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Hydrogeologic Framework, Geochemistry, Groundwater-Flow System, and Aquifer Hydraulic Properties Used in the Development of a Conceptual Model of the Ogallala, Edwards-Trinity (High Plains), and Dockum Aquifers In and Near Gaines, Terry, and Yoakum Counties, Texas

Scientific Investigations Report 2021–5009

U.S. Department of the Interior
U.S. Geological Survey

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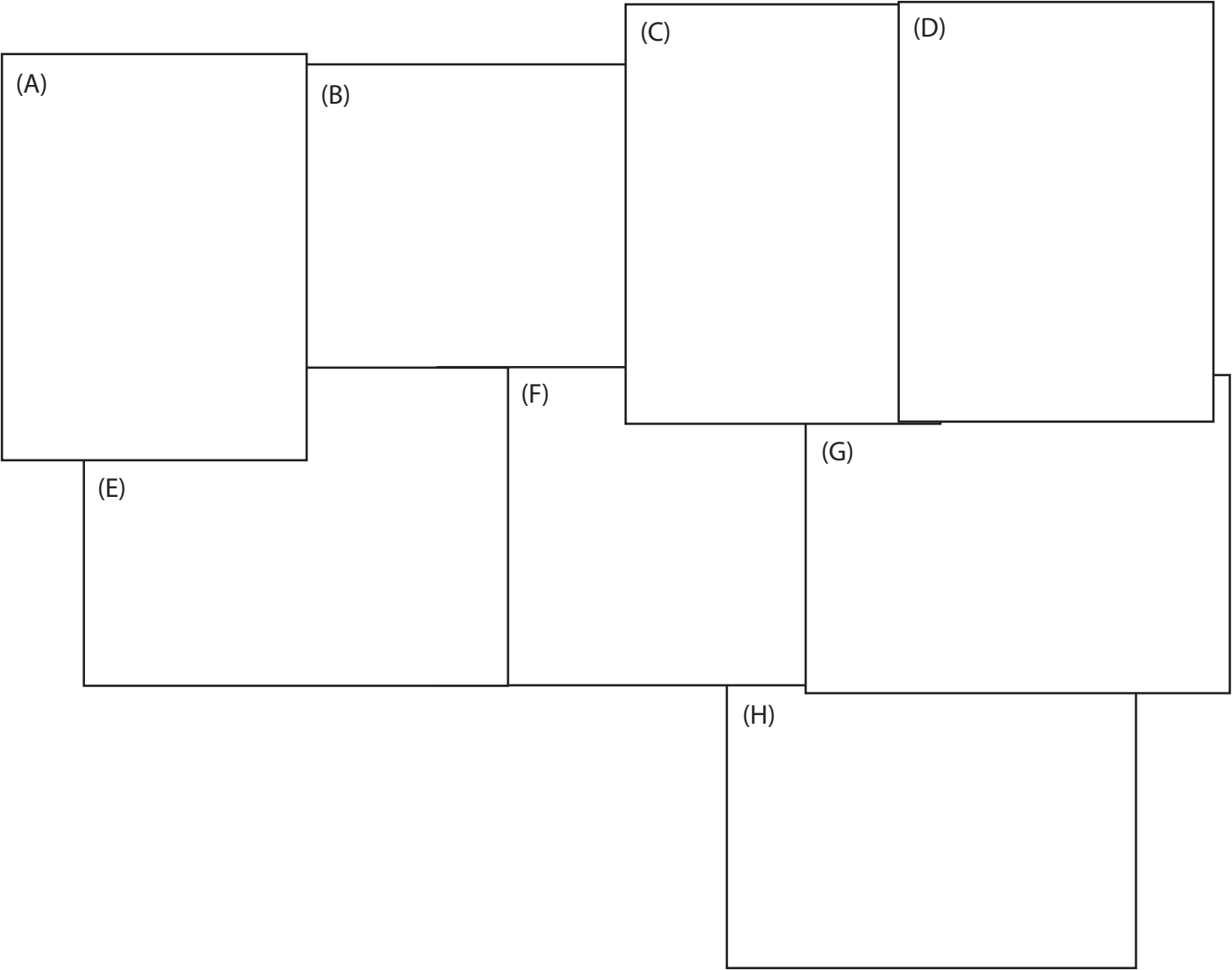
By Andrew P. Teeple, Patricia B. Ging, Jonathan V. Thomas, David S. Wallace, and Jason D. Payne

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U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
ounce, fluid (fl. oz)	0.02957	liter (L)
pint (pt)	0.4732	liter (L)
quart (qt)	0.9464	liter (L)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
cubic inch (in^3)	0.01639	liter (L)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
Flow rate		
gallon per minute (gal/min)	0.06309	liter per second (L/s)
Radioactivity		
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C = (°F − 32) / 1.8.

Datum

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

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

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

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L), micrograms per liter (µg/L), or milliequivalents per liter.

Milligrams per liter are units expressing the mass of the solute per unit volume (liter) of water; milligrams per liter is equivalent to parts per million. Micrograms per liter are units expressing the mass of the solute per unit volume (liter) of water; micrograms per liter is equivalent to parts per billion. Milliequivalents are units expressing the number of electron-millimoles of a solute per unit volume (liter). Milliequivalents per liter is a unit expressing the concentration of chemical constituents in solution as 1/1000 the molecular weight, in milligrams, divided by the valence of one molecule of the constituent per unit volume (liter) of water.

Activities for radioactive constituents in water are given in picocuries per liter (pCi/L).

Tritium concentrations are discussed in tritium units (TU). Based upon a tritium half-life of 12.32 years (Lucas and Unterweger, 2000), 1 TU is equal to 3.22 picocuries per liter (pCi/L).

Resistivity is given in ohm-meters (ohm-m).

Isotope Unit Explanation

Per mil: A unit commonly used to express the ratio of stable isotope abundance of an element in a sample to the abundance of the same element in a standard material. Per mil units are equivalent to parts per thousand. Stable isotope ratios are computed as follows (Kendall and McDonnell, 1998):

$$\delta X = \{(R_{sample} - R_{standard})/ R_{standard}\} \times 1{,}000$$

where

δ is the "delta" notation,

X is the heavier stable isotope, and

R is the ratio of the heavier, less abundant isotope to the lighter, stable isotope in a sample or standard.

The δ values for stable isotope ratios discussed in this report are referenced to the following standard materials:

Element	R	Standard identity and reference
Hydrogen	Hydrogen-2/hydrogen-1 (δD)	Vienna Standard Mean Ocean Water (Fritz and Fontes, 1980)
Oxygen	Oxygen-18/oxygen-16 ($\delta^{18}O$)	Vienna Standard Mean Ocean Water (Fritz and Fontes, 1980)

Abbreviations

3DEP	Three-Dimensional Elevation Program
^3H	tritium
^{12}C	carbon-12
^{14}C	carbon-14
^{14}N	nitrogen-14
$^{87}Sr/^{86}Sr$	strontium isotopic ratio (strontium-87/strontium-86)
AMS	accelerator mass spectrometry
ASTM	American Society of Testing and Materials
CO_2	carbon dioxide
DEM	digital elevation model
DS	dissolved solids
EM	electromagnetic
EPA	U.S. Environmental Protection Agency
FLASH	Flow-Log Analysis of Single Holes
GMWL	Global Meteoric Water Line
Hz	hertz
LAS	Log American Standard Code for Information Interchange (ASCII) Standard
LEUWCD	Llano Estacado Underground Water Conservation District
LRL	laboratory reporting level
NAD 83	North American Datum of 1983
NAVD 88	North American Vertical Datum of 1988
NLCD	National Land Cover Database
NMR	nuclear magnetic resonance
NWIS	National Water Information System
NWQL	National Water Quality Laboratory
PDF	Portable Document Format
pmc	percent modern carbon
PVC	polyvinyl chloride
R^2	R-squared (coefficient of determination)
RPD	relative percent difference
SLUWCD	Sandy Land Underground Water Conservation District
SPUWCD	South Plains Underground Water Conservation District
TDEM	time-domain electromagnetic
USGS	U.S. Geological Survey
UWCD	Underground Water Conservation District

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By Andrew P. Teeple, Patricia B. Ging, Jonathan V. Thomas, David S. Wallace, and Jason D. Payne

Abstract

In 2014, the U.S. Geological Survey, in cooperation with Llano Estacado Underground Water Conservation District, Sandy Land Underground Water Conservation District, and South Plains Underground Water Conservation District (hereinafter referred to collectively as the "UWCDs"), began a multiphase study in and near Gaines, Terry, and Yoakum Counties, Texas, to develop a regional conceptual model of the hydrogeologic framework, geochemistry, groundwater-flow system, and hydraulic properties, primarily for the High Plains and Edwards-Trinity aquifer system and to a lesser degree for the Dockum aquifer. The High Plains aquifer system (hereinafter referred to as the "Ogallala aquifer"), contained within the Ogallala Formation in Texas, is the shallowest aquifer in the study area and is the primary source of water for agriculture and municipal supply in the areas managed by the UWCDs. Groundwater withdrawals from deeper aquifers (primarily the Edwards-Trinity [High Plains] aquifer system that is hereinafter referred to as the "Edwards-Trinity [High Plains] aquifer") augmented by lesser amounts from the Dockum aquifer provide additional water sources in the study area. The Edwards-Trinity (High Plains) aquifer is contained within the Trinity and Fredericksburg Groups. The Dockum aquifer, a relatively minor source of water in the study area, is contained in the Dockum Group, which was evaluated as a single unit. The potential for continual declines of the groundwater in the Ogallala aquifer in the study area and the potential changes in water quality resulting from dewatering and increased vertical groundwater movement between adjacent water-bearing units have raised concerns about the amount and quality of available groundwater.

The developed conceptual model helped in the understanding of the quantity and quality of the groundwater within the Ogallala, the Edwards-Trinity (High Plains), and to a lesser extent, the Dockum aquifers within the study area. The hydrogeologic framework was used to assess the vertical and lateral extents of hydrogeologic units, bed orientations, unit thicknesses, and location and orientation of paleochannels. In general, the Trinity and Fredericksburg Groups and Ogallala Formation exhibit a slight regional dip (dip angle of about 0.14 degrees) to the southeast with dip directions becoming more to the south with each successively overlying unit (105, 110, and 125 degrees for the bases of the Trinity and Fredericksburg Groups and Ogallala Formation, respectively). In general, the Trinity and Fredericksburg Groups thin to the south and are not present in the southern part of Gaines County, whereas the Ogallala Formation becomes thinner from west to east. The combined thickness of the Trinity and Fredericksburg Groups and Ogallala Formation is generally greatest in the north-central part of the study area and thinnest in the southeastern part of the study area. Paleochannel orientation varied over geologic time as formations were deposited and eroded.

Water-quality samples were collected from 51 wells throughout the study area to better understand general water quality and to provide insight into groundwater-flow paths and recharge areas. Groundwater samples were spatially grouped on the basis of similarities found in the physicochemical properties, major ions, trace elements, nutrients, organic compounds, and selected stable isotopes and age tracers. Three groundwater groups were identified in the study area. The first groundwater group (Group 1), represented mostly by groundwater from the Ogallala and Edwards-Trinity (High Plains) aquifers in the northern half of the study area, is considered to be recent recharge, affected by land-use activities, as explained by the younger age, higher concentrations of nitrate plus nitrite, and more frequent detections of organic compounds. Groundwater wells in the second groundwater group (Group 2) are typically in the southwestern and northwestern parts of the study area, and the groundwater in this group is considered to be groundwater recharged during the Pleistocene period, as explained by the relatively old age of the groundwater, high strontium stable

isotope ratios, and hydrogen and oxygen stable isotope ratios. The last groundwater group (Group 3) is likely a mixture of groundwater from the first or second groups (or both) with a third, highly mineralized groundwater as explained by having the highest dissolved-solids concentrations in the study area and having some similarities to geochemical characteristics of samples from the first and second groups.

A groundwater-flow system analysis was done to understand the flow of groundwater throughout the aquifer system. Groundwater-level altitudes for the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers are generally higher in the northwestern part of the study area and lower in the southeastern part of the study area. Groundwater generally flows in a northwest to southeast direction across the study area in each of the aquifers. The groundwater-flow paths closely resemble the mapped paleochannels, indicating that within the study area, the groundwater flows preferentially along the paleochannels, especially within the Ogallala aquifer where dewatering of the aquifer results in a greater effect of the base structure on the flow of groundwater.

The Ogallala aquifer is unsaturated in localized areas in the study area; unsaturated areas are generally near the southern extent of the Edwards-Trinity (High Plains) aquifer, with the largest unsaturated area west of Seminole, Tex. The saturated thickness of the Ogallala aquifer is thickest (more than 125 feet) southeast of Seminole and west of Brownfield, Tex., near the border between Terry and Yoakum Counties. The saturated thickness of the combined Ogallala and Edwards-Trinity (High Plains) aquifers ranges from less than 10 feet along the far southern edge of the study area to more than 350 feet north and east of Brownfield, Tex., and along the border between Terry and Yoakum Counties.

The aquifer hydraulic properties, including hydraulic conductivity and specific yield, were estimated to better understand the ability of groundwater to move through the aquifer system and quantify the volume of available water in storage. The hydraulic-conductivity values varied greatly within the study area (ranging from about 0.03 to about 350 feet per day), and often large variations were found in the same area. Terry County contained the highest and lowest hydraulic conductivity values for the Ogallala aquifer, whereas Yoakum County contained the highest and lowest hydraulic conductivity values for the Edwards-Trinity (High Plains) aquifer. The highest hydraulic-conductivity values for the Dockum aquifer were in Gaines County, whereas the lowest hydraulic-conductivity values were in Terry County. The estimated specific yield values within the study area range from 0.01 to 0.36. Higher specific yield values generally occurred in the western part of the study area except in the Ogallala aquifer where higher specific yield values were in the east. The Ogallala aquifer had the lowest specific yield range and the least specific yield variability among the three aquifers, whereas the Dockum aquifer had the highest specific yield range and the greatest specific yield variability.

