific Hydrology, publication 63, p. 432–441.

Rutledge, A.T., 1998, Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow records—Update: U.S. Geological Survey Water-Resources Investigations Report 98–4148, 43 p.

Schwartz, F.W. and Zhang, H., 2003, Fundamentals of ground water: New York, NY, John Wiley & Sons, Inc., 583 p.

Stanley, T.M., Miller, G.W., and Galen, W., 2008, Geologic map of the Enid 30' X 60' quadrangle, Garfield, Kingfisher, Logan, Noble, Osage, Pawnee, and Payne counties: Oklahoma, Oklahoma Geological Survey Oklahoma Geologic Quadrangle OGQ-73, scale 1:100,000.

Stanley, T.M., Miller, G.W., Galen, W., and Suneson, N.H., 2002, Geologic map of the fairview 30' X 60' quadrangle, Alfalfa, Blaine, Dewey, Garfield, Kingfisher, Major, Woods, and Woodward counties: Oklahoma, Oklahoma Geological Survey Oklahoma Geologic Quadrangle OGQ-41, scale 1:100,000.

United States Census Bureau, 2010, Quick facts for Enid, Oklahoma: accessed November 2013, at *http://www.census.gov/quickfacts/table/PST045215/4023950,40*.

United States Environmental Protection Agency, 2012, 2012 edition of the drinking water standards and health advisories: EPA 822-S-12-001, 12 p.

Weaver, J.E., 1926, Root development of field crops: New York, McGraw-Hill, 291 p.

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.

Wu, Lin, 1985, Matching irrigation to turfgrass root depth: University of California Cooperative Extension, California Turfgrass Culture, v. 35, nos. 1-4, p. 1-2.