Using the estimated saturated thickness and estimated specific yield grids, the water volumes of the Ogallala and Edwards-Trinity (High Plains) aquifers and the combined Ogallala and Edwards-Trinity (High Plains) aquifers were estimated. The available water in the Edwards-Trinity (High Plains) aquifer (16.6 million acre-feet) is almost double the available water in the Ogallala aquifer (8.8 million acre-feet). Although the Edwards-Trinity (High Plains) aquifer contains more available groundwater, pumping is more difficult because of the relatively low hydraulic conductivity and specific yield values compared to the Ogallala aquifer. Overall, the available water within the combined Ogallala and Edwards-Trinity (High Plains) aquifers is about 6.6, 10.2, and 8.6 million acre-feet for Gaines, Terry, and Yoakum Counties, respectively.

Introduction

Llano Estacado Underground Water Conservation District (LEUWCD), Sandy Land Underground Water Conservation District (SLUWCD), and South Plains Underground Water Conservation District (SPUWCD) (hereinafter referred to collectively as the "UWCDs") manage groundwater resources in a part of west Texas near the Texas-New Mexico State line (figs. 1 and 2). As described in Thomas and others (2016) and Thomas and others (2019), the UWCDs are responsible for managing the groundwater resources in their respective jurisdictions, which are Gaines County for the LEUWCD, Terry County and a small part of Hockley County for the SPUWCD, and Yoakum County for the SLUWCD; the study area for this report consists of the areas managed by the three UWCDs (fig. 2). Hockley County is a small part of the overall study area and will not be explicitly mentioned within the report. If data pertain to Hockley County, they will be referred to as "in and near Gaines, Terry, and Yoakum Counties" as opposed to "in Gaines, Terry, and Yoakum Counties."

An important source of water in the study area is the High Plains aquifer system, a vast regional aquifer system that underlies about 174,000 square miles (mi^2) from South Dakota to Texas (fig. 1) (Gutentag and others, 1984). Historically, the High Plains aquifer system was often referred to as the "Ogallala aquifer" throughout its extent in reference to the predominant water-bearing unit of the aquifer system, the Ogallala Formation (Dugan and others, 1994). The High Plains aquifer system is hereinafter referred to as "Ogallala aquifer" in this report because the Ogallala Formation is the only geologic unit of the High Plains aquifer system in Texas and because of the historical use of the term in the region. The Ogallala aquifer is the shallowest aquifer in the study area and is the primary source of water for agriculture and municipal supply in the areas managed by the UWCDs (Rettman and Leggat, 1966). Groundwater withdrawals from deeper aquifers (primarily from the Edwards-Trinity [High Plains] aquifer system, hereinafter referred to as the "Edwards-Trinity [High Plains] aquifer," as identified by the Texas Water Development
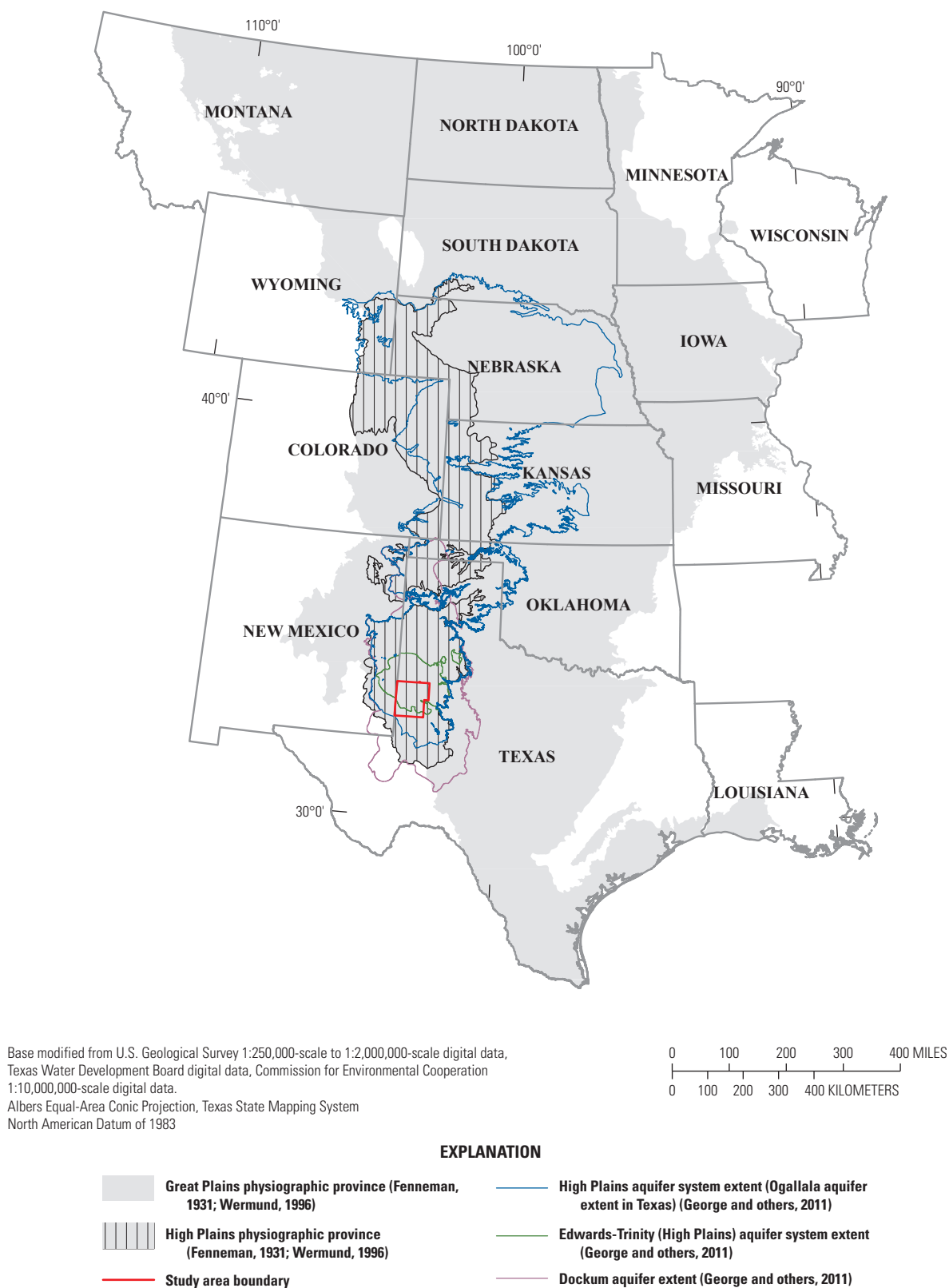
Figure 1. Location of the study area in Gaines, Terry, and Yoakum Counties, Texas, within the regional extent of the major aquifers and physiographic provinces pertaining to this assessment. Reprinted from Thomas and others (2016, fig. 2).
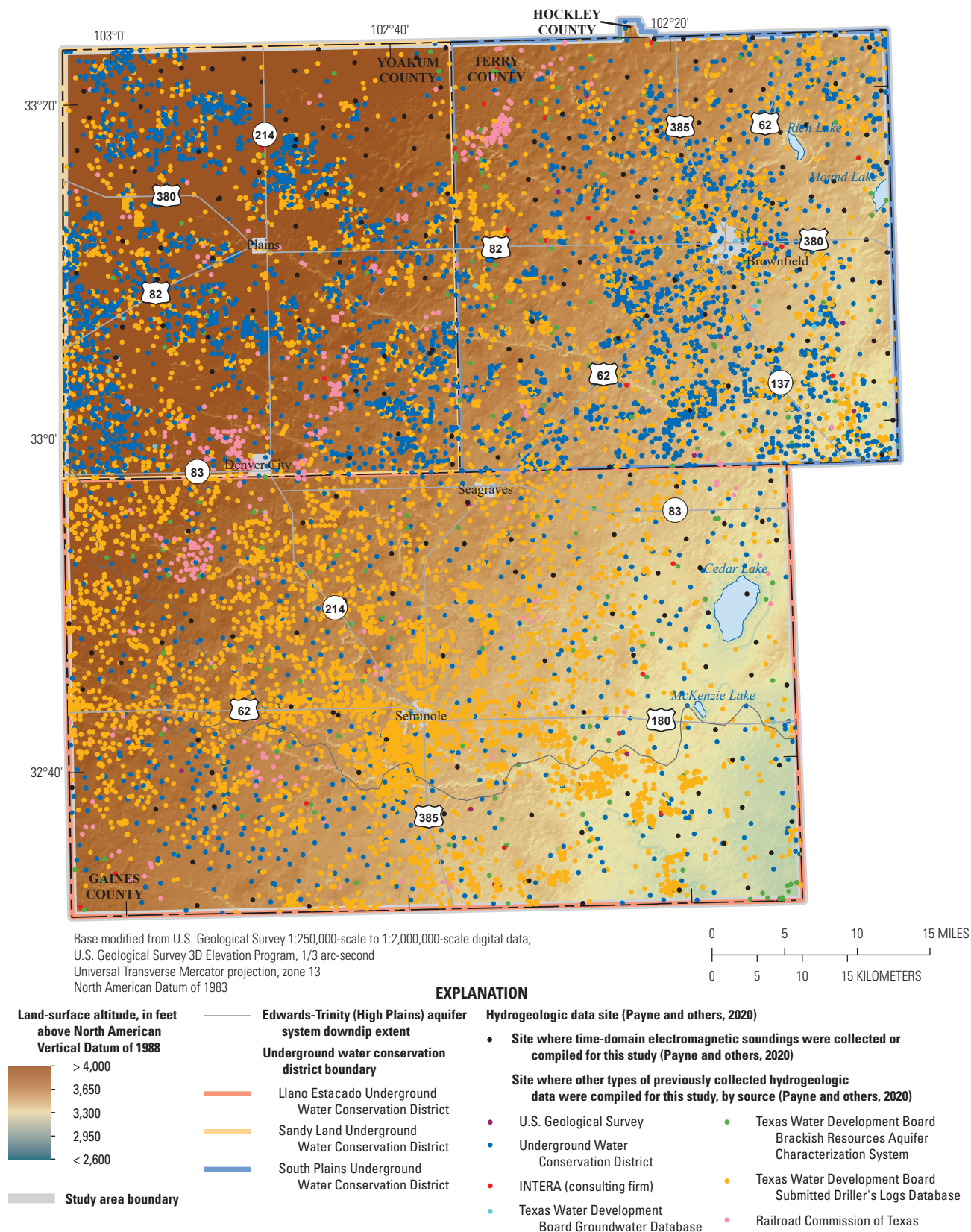
Figure 2.   Hydrogeologic data sites, land-surface altitude, downdip extent of the Edwards-Trinity (High Plains) aquifer system, and study area extent, composed of the areas of jurisdiction of the Llano Estacado Underground Water Conservation District, Sandy Land Underground Water Conservation District, and South Plains Underground Water Conservation District, in and near Gaines, Terry, and Yoakum Counties, Texas.

Board[1] [Texas Water Development Board, 2020a], augmented by lesser amounts from the Dockum aquifer) provide additional water sources in the study area (fig. 1). The Edwards-Trinity (High Plains) aquifer is contained within the Trinity and Fredericksburg Groups, whereas the Dockum aquifer, a relatively minor source of water in the study area, is contained in the Dockum Group.

Groundwater levels have declined (decreased more than 50 feet [ft] compared to historical groundwater levels) in parts of west Texas including Gaines, Terry, and Yoakum Counties since 1938 with overall patterns of declines in the Ogallala aquifer beginning soon after the start of widespread irrigation practices relying on groundwater withdrawals from the aquifer (about 1950) (Gaum, 1953; Gutentag and others, 1984). In their report on the history of groundwater-level changes in the Ogallala aquifer from predevelopment to 1980, Dugan and others (1994) report groundwater-level declines in the Ogallala aquifer of as much as 150 ft. During the past 50–60 years (1960–70), the rate of decline has slowed, and groundwater levels in the Ogallala aquifer have risen in a few areas (McGuire, 2017). The potential for continual declines of the groundwater in the Ogallala aquifer in the study area has raised concerns about the amount of available groundwater and long-term aquifer sustainability (Knowles and others, 1984; Peckham and Ashworth, 1993; Stovall, 2001; Blandford and others, 2003).

Also of concern are the potential changes in water-quality resulting from dewatering and increased vertical groundwater movement between adjacent water-bearing units (Weeks and others, 1988; Deeds and others, 2015). Large groundwater withdrawals in localized areas can lower hydraulic heads and cause vertical flow in hydraulically connected aquifer units because groundwater moves from areas of high hydraulic head to areas of low hydraulic head (Pischel and Gannett, 2015). Because the Ogallala aquifer and underlying aquifers are hydraulically connected in some locations, groundwater-level declines in the Ogallala aquifer and in the underlying Edwards-Trinity (High Plains) aquifer can result in changes in water quality when the waters are mixed by the upward movement of deeper, relatively more saline groundwater (Bradley and Kalaswad, 2003).

In 2014, the U.S. Geological Survey (USGS), in cooperation with the UWCDs, began a multiphase study to refine the understanding of the hydrogeologic framework, geochemistry, groundwater-flow system, and hydraulic properties to be included in the development of a regional conceptual model for the Ogallala, Edwards-Trinity (High Plains), and the Dockum aquifers (fig. 1). Available data were supplemented with additional geophysical data collected in selected areas to improve the spatial coverage and to reduce uncertainty

regarding hydrogeologic unit extents. Water-quality samples were collected to characterize water quality and to provide insights into groundwater-flow paths and recharge areas. The results of the first phase of the study are documented in Thomas and others (2016) and included an assessment of the differences between early development (1930–60) and recent (2005–15) groundwater-level altitudes and selected water-quality constituents (dissolved-solids [DS] and nitrate concentrations) for the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers. The results of the second phase of the study are documented in Thomas and others (2019) and include a refined understanding of the hydrogeologic framework in the study area.

Purpose and Scope

This report synthesizes previously collected data from Thomas and others (2016) and Thomas and others (2019) concerning the hydrogeologic framework, geochemistry, groundwater-flow system, and hydraulic properties of the groundwater system from the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers in west Texas with newly collected data in a regional conceptual model of the aquifers. A regional conceptual model was developed in order to better understand the amount and quality of available groundwater by combining information from a refined understanding of the hydrogeologic framework, geochemistry data, and information pertaining to the groundwater-flow system and aquifer hydraulic properties.

A groundwater-flow system analysis was done to gain a better understanding of the flow of groundwater throughout the aquifer system by incorporating information identified from the hydrogeologic framework and the geochemical analysis. Synoptic groundwater-level measurements were made within each of the aquifers to aid in the understanding of the groundwater-flow system. To estimate the hydraulic properties for the aquifer system, historical data were compiled and supplemented by collecting additional borehole and surface geophysical data. The Dockum Group, a relatively minor source of water in the study area, was evaluated as a single unit. The water-bearing units of the Dockum Group were not evaluated for this study; only ancillary data from the Dockum aquifer were used to aid in the interpretation of the overlying units. Neither the unit thickness nor storage properties of the Dockum aquifer were determined.

Description of Study Area

The study area is in the Great Plains physiographic province (fig. 1) and consists of an elevated and relatively undissected plain (Ryder, 1996). The study area covers about 3,225 mi[2], including 1,525 mi[2] in LEUWCD, 798 mi[2] in SLUWCD, and 902 mi[2] in SPUWCD (fig. 2) (Llano Estacado Underground Water Conservation District, 2020a; Sandy Land Underground Water Conservation District, 2020; South

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[1]The Edwards-Trinity aquifer is divided into two parts by the Texas Water Development Board—a "High Plains" part in west Texas referred to as the "Edwards-Trinity (High Plains) aquifer" that coincides with the study area of this report, and a "Plateau" part extending across much of the southwestern part of the State referred to as the "Edwards-Trinity (Plateau) aquifer" (George and others, 2011).

Plains Underground Water Conservation District, 2020a). As of July 1, 2018, the population of the study area was about 42,000 (U.S. Census Bureau, 2020).

The climate of the study area is semiarid (Larkin and Bomar, 1983). Precipitation averages 18.8 inches per year, mostly in the form of rain (National Oceanic and Atmospheric Administration, 2010). The potential evapotranspiration is more than three times the annual precipitation (Larkin and Bomar, 1983). The average annual temperature during 1981–2010 for the study area was about 60.5 degrees Fahrenheit (°F), with the warmest average monthly temperature in July (79.1 °F) and the coolest average monthly temperature in January (40.0 °F) (National Oceanic and Atmospheric Administration, 2010).

The combination of minimal topographic relief, availability of groundwater for irrigation, and excellent soils makes this an important agricultural region in Texas (Ryder, 1996). From the USGS National Land Cover Database (NLCD) 2011, the land-cover categories for rangeland (shrubs/scrubs [31 percent] and grassland/herbaceous [19 percent]) and for cultivated crops (42 percent) dominate in the study area (fig. 3) (Homer and others, 2015). The top crop in the study area is cotton with about 858 mi2 planted in 2017 (U.S. Department of Agriculture, 2019). Other important crops in the study area are peanuts (184 mi2 planted), sorghum (65 mi2 planted), forage (37 mi2 planted), wheat (33 mi2 planted), corn (12 mi2 planted), vegetables (7 mi2 planted), and sunflower seeds (7 mi2 planted). Water use in the study area is almost all from groundwater sources (99 percent) with 97 percent of the groundwater used for irrigation (Texas Water Development Board, 2017).

Geologic Setting

The Triassic-age Dockum Group underlies the Cretaceous-age Trinity and Fredericksburg Groups and the Ogallala Formation (fig. 4) throughout much of the southern part of the High Plains physiographic province (fig. 1). The Dockum Group consists of siltstone, mudstone, and shale with a small amount of sandstone originally deposited in fluvial and lacustrine environments (McGowen and others, 1979; Bradley and Kalaswad, 2003). The overlying Trinity Group consists of sand and gravel layers (fig. 4). The Trinity Group is overlain by the Fredericksburg Group, which is composed of clay, shale, and limestone (Bell and Morrison, 1979). A thin layer of the Cretaceous-age Washita Group is present in the northern and northeastern parts of the study area. The Washita Group, which overlies the Fredericksburg Group, consists of shale and limestone. For this study, the Washita Group is interpreted to be part of the Fredericksburg Group because it is difficult to distinguish the contact between the Fredericksburg and Washita Groups and because the Washita Group has been thinned or completely removed at many locations in the study area (Brand, 1953; Fallin, 1989). Prior to the deposition of the

Ogallala Formation, erosional processes formed a complex, irregular surface in the underlying sediments of the Trinity and Fredericksburg Groups and thinned the geologic units in many places. The late Miocene- to early Pliocene-age Ogallala Formation is composed primarily of poorly sorted gravel, sand, silt, and clay, which in many places were deposited in paleochannels and alluvial deposits. Thicker alluvial deposits of Ogallala Formation rocks occur in areas where erosion of the underlying Cretaceous-age rocks was most extensive (Bradley and Kalaswad, 2003). The Ogallala Formation directly overlies the Dockum Group where the Trinity and Fredericksburg Groups are absent (Ashworth and Hopkins, 1995) (fig. 4).

Hydrogeologic Setting

The Ogallala aquifer is a major aquifer in the study area; it is unconfined and is contained within the Ogallala Formation (fig. 4). Multiple studies describe the general structure of the Ogallala aquifer as featuring paleochannels eroded into the underlying hydrogeologic units; paleochannels are important conduits for groundwater flow and are filled with coarse gravel in the channel and often filled with sand and finer sediments in the interchannel areas (for example, Cronin, 1969; Seni, 1980; Gustavson, 1996). The variable distribution of coarse, permeable sediments affects the spatial differences in the water-storage capacity and water-availability characteristics (Seni, 1980; Texas Water Development Board, 2020b). DS concentrations in the Ogallala aquifer typically are less than 1,000 milligrams per liter (mg/L) (the upper limit for what is generally considered freshwater [Winslow and Kister, 1956]) but can range from less than 600 to more than 6,000 mg/L within localized parts of the study area (Llano Estacado Underground Water Conservation District, 2020a; Llano Estacado Underground Water Conservation District, 2020b; South Plains Underground Water Conservation District, 2020b). In many areas, groundwater moves vertically between the Ogallala aquifer and the underlying Edwards-Trinity (High Plains) and Dockum aquifers (fig. 1; fig. 4).

The Edwards-Trinity (High Plains) aquifer is a minor, semiconfined aquifer underlying the Ogallala aquifer, except in the southern part of the study area where the Edwards-Trinity (High Plains) aquifer is absent (George and others, 2011) (fig. 1; fig. 4). The Edwards-Trinity (High Plains) aquifer is contained within the Trinity and Fredericksburg Groups where the Fredericksburg Group acts as a semiconfining unit to the more permeable Trinity Group. Groundwater flow in the Edwards-Trinity (High Plains) aquifer is controlled by facies changes, structure orientation, local cementation, and paleochannels that can produce local deviations in flow patterns (Fallin, 1989). Groundwater from the Edwards-Trinity (High Plains) aquifer is typically slightly saline (DS concentrations range from 1,000 to 3,000 mg/L) (Winslow and Kister,
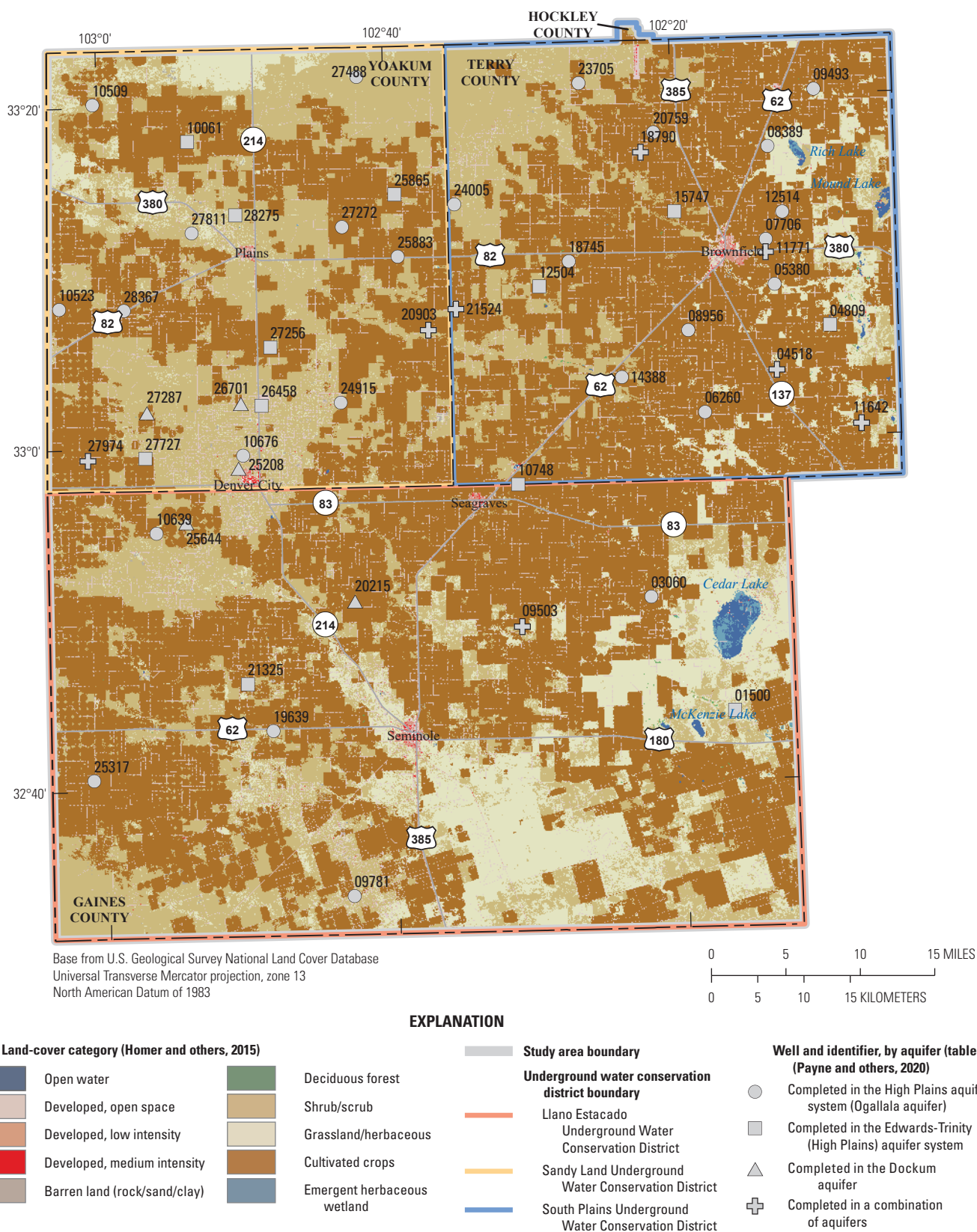
Figure 3. National Land Cover Database 2011 land-cover categories and locations of wells from which samples for water-quality data were collected in Gaines, Terry, and Yoakum Counties, Texas, 2014 and 2016.

Era	Period	Epoch or series	Geologic unit group or formation	Lithologic descriptions	Hydrogeologic unit
Cenozoic	Tertiary	Pliocene	Ogallala Formation	Gravel, sand, silt, and clay	High Plains aquifer system (Ogallala aquifer)
		Miocene			
Mesozoic	Cretaceous[1]	Comanchean Series	Washita Group[2]	Shale and limestone	Edwards-Trinity (High Plains) aquifer system
			Fredericksburg Group	Clay, shale, and limestone	
			Trinity Group	Sand and gravel	
	Triassic	Upper	Dockum Group	Siltstone, mudstone, shale, and sandstone	Dockum aquifer

[1]Geologic and hydrogeologic units and lithologic descriptions are absent outside the spatial extents of the Edwards-Trinity (High Plains) aquifer system.

[2]For this study, the Washita Group has been interpreted to be part of the Fredericksburg Group because it is difficult to distinguish from the top of the Fredericksburg Group and has been thinned or completely removed at many locations (Brand, 1953; Fallin, 1989).

Figure 4.   Geologic and hydrogeologic units and lithologic descriptions in and near Gaines, Terry, and Yoakum Counties, Texas. Modified from Knowles and others (1984); Clark and others (2014); Thomas and others (2016); Thomas and others (2019).

1956; Fallin, 1989) and contains more DS than groundwater from the overlying Ogallala aquifer (George and others, 2011) (fig. 1; fig. 4).

The Dockum aquifer is a minor confined aquifer in the study area (George and others, 2011) and underlies the Ogallala and Edwards-Trinity (High Plains) aquifers (fig. 4) throughout much of the southern part of the High Plains physiographic province (fig. 1). Groundwater in the Dockum aquifer is characterized by high concentrations of DS and other constituents that exceed secondary drinking water standards (U.S. Environmental Protection Agency, 2020) as well as high concentrations of sodium that may negatively affect irrigated crops (Bradley and Kalaswad, 2003).

Synopsis of Previous Studies for This Multiphase Project

Thomas and others (2016) described the results of the first phase of the study, during which groundwater-level-altitude and selected water-quality data from wells in and near Gaines, Terry, and Yoakum Counties, Texas, were compiled and evaluated for the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers. Readily available digital groundwater data for the study area (geologic, well-construction, groundwater-level-altitude, and selected water-quality data) were compiled to assess temporal and spatial changes in groundwater resources from early development (1930–60) to recent (2005–15) periods. Potentiometric-surface maps were created to depict changes in groundwater-level altitudes for the Ogallala and Edwards-Trinity (High Plains) aquifers.

Existing DS and nitrate concentration data were compiled and assessed for spatial patterns and changes over time. It was determined that groundwater-level altitudes of the Ogallala aquifer were generally higher in the northwestern part of the study area and lower in the southeastern part of the study area with groundwater-flow paths generally adhering to a northwest to southeast direction across the study area. For the Edwards-Trinity (High Plains) aquifer potentiometric-surface map, a general northwest to southeast flow gradient was evident. Maps of groundwater-level-altitude changes between the early development (1930–60) and recent periods (2005–15) for the Ogallala aquifer and the Edwards-Trinity (High Plains) aquifer were generally similar and indicate that groundwater-level altitudes have declined over a large part of the area. DS concentrations of less than 1,000 mg/L were predominantly measured in the western part of the study area. A general pattern of increasing nitrate concentrations from west to the northeast was evident in the study area.

Thomas and others (2019) refined the hydrogeologic framework of the study area by compiling available hydrogeologic data and information from interpretive studies with additional borehole and surface-geophysical data. The resulting dataset was analyzed to identify the extent and thickness of selected hydrogeologic units in the study area. Most of the locations where the altitude of the base (bottom) of the Ogallala aquifer was higher (shallower) than previously depicted are in the southern part of the study area. Thomas and others (2019) determined that the average altitude of the base of the Ogallala aquifer is approximately 1.7 ft lower (deeper) compared to previously published information on the altitude of the base of the aquifer (Deeds and others, 2015),

resulting in a subsequent increase in the saturated thickness by the same amount. The saturated thickness of the Ogallala aquifer ranges from less than 10 ft in the far southern extent of the study area to more than 150 ft southeast of Seminole, Tex., and northwest of Brownfield, Tex. (fig. 2). Although the Trinity and Fredericksburg Groups are present throughout most of the northern parts of the study area, there are localized areas where one or both groups are thin or absent. The average unit thicknesses of the Trinity and Fredericksburg Groups are 55 ft and 86 ft, respectively. The Trinity Group is generally thicker in the eastern part of the study area with the thickest part in a localized area in northeastern Yoakum County (about 164 ft thick). The Fredericksburg Group is generally thicker in the north-central part of the study area with the thickest part being about 237 ft thick. Relative to the other geologic units assessed for the study, the Dockum Group has a much larger average unit thickness of approximately 1,795 ft. The top of the Dockum Group is deepest to the north where the Trinity and Fredericksburg Groups are present and shallowest to the south where it directly underlies the Ogallala Formation.

Development of a Refined Hydrogeologic Framework

The term "hydrogeologic framework" as used in this report refers to the geospatial extents of hydrogeologic units, bed orientation, unit thickness, and outcrop and subcrop locations in the study area. The hydrogeologic framework of Thomas and others (2019) was updated by using newly collected hydrogeologic data. The resulting dataset was analyzed to refine the extents and thicknesses of the Dockum, Trinity, and Fredericksburg Groups and the Ogallala Formation.

Data Compilation and Collection

For this study, the data in Teeple and others (2018), which were used to develop the hydrogeologic framework in Thomas and others (2019), were used as the base dataset in the refinement of the hydrogeologic framework. The data were modified to account for duplicate sites, redefined tops and bases of the hydrogeologic units, and updated site altitudes obtained from a digital elevation model (DEM). More than 12,000 additional digital data records consisting of hydrogeologic information were compiled and added to the existing 9,822 hydrogeologic records. Although the composite dataset contained more than 22,000 hydrogeologic records, spatial gaps existed within the dataset. Additional time-domain electromagnetic (TDEM) soundings were collected at 24 targeted locations, where spatial gaps were identified, to supplement the original 234 TDEM soundings to improve the spatial coverage across the study area and to further reduce uncertainty within the hydrogeologic framework.

Surface geophysical resistivity methods such as TDEM soundings, can be used to detect changes in the electrical properties of the subsurface (Zohdy and others, 1974). The electrical properties of soil and rock are determined by water content, porosity, clay content and mineralogy, and conductivity (or reciprocal of electrical resistivity) of the pore water (Lucius and others, 2007). TDEM instruments measure the bulk resistivity of the subsurface by producing an alternating electrical current in a transmitter loop deployed on the land surface (Vignesh and others, 2015). TDEM soundings were collected using the Geonics Protem 47 and 57 systems (Geonics Limited, 2006a; Geonics Limited, 2006b). The Geonics Protem 47 and 57 systems use a multiturn receiver coil to measure electromagnetic (EM) fields in the center of a transmitter loop. The TDEM soundings were collected at two frequencies using the Geonics Protem 47 (285 and 75 hertz [Hz]) and three frequencies using the Geonics Protem 57 (30, 7.5, and 3.0 Hz) for a total of five frequencies. The lower frequencies receive data from deeper in the subsurface. For each frequency, 10 stacks were collected by using an integration time of either 8 or 15 seconds. The longer integration time (15 seconds) was used for collecting 3.0-Hz data with the Geonics Protem 57; the longer integration time helped compensate (improve signal to noise ratio) for the dissipation of the transmitted signal at depth and for the greater potential for EM background noise with these soundings compared to soundings collected at higher frequencies (shallower depths). Additional information about the TDEM method and data collected in this study are available in Payne and others (2020). The TDEM data were collected in accordance with methods defined by the American Society of Testing and Materials (ASTM) (American Society of Testing and Materials, 1999).

For each TDEM sounding, the voltages measured from the eddy currents were averaged and evaluated statistically by using preprocessing scripts that use the raw field data (voltage data) and compute the uncertainty of each time gate (discrete voltages measured at increasingly later times after shutoff of the current) independently. Variability observed in a time gate could represent signal noise or a systematic change not representative of stable data. In this application, 10 percent of the data from each end of the distribution were removed, and an average of the central 80 percent of the data was computed. The resulting averages were then compared to a noise sample collected at the sounding location, and any values less than one-half the associated EM background noise value were removed from the final sounding. The final averaged values for each time gate were saved as processed data files and used for inverse modeling. Inverse modeling is the process of estimating the spatial distribution of subsurface resistivity from the measured voltage. The IX1D v3 program, developed by Interpex Limited (1996), was used for inverse modeling of the TDEM soundings. A smooth inverse model (a multilayered model that holds the depth values fixed and allows the resistivity values to vary during inversion) was fit to the data by using Occam's inversion principle, a preferred-homogeneity regularization condition (Constable and others, 1987). To better represent the electrical stratigraphy of each sounding, layered-earth models

(simplified models used to represent hydrogeologic units) were then generated and fit to the data. The changes in resistivity from the inverse modeling results of the final processed TDEM data were used to determine changes of hydrogeologic contacts (the tops and bases of hydrogeologic units).

Land-surface altitudes were determined from a DEM for all well and TDEM locations using their horizontal coordinates to provide consistency and improve accuracy. DEM data were obtained from the Three-Dimensional Elevation Program (3DEP) (U.S. Geological Survey, 2017) to estimate land-surface altitudes across the study area. Depths to tops and bases of the hydrogeologic units were converted to altitudes by subtracting the depths from the 3DEP DEM. Then, depth data were referenced by altitude and spatial location for correlation among neighboring wells to create a regional network of data points.

Methods of Interpretation

The tops and bases of the hydrogeologic units from all the data released in Payne and others (2020) was used to create hydrogeologic unit surface grids. Hydrogeologic unit surface grids were created by using Oasis montaj (Seequent, 2020a) and kriging techniques as described in Thomas and others (2019, p. 8). Gridded hydrogeologic unit surface grids were iteratively compared to interpreted contact altitudes to evaluate outliers, grid accuracy, and clustered data. All outlier locations were evaluated through a correlation process to determine data-point uncertainty. The correlation process involved the comparison of hydrogeologic unit contacts between given sites to nearby sites and preliminary grids. After hydrogeologic unit data were processed, outlying data were reviewed by comparing them with the original source data. If the original source data were deemed questionable, then the outlying data were removed. Throughout the process, all hydrogeologic unit contacts were reviewed and revised as needed to provide the best possible final representation of each hydrogeologic unit (Payne and others, 2020).

Paleochannel location and orientation varied over geologic time as formations were deposited and eroded. Two methodologies were utilized to evaluate paleochannels in each formation across the study area: (1) trend-removal grid analysis and (2) hydrology toolset analysis. Trend-removal grids were developed by removing the third-order regional trend from all the point values within the hydrogeologic unit surface grids (Seequent, 2020b). The resulting trend-removal grid shows changes from the removed regional trend. Relatively low values represent low points in the hydrogeologic unit surface grid where continuous stretches of low points can be indicative of paleochannels. For the second method, the hydrogeologic unit surface grids were treated as if they were surface DEMs, and a topographic watershed delineation was simulated across the surface. Esri's ArcMAP Hydrology toolset was utilized to determine the flow direction, flow accumulation, stream links, and stream order (Esri, 2016). Ultimately, the hydrology toolset simulates the movement of water across a surface, which for this study would correspond to paleochannels in the hydrogeologic unit surface grids.

Hydrogeologic Framework Refinements

Hydrogeologic unit surface grids were used to assess the thickness and extent of the hydrogeologic units and to interpret paleochannel locations. The refined hydrogeologic unit surface grids revised during this assessment (fig. 5) were compared to previously mapped surfaces to evaluate recent hydrogeologic framework refinements (fig. 6; Thomas and others, 2019). Both trend-removal grid analysis and hydrology toolset analysis methods were used to locate the paleochannels eroded into the Dockum, Trinity, and Fredericksburg Groups (as observed in the base of the Trinity and Fredericksburg Groups and Ogallala Formation, respectively) (fig. 7). In this report, a deep paleochannel is defined as having a trend-removal value of less than -25 ft, and a moderately deep paleochannel is defined as having a trend-removal value between -10 and -25 ft. Thickness grids for each hydrogeologic unit were computed by subtracting the altitudes of the lower hydrogeologic unit surface grid from the altitudes of the overlying hydrogeologic unit surface grid (fig. 8). Descriptive statistics for the hydrogeologic framework results are summarized in table 1.

Dockum Group

The altitudes of the base of the Dockum Group range from about 350 ft above North American Vertical Datum of 1988 (NAVD 88) north of Cedar Lake near the border between Gaines County and Terry County to about 2,120 ft above NAVD 88 at the southwest corner of the study area (fig. 5A). The revised base of the Dockum Group is deeper than previously reported in Thomas and others (2019) (table 1; fig. 6A). The base of the Dockum Group is less than -150 ft (shallower) than previously reported, mostly in the eastern Gaines County and southern Terry County. The western part of the study area is greater than 300 ft (deeper) than previously reported in Thomas and others (2019). Large differences in the revised base of the Dockum Group from the previously reported base in Thomas and others (2019) are a result of the inclusion of an additional 29 values (an increase from 312 to 341 values) used to revise the hydrogeologic unit surface. Also, there were relatively few points to interpolate the base of the Dockum Group throughout the study area, which introduces large variations with the inclusion or redefinition of data values.

The altitudes of the top of the Dockum Group (bases of the Trinity Group and Ogallala Formation [where the Trinity Group is not present]) range from about 2,790 ft to about 3,610 ft above NAVD 88. The highest altitudes are in the

Table 1.   Descriptive statistics for the primary geologic units for each conservation district in the study area in and near Gaines, Terry, and Yoakum Counties, Texas.

[LEUWCD, Llano Estacado Underground Water Conservation District; SPUWCD, South Plains Underground Water Conservation District; SLUWCD, Sandy Land Underground Water Conservation District]

		LEUWCD (Gaines County)	SPUWCD (Terry County and part of Hockley County)	SLUWCD (Yoakum County)	Study area (Gaines, Terry, and Yoakum Counties and part of Hockley County)
		Dockum Group			
Depth to base (feet)	Minimum	1,415	1,764	2,080	1,413
	Maximum	3,184	3,175	3,263	3,263
	Average	2,297	2,143	2,800	2,381
Thickness (feet)	Minimum	1,308	1,493	1,789	1,308
	Maximum	2,921	2,792	2,970	2,970
	Average	2,100	1,818	2,476	2,115
Change in base from Thomas and others (2019) (feet)	Minimum	-348	-255	-126	-348
	Maximum	1,425	1,044	1,174	1,425
	Average	348	-2	618	318
		Trinity Group			
Depth to base (feet)	Minimum	83	185	203	83
	Maximum	372	454	448	454
	Average	218	325	325	290
Thickness (feet)	Minimum	0	3	0	0
	Maximum	146	197	167	197
	Average	34	77	59	57
Change in base from Thomas and others (2019) (feet)	Minimum	-85	-115	-101	-115
	Maximum	79	100	102	102
	Average	-4	-13	2	-5
		Fredericksburg Group			
Depth to base (feet)	Minimum	49	72	135	49
	Maximum	316	389	404	404
	Average	184	249	267	233
Thickness (feet)	Minimum	0	3	0	0
	Maximum	117	218	280	280
	Average	37	108	106	84
Change in base from Thomas and others (2019) (feet)	Minimum	-80	-155	-147	-155
	Maximum	82	90	115	115
	Average	-8	-7	-7	-7
		Ogallala Formation			
Depth to base (feet)	Minimum	33	20	59	20
	Maximum	298	243	302	302
	Average	158	141	161	154
Thickness (feet)	Minimum	33	20	59	20
	Maximum	298	243	302	302
	Average	158	141	161	154
Change in base from Thomas and others (2019) (feet)	Minimum	-120	-63	-106	-120
	Maximum	131	43	55	131
	Average	-6	-5	-8	-6
Change in base from original (feet)	Minimum	-143	-98	-61	-143
	Maximum	108	82	173	173
	Average	-19	0	20	-4
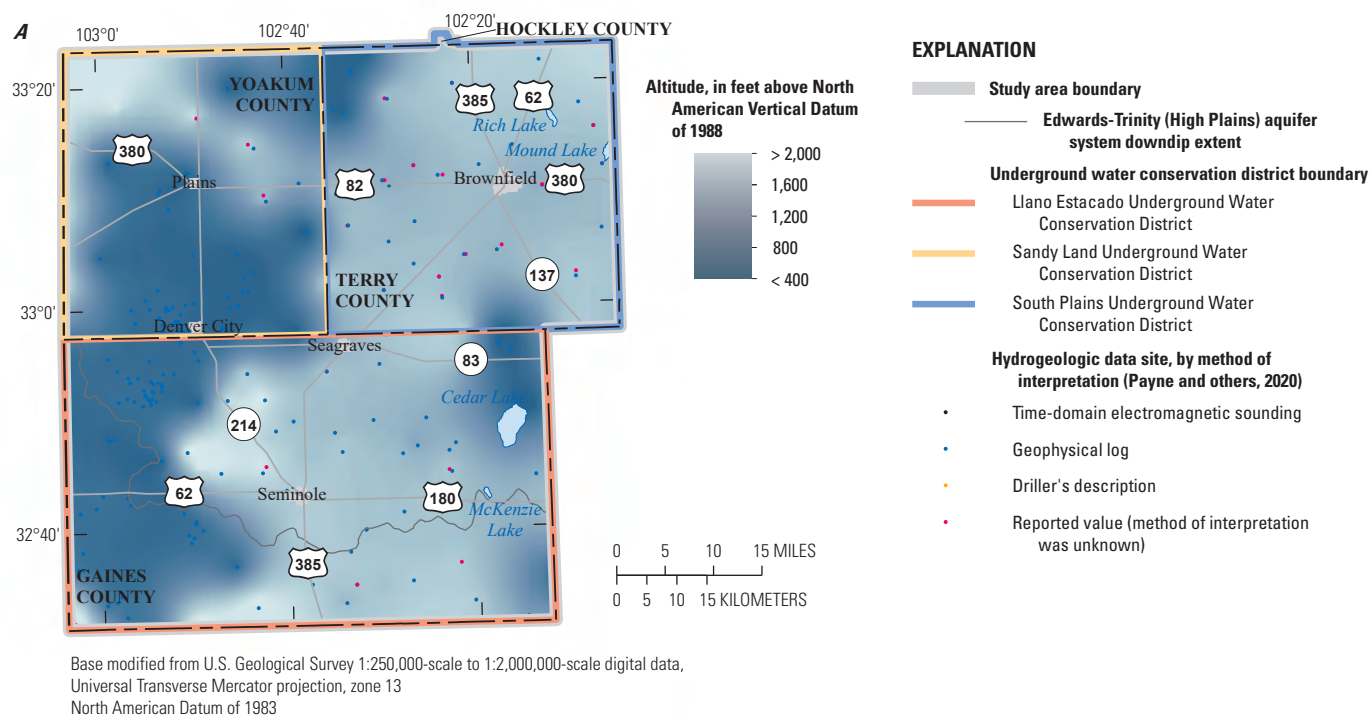
Base modified from U.S. Geological Survey 1:250,000-scale to 1:2,000,000-scale digital data,
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

Figure 5.   Revised (2020) hydrogeologic unit surfaces for *A*, the base (bottom) of the Dockum Group, *B*, the base of the Trinity Group, *C*, the base of the Fredericksburg Group, and *D*, the base of the Ogallala Formation in and near Gaines, Terry, and Yoakum Counties, Texas.

Figure 5. Revised (2020) hydrogeologic unit surfaces for *A*, the base (bottom) of the Dockum Group, *B*, the base of the Trinity Group, *C*, the base of the Fredericksburg Group, and *D*, the base of the Ogallala Formation in and near Gaines, Terry, and Yoakum Counties, Texas.—Continued

Base modified from U.S. Geological Survey 1:250,000-scale to 1:2,000,000-scale digital data,
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

Base modified from U.S. Geological Survey 1:250,000-scale to 1:2,000,000-scale digital data,
Universal Transverse Mercator projection, zone 13
North American Datum of 1983
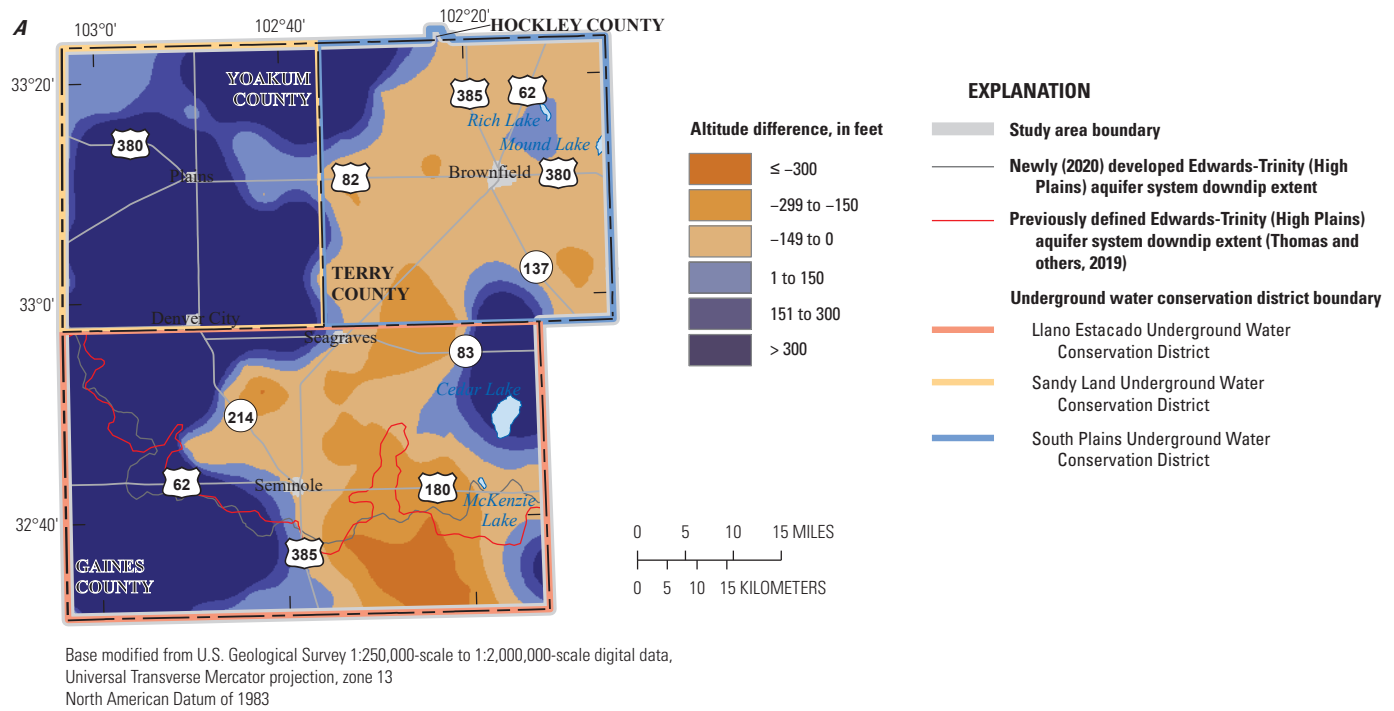
Figure 6.   Differences in mapped altitudes between the hydrogeologic unit surfaces from Thomas and others (2019) and the newly (2020) developed hydrogeologic unit surfaces for *A*, the base (bottom) of the Dockum Group, *B*, the base of the Trinity Group, *C*, the base of the Fredericksburg Group, and *D*, the base of the Ogallala Formation in and near Gaines, Terry, and Yoakum Counties, Texas.

Figure 6. Differences in mapped altitudes between the hydrogeologic unit surfaces from Thomas and others (2019) and the newly (2020) developed hydrogeologic unit surfaces for *A*, the base (bottom) of the Dockum Group, *B*, the base of the Trinity Group, *C*, the base of the Fredericksburg Group, and *D*, the base of the Ogallala Formation in and near Gaines, Terry, and Yoakum Counties, Texas.—Continued

Base modified from U.S. Geological Survey 1:250,000-scale to 1:2,000,000-scale digital data,
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

EXPLANATION

Difference from regional trend, in feet

> 50
25
0
−25
< −50

Study area boundary

Edwards-Trinity (High Plains) aquifer system downdip extent

Paleochannel from hydrology toolset

Underground water conservation district boundary

Llano Estacado Underground Water Conservation District

Sandy Land Underground Water Conservation District

South Plains Underground Water Conservation District
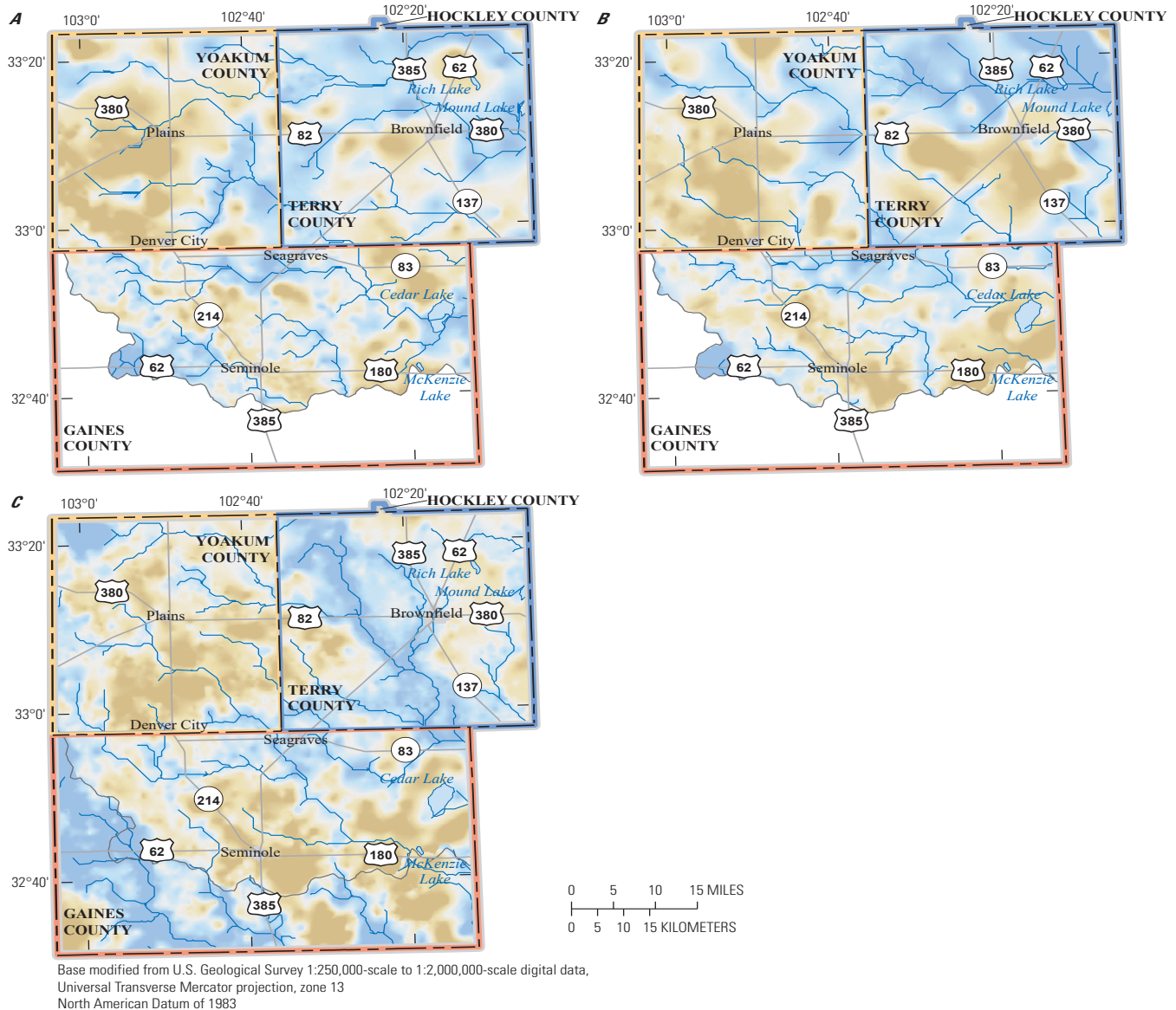
Figure 7.   Results of trend-removal grids and hydrology toolset analysis used to identify paleochannel locations in the hydrogeologic unit surfaces for *A*, the base (bottom) of the Trinity Group, *B*, the base of the Fredericksburg Group, and *C*, the base of the Ogallala Formation in and near Gaines, Terry, and Yoakum Counties, Texas.

northwest corner of the study area (fig. 5*B*), and the lowest altitudes are in the southeast corner of the study area (fig. 5*D*). The Dockum Group has a dip direction of about 105 degrees from north with a dip angle of about 0.14 degrees, resulting in about 2.4 ft of vertical change per 1,000 ft of horizontal distance.

Paleochannels eroded into the Dockum Group as represented by the bases of the Trinity Group and Ogallala Formation (where the Trinity Group is not present) generally have a west to east direction with some southerly direction in selected locations, as indicated by the low values from the trend-removal grids and from the potential paleochannel paths from the hydrology toolset analysis (fig. 7*A*; fig. 7*C*). Deep paleochannels were found in northern Terry County eroded into the Dockum Group (fig. 7*A*). Moderately deep paleochannels were found in the central part of the study area, which may provide possible pathway links (as shown by some of the stream paths from the hydrology toolset analysis) between deeper paleochannels.

The average thickness of the Dockum Group for the entire study area is 2,115 ft (table 1). The total thickness of the Dockum Group ranges from 1,308 ft near the south-central part of the study area in Gaines County to 2,970 ft, west of Plains, Tex., in Yoakum County (table 1; fig. 8*A*). Even with the inclusion of new data in this phase of the study, there is a relatively small amount of data pertaining to the Dockum Group. Hydrogeologic data pertaining to the Dockum Group were available from 540 wells, representing about 2 percent of the more than 22,000 hydrogeologic records that were compiled. To better quantify the water content of the Dockum Group, additional data are needed to further define various layers, including the water-bearing sandstone layers of the Dockum Group and the viability of the unit as a water-supply resource for the area.

Trinity Group

The altitudes of the base of the Trinity Group range from about 2,830 ft to about 3,610 ft above NAVD 88 (fig. 5*B*). The altitudes of the top of the Trinity Group (the base of the Fredericksburg Group) range from about 2,880 ft to about 3,610 ft above NAVD 88 (fig. 5*C*). The highest altitudes for both the base and top of the Trinity Group are in the northwest corner of the study area, and the lowest altitudes are along the eastern part of Gaines and Terry Counties. The dip direction is 105 and 110 degrees from north for the base and top of the Trinity Group, respectively. The base and top of the Trinity Group have the same dip angle of about 0.14 degrees, resulting in about 2.4 feet of vertical change per 1,000 ft of horizontal distance.

Across most of the study area there was relatively minimal change in the depiction of the base of the Trinity Group and the top of the Trinity Group (the base of the Fredericksburg Group) from that previously reported in Thomas and others (2019) (table 1). The base of the Trinity Group is shallower in most of Terry County and is greater than 25 ft (deeper) in large parts of Yoakum County and to the east and south of Seminole, Tex. (fig. 6*B*). The top of the Trinity Group is less than -50 ft (shallower) in Terry and Yoakum Counties (fig. 6*C*). There are two areas where the top of the Trinity Group is greater than 50 ft (deeper), about 10 miles northeast of Plains, Tex., and about 15 miles east of Seagraves, Tex.

Paleochannels eroded into the Trinity Group, as represented by the base of the Fredericksburg Group, generally have a west to east direction with some southerly direction in some locations, as indicated by the low values from the trend-removal grids and from the potential paleochannel paths from the hydrology toolset analysis (fig. 7*B*). Deep paleochannels are present in northern Terry County. Moderately deep paleochannels are present in the central part of the study area, which may provide possible pathway links (as shown by some of the potential paleochannel paths from the hydrology toolset analysis) between deeper paleochannels.

Although the Trinity Group is present throughout most of the northern parts of the study area, it thins to the south and is not present in the southern part of Gaines County (fig. 8*B*). The average unit thickness of the Trinity Group is 57 ft (table 1). The Trinity Group is thickest in eastern Terry County about 10 miles southeast of Brownfield, Tex. (197 ft thick) (fig. 8*B*). Among the three counties that compose most of the study area (Gaines, Terry, and Yoakum Counties), the average thickness of the Trinity Group is the greatest in Terry County (77 ft thick) (table 1). The Trinity Group increases in thickness to the east starting near the Yoakum-Gaines County line, south of Plains, Tex., where it is about 50 ft thick to near Brownfield where it is more than 190 ft thick (fig. 8*B*).

Fredericksburg Group

The altitudes of the base of the Fredericksburg Group range from about 2,880 ft to about 3,610 ft above NAVD 88 (fig. 5*C*). The altitudes of the top of the Fredericksburg Group (base of the Ogallala Formation within the extent of the Trinity and Fredericksburg Groups, geologic units comprising the Edwards-Trinity [High Plains] aquifer) range from about 2,880 ft to about 3,720 ft above NAVD 88 (fig. 5*D*). The highest altitudes for the base and top of the Fredericksburg Group are in the northwest corner of the study area, and the lowest altitudes are along the eastern part of Gaines County and the eastern part of Terry County for the base. The dip direction is 110 and 125 degrees from north for the base and top of the Fredericksburg Group, respectively. The dip angle for both the top and base is about 0.14 degrees, resulting in about 2.4 feet of vertical change per 1,000 ft of horizontal distance.

Across most of the study area there is relatively minimal change in the depiction of the base of the Fredericksburg Group and the top of the Fredericksburg Group (base of
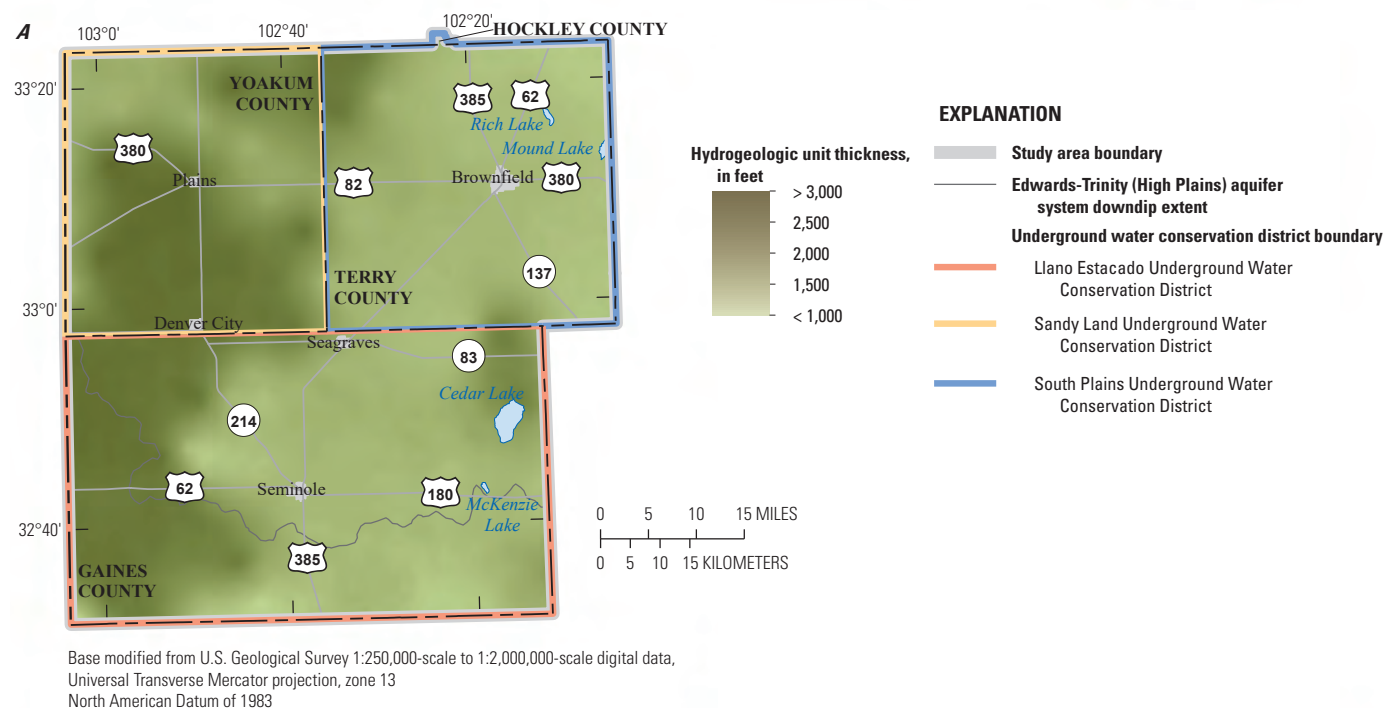
Base modified from U.S. Geological Survey 1:250,000-scale to 1:2,000,000-scale digital data,
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

Figure 8.   Hydrogeologic unit thickness of *A*, the Dockum Group, *B*, the Trinity Group, *C*, the Fredericksburg Group, and *D*, the Ogallala Formation in and near Gaines, Terry, and Yoakum Counties, Texas.
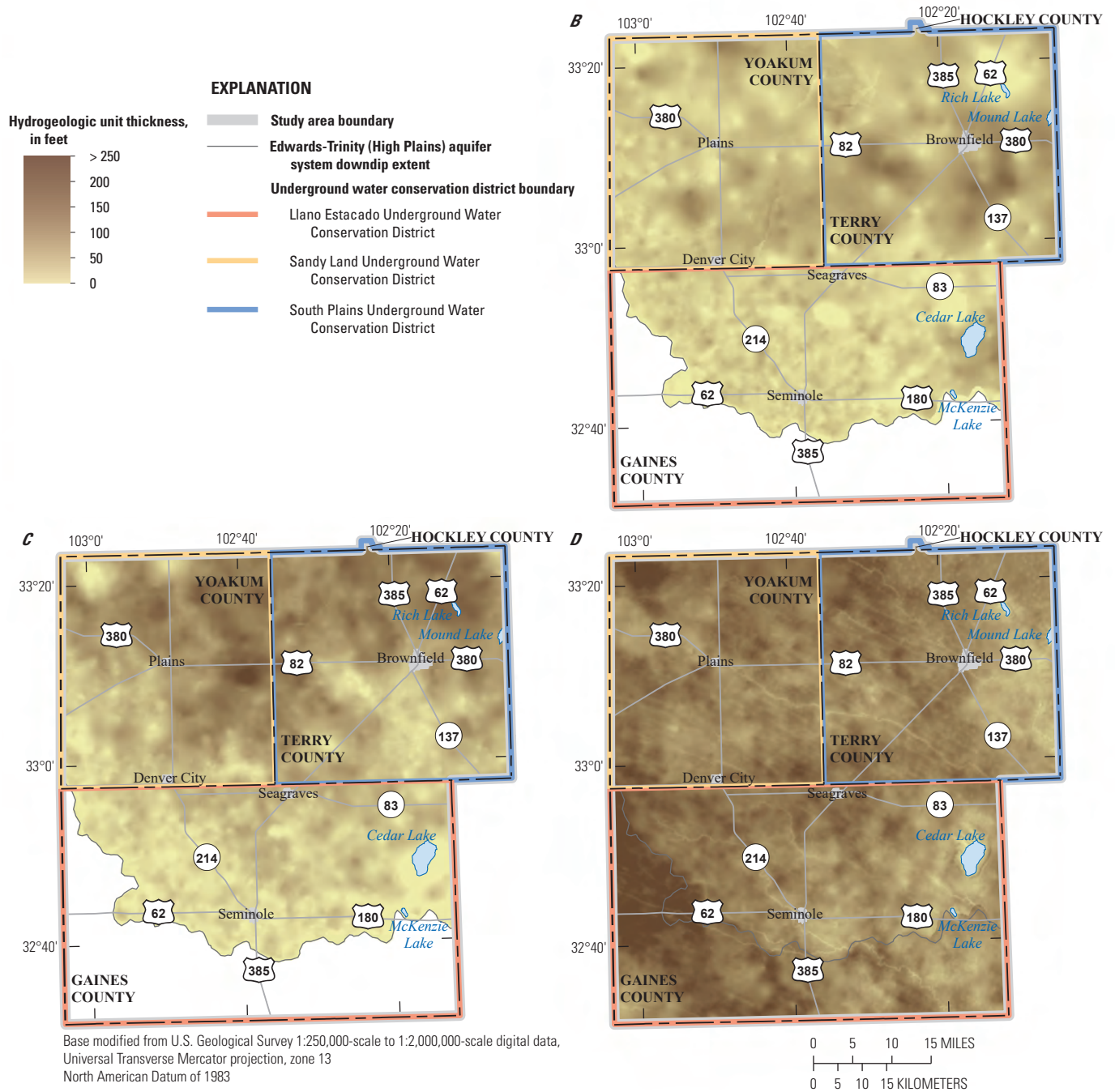
Figure 8. Hydrogeologic unit thickness of *A*, the Dockum Group, *B*, the Trinity Group, *C*, the Fredericksburg Group, and *D*, the Ogallala Formation in and near Gaines, Terry, and Yoakum Counties, Texas.—Continued
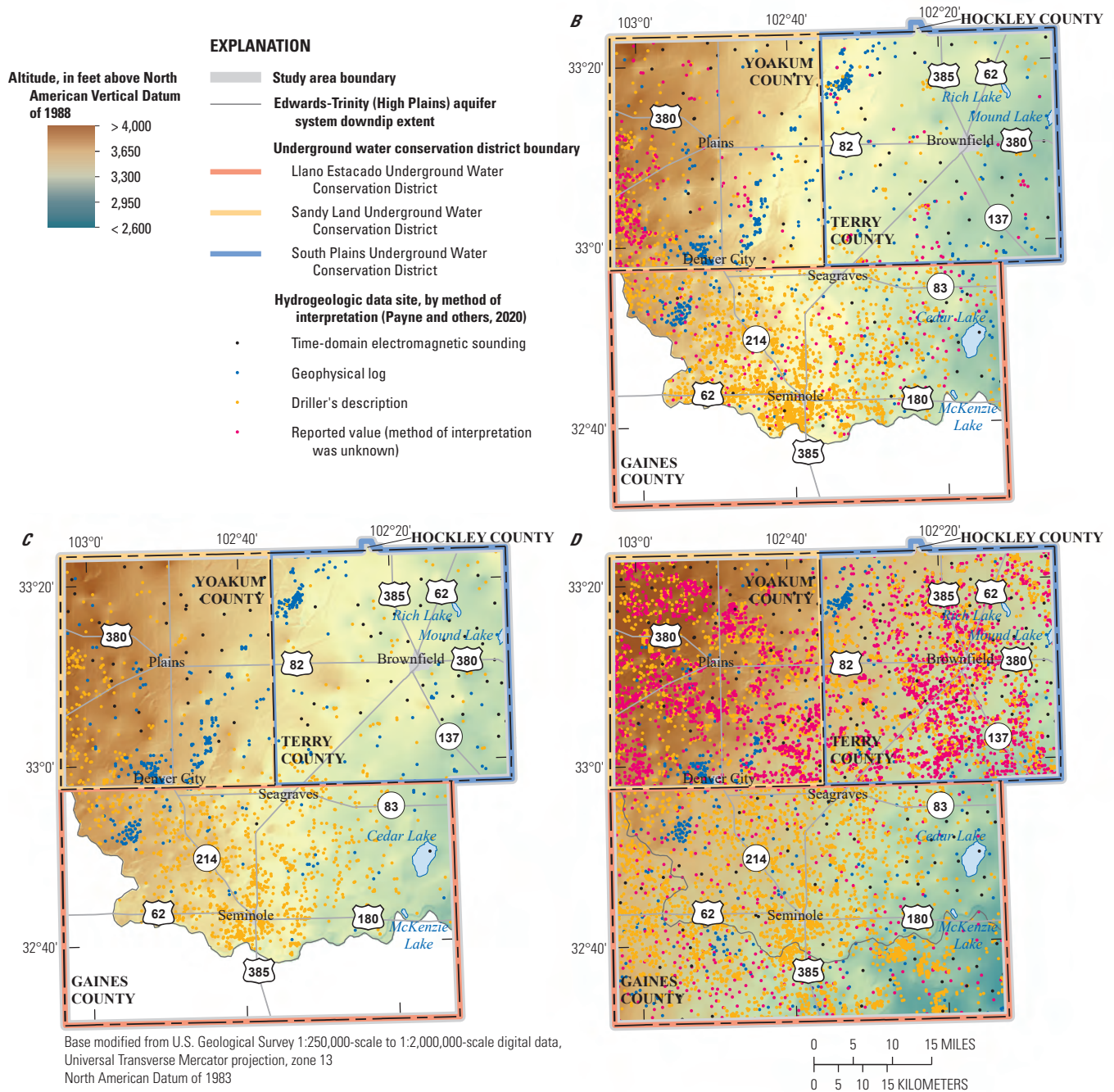
the Ogallala Formation within the extent of the Trinity and Fredericksburg Groups (geologic units comprising the Edwards-Trinity [High Plains] aquifer) from that previously reported in Thomas and others (2019). The base of the Fredericksburg Group is less than -50 ft shallower in Terry and Yoakum Counties than previously reported (fig. 6C). The base of the Fredericksburg Group is more than 50 ft deeper than previously identified in two areas, about 10 miles northeast of Plains, Tex., and about 15 miles east of Seagraves, Tex. Most of the locations where the top of the Fredericksburg Group is shallower than previously reported are generally near the southern extent of the Trinity and Fredericksburg Groups (geologic units comprising the Edwards-Trinity [High Plains] aquifer) (fig. 6D). The erosional features (one 10 miles east of Seminole, Tex., and the other 15 miles west of Seminole, Tex.) defined by Thomas and others (2019) were removed in response to insights provided by the expanded dataset such that points with existing Fredericksburg Group contacts were included in the analysis at these locations. The inclusion of these points resulted in more constraint to match the altitudes of the Fredericksburg Group on either side of the erosional features, causing the Ogallala Formation to be shallower in these features.

Paleochannels eroded into the Fredericksburg Group, as represented by the base of the Ogallala Formation within the extent of the Trinity and Fredericksburg Groups (geologic units comprising the Edwards-Trinity [High Plains] aquifer), have a northwest to southeast direction as indicated by the low values from the trend-removal grids and from the potential paleochannel paths from the hydrology toolset analysis (fig. 7C). A paleochannel was found within Terry County beginning near the northwest border of the county and traversing to the northeast border of Gaines County (fig. 7C). Moderately deep paleochannels were found in the central part of the study area that may provide possible pathway links (as shown by some of the potential paleochannel paths from the hydrology toolset analysis) between deeper paleochannels.

Although the Fredericksburg Group is present throughout most of the northern parts of the study area, it thins to the south and is not present in the southern part of Gaines County (fig. 8C). The average unit thickness of the Fredericksburg Group is 84 ft (table 1). The thickness of the Fredericksburg Group (table 1; fig. 8C) is more variable than the thickness of the Trinity Group (table 1; fig. 8B). The Fredericksburg Group is thickest in the north-central part of the study area in between Plains and Brownfie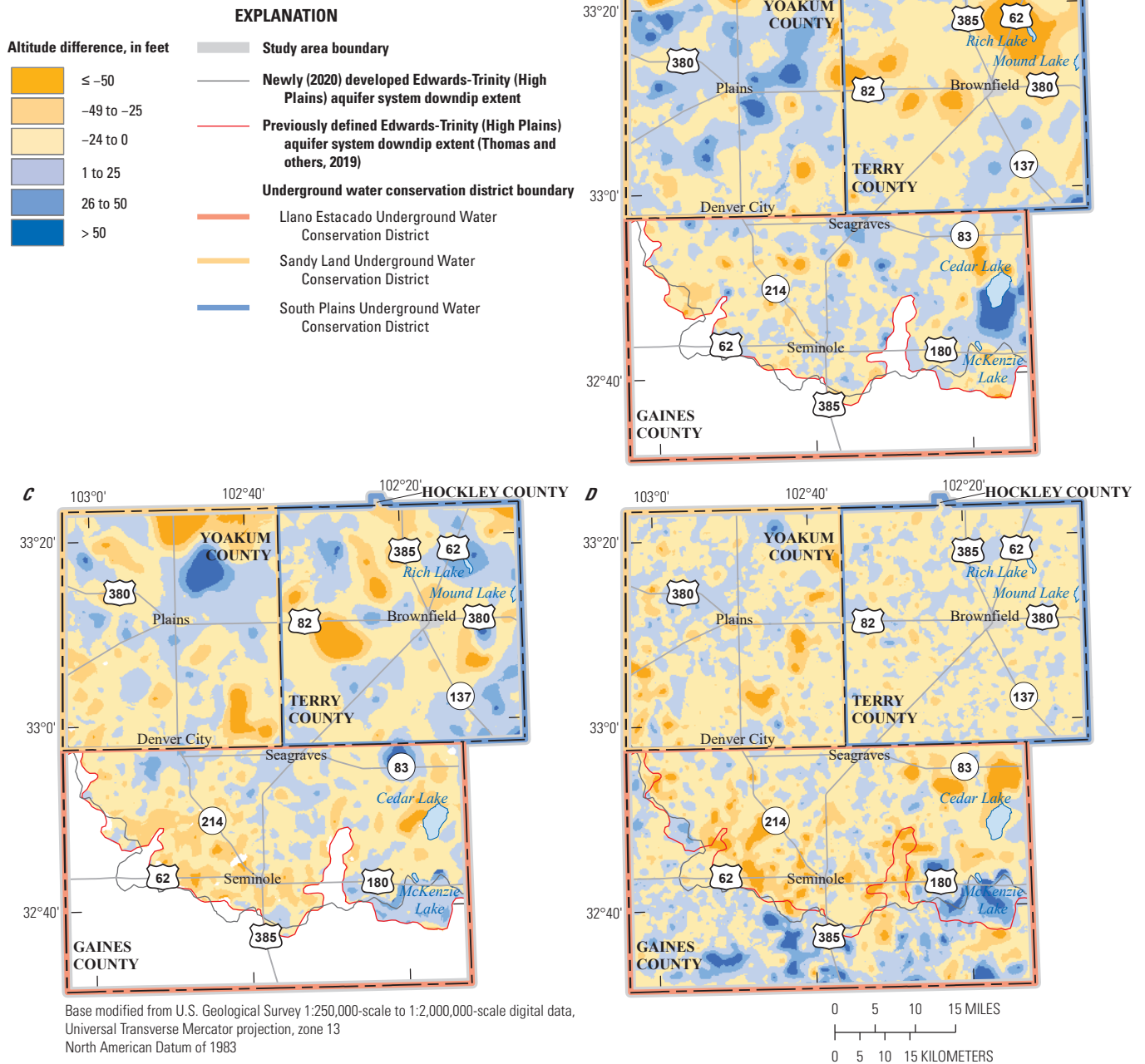ld, Tex. (280 ft thick) (fig. 8C). Among the three counties that compose most of the study area (Gaines, Terry, and Yoakum Counties), the average thickness of the Fredericksburg Group is the greatest in Terry County (108 ft thick) (table 1).

Ogallala Formation

The altitudes of the base of the Ogallala Formation range from about 2,790 ft to about 3,720 ft above NAVD 88 (fig. 5D). The altitudes of the top of the Ogallala Formation range from about 2,930 ft to about 3,900 ft above NAVD 88 (fig. 2), and the formation crops out in much of the study area. For the base and top of the Ogallala Formation, the highest altitudes are in the northwest corner of the study area, and the lowest altitudes are in the southeast corner of the study area. The dip direction for the base of the Ogallala Formation is about 125 degrees from north with a dip angle of about 0.14 degrees, resulting in about 2.4 ft of vertical change per 1,000 ft of horizontal distance. The dip direction for the top of the Ogallala Formation is about 120 degrees from north with a dip angle of about 0.15 degrees, resulting in about 2.6 ft of vertical change per 1,000 ft of horizontal distance.

Across most of the study area there is relatively minimal change in the depiction of the base of the Ogallala Formation from that previously reported in Thomas and others (2019) (table 1; fig. 6D). Most of the locations where the base of the Ogallala Formation is shallower than previously reported are in the southern part of the study area, specifically, in areas where the Ogallala Formation overlies the southern extent of the Trinity and Fredericksburg Groups (geologic units comprising the Edwards-Trinity [High Plains] aquifer); the base of the Ogallala Formation deepened south of the extent (fig. 6D). The deeper base of the Ogallala Formation is a result of redefining the base to include the isolated parts of the Trinity and Fredericksburg Groups. Effectively, in these areas, the Ogallala Formation is a composition of the eroded remnants of the Trinity and Fredericksburg Groups and Ogallala Formation. Because of the complexity of the hydrogeologic extents of the isolated parts of Trinity and Fredericksburg Groups, for the purpose of this report, they were included together with the Ogallala Formation.

Paleochannels eroded into the Dockum (where the Fredericksburg Group is not present) and Fredericksburg Groups, as represented collectively by the base of the Ogallala Formation, generally have a northwest to southeast direction, as indicated by the low values from the trend-removal grids and from the potential paleochannel paths from the hydrology toolset analysis (fig. 7C). A paleochannel was found in the southwest corner of the study area, beginning near the northwest border of Gaines County and traversing southeast to the south border of Gaines County south of Seminole, Tex. Another paleochannel was found within Terry County beginning near the northwest border of the county and traversing to the northeast border of Gaines County. Moderately deep paleochannels were found in the central part of the study area that may provide possible pathway links (as shown by some of the potential paleochannel paths from the hydrology toolset analysis) between deeper paleochannels.

The refinement of the base of the Ogallala Formation did not result in a substantial change in the final thickness statistics across the study area. The total unit thickness of the Ogallala Formation ranges from 20 ft to 302 ft (table 1), with an average thickness of 154 ft (Payne and others, 2020), whereas the average thickness reported in Thomas and others (2019) is 165 ft. In general, the thickest parts of the Ogallala Formation are in western Gaines County and the northwest

corners of Yoakum and Terry Counties (fig. 8*D*); the thinnest parts are in the eastern part of the study area and southeast of Seminole, Tex. Localized areas where the Ogallala Formation is relatively thin are present in some low-lying areas (for example, near Cedar Lake, Mound Lake, and Rich Lake).

Geochemistry

The geochemical methods and procedures presented in the "Sample Collection and Analysis" and "Quality-Assurance and Quality-Control Procedures" sections of this report have been described previously (Teeple, 2017). Additional information relevant to the current study (such as matrix spike comparisons) is discussed. These sections have been included in this report to document the sample collection and analysis methods and the quality-assurance and quality control procedures used to collect, analyze, and verify the data used in this report.

Sample Collection and Analysis

A total of 51 groundwater samples were collected in Gaines, Terry, and Yoakum Counties in Texas to assess groundwater quality conditions (fig. 3, table 2). In July and August 2014, 20 wells in Terry County and one well in Gaines County were sampled, whereas in July 2016, 10 wells in Gaines County and 20 wells in Yoakum County were sampled. Wells sampled were completed in either the Ogallala, Edwards-Trinity (High Plains), Dockum, or a mix of those aquifers. Physicochemical properties (pH, specific conductance, dissolved oxygen, water temperature, turbidity, and alkalinity) along with barometric pressure, groundwater pumping rates, and depth to water were measured in the field during sample collection. Samples were collected and shipped for laboratory analyses of major ions, trace elements, nutrients, organic compounds, strontium-87/strontium-86 isotopic ratio ($^{87}Sr/^{86}Sr$), hydrogen-2/hydrogen-1 isotopic ratio (δD), oxygen-18/oxygen-16 isotopic ratio ($\delta^{18}O$), tritium (^3H), and carbon-14 (^{14}C). All water-quality results were reviewed for completeness and accuracy and stored in the National Water Information System (NWIS) (U.S. Geological Survey, 2020b).

Field Procedures

The field procedures used to collect most groundwater samples are described in the USGS "National Field Manual for the Collection of Water-Quality Data" (U.S. Geological Survey, variously dated). Samples for isotope analyses were collected in accordance with procedures from the USGS Reston Groundwater Dating Laboratory in Reston, Virginia. (U.S. Geological Survey, 2012a), and the USGS Reston Stable Isotope Laboratory in Reston, Va. (U.S. Geological Survey, 2012b). Groundwater-level measurements were made prior to pumping each well by using an electric or steel tape and

following methods described in Cunningham and Schalk (2011). Prior to sample collection, each well usually was pumped to purge three casing volumes of water. The number of casing volumes that were purged depended on depth of the well, well-casing diameter, and the frequency of pumping performed at the well. After the necessary casing volumes were purged, the wells were pumped continually until steady-state measurements for all the physicochemical properties were obtained to ensure representative samples of the water in the aquifer were collected (U.S. Geological Survey, variously dated). When steady-state measurements indicating the system had reached equilibrium were obtained, water samples were collected from the well through fluoropolymer tubing and stored in new, precleaned bottles. Samples were collected prior to well water entering pressure tanks and prior to being filtered or undergoing other forms of treatment. Samples were processed onsite according to each laboratory's protocols to minimize chemical changes or contamination. In addition, samples were preserved by adding the appropriate acid (when necessary), chilled to 4 degrees Celsius (°C) (when necessary), or both before being shipped to the laboratory for analysis. Time-sensitive samples were shipped overnight to the analyzing laboratories, and the remaining samples were shipped to analyzing laboratories upon return from the field. After sample collection and processing, the sampling equipment was cleaned according to the established protocols prior to use at the next well scheduled for sampling (Wilde, 2004).

Analytical Methods

Major ions, trace elements, nutrients, and organic compounds were analyzed by the USGS National Water Quality Laboratory (NWQL), Denver, Colorado, using published methods. Analytical methods for major ions are published in Fishman and Friedman (1989), Fishman (1993), and American Public Health Association (1998). Trace-element analytical methods are published in Fishman and Friedman (1989), Garbarino (1999), and Garbarino and others (2006). Nutrients analytical methods are published in Fishman (1993) and Patton and Kryskalla (2003). Organic compounds analysis methods are published in Zaugg and others (1995), Lindley and others (1996), Sandstrom and others (2001), and Madsen and others (2003).

Environmental Tracers

Environmental tracers, such as $^{87}Sr/^{86}Sr$, δD, $\delta^{18}O$, ^3H, and ^{14}C concentrations in groundwater, are useful for understanding where and when groundwater recharge occurred in an aquifer system. $^{87}Sr/^{86}Sr$ isotopic ratios can be a useful tool for determining the source of dissolved constituents in groundwater; the isotopes were analyzed at the Menlo Park Isotope Laboratory in Menlo Park, California, in accordance with methods described by Kendall and McDonnell (1998). δD and $\delta^{18}O$ are useful indicators of conditions at the time

Table 2.   Selected well completion information, aquifer designation, and sampling date for groundwater-quality samples collected from wells in and near Gaines, Terry, and Yoakum Counties, Texas.

[USGS, U.S. Geological Survey; bls, below land surface; OGLL, High Plains aquifer system (Ogallala aquifer); ETHP; Edwards-Trinity (High Plains) aquifer system; DOCK, Dockum aquifer; COMB, Combination; --, no value]

Site identifier (fig. 3)	USGS well number	County	Well depth (feet bls)	Screened or open interval (feet bls)	Aquifer in which the well is completed	Aquifer designation	Sampling date
01500	324401102163401	Gaines	110	96–110	ETHP	ETHP	7/19/2016
03060	325046102221001	Gaines	60	--	OGLL	OGLL	7/19/2016
04518	330351102130301	Terry	90	50–90	OGLL; ETHP	COMB	7/30/2014
04809	330624102091701	Terry	275	235–275	ETHP	ETHP	8/2/2014
05380	330852102130401	Terry	53	23–53	OGLL	OGLL	7/30/2014
06260	330129102180701	Terry	157	0–157	OGLL	OGLL	8/1/2014
07706	331131102133701	Terry	--	--	OGLL	OGLL	8/1/2014
08389	331657102131801	Terry	80	40–80	OGLL	OGLL	8/4/2014
08956	330618102190801	Terry	165	125–165	OGLL	OGLL	7/29/2014
09493	332014102100101	Terry	147	107–147	OGLL	OGLL	7/31/2014
09503	324911102310901	Gaines	190	150–190	OGLL; ETHP	COMB	7/19/2016
09781	323339102431001	Gaines	160	--	OGLL	OGLL	7/21/2016
10061	331802102535902	Yoakum	155	--	ETHP	ETHP	7/29/2016
10509	332013103001501	Yoakum	220	--	OGLL	OGLL	7/29/2016
10523	330817103025002	Yoakum	160	92–159	OGLL	OGLL	7/29/2016
10639	325505102562201	Gaines	100	--	OGLL	OGLL	7/20/2016
10676	325933102501701	Yoakum	137	87–137	OGLL	OGLL	7/26/2016
10748	325731102311201	Gaines	380	308–380	ETHP	ETHP	8/6/2014
11642	330036102071701	Terry	250	210–250	ETHP; DOCK	COMB	8/4/2014
11771	331045102133901	Terry	340	80–100, 300–340	OGLL; ETHP	COMB	8/1/2014
12504	330904102292501	Terry	113	--	ETHP	ETHP	8/6/2014
12514	331305102122401	Terry	100	60–100	OGLL	OGLL	8/5/2014
14388	330339102235001	Terry	172	100–172	OGLL	OGLL	8/4/2014
15747	331316102195401	Terry	420	100–140, 300–420	ETHP	ETHP	8/6/2014
18745	331029102272001	Terry	145	105–145	OGLL	OGLL	8/2/2014
18790	331646102220901	Terry	170	110–170	OGLL; ETHP	COMB	8/2/2014
19639	324324102483201	Gaines	80	--	OGLL	OGLL	7/20/2016
20215	325053102424201	Gaines	360	--	DOCK	DOCK	7/20/2016
20759	331755102211401	Terry	159	0–159	OGLL	OGLL	7/30/2014
20903	330639102371201	Yoakum	65	45–65	OGLL; ETHP	COMB	7/26/2016
21325	324610102501401	Gaines	240	195–235	ETHP	ETHP	7/21/2016
21524	330751102351501	Terry	110	80–110	OGLL; ETHP	COMB	7/29/2014
23705	332054102262101	Terry	--	--	OGLL	OGLL	8/5/2014
24005	331359102351201	Terry	161	0–161	OGLL	OGLL	7/31/2014
24915	330232102432301	Yoakum	161	110–161	OGLL	OGLL	7/26/2016
25208	325848102503501	Yoakum	255	--	DOCK	DOCK	7/27/2016
25317	324040103010001	Gaines	242	180–242	OGLL	OGLL	7/21/2016

Table 2.   Selected well completion information, aquifer designation, and sampling date for groundwater-quality samples collected from wells in and near Gaines, Terry, and Yoakum Counties, Texas.—Continued

[USGS, U.S. Geological Survey; bls, below land surface; OGLL, High Plains aquifer system (Ogallala aquifer); ETHP; Edwards-Trinity (High Plains) aquifer system; DOCK, Dockum aquifer; COMB, Combination; --, no value]

Site identifier (fig. 3)	USGS well number	County	Well depth (feet bls)	Screened or open interval (feet bls)	Aquifer in which the well is completed	Aquifer designation	Sampling date
25644	325540102541901	Gaines	2,150	1,858–1,930, 1,933–1,940, 1,944–1,984	DOCK	DOCK	7/22/2016
25865	331438102392001	Yoakum	180	--	ETHP	ETHP	7/27/2016
25883	331100102391301	Yoakum	175	125–175	OGLL	OGLL	7/25/2016
26458	330227102485401	Yoakum	300	--	ETHP	ETHP	7/24/2016
26701	330235102502001	Yoakum	250	--	DOCK	DOCK	7/27/2016
27256	330559102482101	Yoakum	154	--	ETHP	ETHP	7/25/2016
27272	331248102430301	Yoakum	210	150–210	OGLL	OGLL	7/25/2016
27287	330209102565201	Yoakum	235	--	DOCK	DOCK	7/24/2016
27488	332134102414901	Yoakum	150	110–150	OGLL	OGLL	7/28/2016
27727	325929102570201	Yoakum	260	--	ETHP	ETHP	7/24/2016
27811	331238102533401	Yoakum	57	--	OGLL	OGLL	7/22/2016
27974	325923103010101	Yoakum	321	201–321	OGLL; ETHP	COMB	7/29/2016
28275	331335102492001	Yoakum	235	165–235	ETHP	ETHP	7/28/2016
28367	330809102581901	Yoakum	200	120–200	OGLL	OGLL	7/22/2016

and place of groundwater recharge and were analyzed at the USGS Stable Isotope Laboratory in Reston, Va. δD analytical methods are described in Révész and Coplen (2008a), and δ^{18}O analytical methods are described in Révész and Coplen (2008b). ^{3}H and ^{14}C can provide information on the apparent age of the groundwater. ^{3}H was analyzed at the Menlo Park Tritium Laboratory in Menlo Park, Calif. Analytical methods for ^{3}H are documented in Östlund and Werner (1962) and Thatcher and others (1977). ^{14}C was analyzed at the National Ocean Sciences Accelerator Mass Spectrometry Facility at the Woods Hole Oceanographic Institution in Woods Hole, Massachusetts (Woods Hole Oceanographic Institution, 2020). ^{14}C was analyzed by accelerator mass spectrometry (AMS). Methods for analyzing AMS results are described by Roberts and others (2010) and are reported in the standard ^{14}C format (Stuiver and Polach, 1977). Methods for determining and reporting ^{14}C ages are described in Karlen and others (1964), Olsson and Klasson (1970), Stuiver and Polach (1977), and Stuiver (1980).

Strontium Isotopic Ratios

Strontium isotope ratios, specifically ^{87}Sr/^{86}Sr, are useful in describing the source of water as defined by changes in the composition of the salts dissolved in the water (Kendall and McDonnell, 1998). When ^{87}Sr/^{86}Sr values increase or decrease from one location to the next along a flow path, mixing of geochemically different sources of water or mixing of water

from different aquifer units could be occurring. Strontium can substitute for calcium especially in carbonate rocks that are commonly found in subsurface geologic units in the study area (Hem, 1985; Banner, 2004; Musgrove and others, 2010; Bumgarner and others, 2012). As a result of this rock-water interaction, ^{87}Sr/^{86}Sr values can be used to evaluate sources of dissolved constituents to groundwater and to determine possible groundwater mixing (McNutt and others, 1990; Musgrove and Banner, 1993; Banner and others, 1994; Uliana and others, 2007; Musgrove and others, 2010). Water in specific geologic units is expected to have ^{87}Sr/^{86}Sr values that reflect the isotopic ratio of minerals in that specific unit; therefore, ^{87}Sr/^{86}Sr values can be used as a geochemical tracer of source waters originating from different geologic units (Kendall and McDonnell, 1998). By using ^{87}Sr/^{86}Sr values obtained from previous studies such as McMahon and others (2004) and Bumgarner and others (2012), ^{87}Sr/^{86}Sr values measured in groundwater samples from Gaines, Terry, and Yoakum Counties can be compared to ^{87}Sr/^{86}Sr values in water samples collected from various aquifers within the study area, such as the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers.

Hydrogen and Oxygen Isotopic Ratios

Ratios of the stable isotopes of the water molecule (hydrogen and oxygen) can yield isotopic signatures that are useful indicators of the regional recharge regimes of a hydrogeologic system (Faure, 1986). Plotting the relation between

δD and δ^{18}O can aid in analyzing the time and place that surface water or precipitation initially recharged the groundwater system; δD and δ^{18}O are measured in units of per mil (Faure, 1986; Uliana and others, 2007; Bumgarner and others, 2012). Craig (1961) used δD and δ^{18}O isotopic analyses from multiple precipitation samples collected around the world to create a Global Meteoric Water Line (GMWL), a linear regression line computed as δD = 8 $\times$ δ^{18}O + 10. Changes along this line can be attributed to multiple factors, including altitude, storm intensity, latitude, seasons, and continental climate (Fontes, 1980). Precipitation with greater amounts of the δD and δ^{18}O (isotopically heavier) elevated above background values generally occurs at lower altitudes, at lower latitudes, during warmer weather, and closer to the coasts (Witcher and others, 2004). Values of δD and δ^{18}O that deviate from the GMWL can result from one of two processes: (1) evaporation prior to recharge and (2) oxygen isotope exchange with rocks (Witcher and others, 2004). Evaporation can cause preferential loss of water molecules containing the lighter stable isotopes of hydrogen and oxygen, which can be identified by elevated δD and δ^{18}O values. Water samples that indicate gains or losses of oxygen atoms from rock-water interaction tend to deviate from the GMWL in the lateral position because there is the gain or loss of only the oxygen element (Teeple, 2017).

Tritium

^{3}H is a radioactive isotope of hydrogen with a half-life of 12.32 years and usually has two sources: natural cosmogenic ^{3}H and ^{3}H produced by the atmospheric testing of nuclear weapons (Clark and Fritz, 1997; Lucas and Unterweger, 2000). The release of excess ^{3}H into the atmosphere occurred during widespread nuclear weapons testing from about 1950 to about 1970 (Motzer, 2008). Before nuclear weapons testing, the naturally occurring concentration of ^{3}H in the atmosphere ranged from about 2 to 8 tritium units (TU) (Motzer, 2008). From about 1950 to about 1970, widespread nuclear weapons testing resulted in a substantial increase (more than 1.1×10^{9} TU) of ^{3}H in the atmosphere of the Northern Hemisphere (Motzer, 2008). Concentrations of ^{3}H in precipitation since 2006 have decreased globally to approximately pre-bomb background levels of 2 to 10 TU (Clark and Fritz, 1997; Phillips and Castro, 2003). The elevated ^{3}H concentrations in the atmosphere beginning in about 1950 resulted in groundwater recharge containing appreciably higher ^{3}H concentrations compared to groundwater recharged before 1950. Consequently, ^{3}H is a good tracer for groundwater that was recharged after about 1950. The use of ^{3}H to analyze groundwater is qualitative in that definitive ages of groundwater cannot be determined, but rather, differences in ^{3}H concentrations can potentially distinguish whether the groundwater was recharged before, during, or after widespread nuclear weapons testing began in the 1950s. As noted by Hinkle (1996, p. 5) "the definition of modern water is a function of the dating tool used. Although different dating tools rely on different dates in defining the boundary between modern and old water, the

range of these dates is small." The determination of groundwater age by using ^{3}H is relative to ^{3}H concentrations when samples were collected. ^{3}H is commonly measured in picocuries per liter (pCi/L) or in TU, where 3.22 pCi/L is equivalent to 1 TU or 1 part ^{3}H in 10^{18} parts hydrogen (Lucas and Unterweger, 2000).

Carbon-14

^{14}C is the radioactive isotope of carbon and is naturally produced in the upper atmosphere (Plummer and others, 1994). Kalin (2000) notes that the half-life used for computing the radiocarbon age of most geologic and some hydrogeologic samples is the Libby half-life (Libby, 1955), which is 5,568 years. Because ^{14}C has a long radioactive half-life, it is useful for dating groundwater that is thousands to tens of thousands of years old (Kalin, 2000; Banner, 2004; Oden and Truini, 2013). Citing the work of Kalin (2000), Nishikawa and others (2004, p. 39) explain "carbon-14 data are expressed as percent modern carbon (pmc) by comparing ^{14}C activities to the specific activity of National Bureau of Standards [now the National Institute of Standards and Technology] oxalic acid: 13.56 disintegrations per minute per gram of carbon in the year 1950 equals 100 pmc (Kalin, 2000)."

Groundwater recharged after 1950 likely results in a ^{14}C activity value of 100 pmc or greater because atmospheric ^{14}C concentrations increased by as much as 20 percent owing to widespread nuclear weapons testing in the 1950s and 1960s (Plummer and others, 1994). ^{14}C typically moves into groundwater in carbon dioxide (CO_2) dissolved in precipitation or in organic carbon dissolved in surface water and soil pore water (Ingebritsen and Sanford, 1999; Raymond and Bauer, 2001). ^{14}C can enter surface water directly as water flows over the land towards stream channels (overland flow) or indirectly as the result of soil-pore water moving through the soil zone and discharging to a surface-water body (Linsley and others, 1982). Surface water in turn can provide a source of groundwater recharge through surface-water/groundwater interactions. Along the groundwater's flow path, ^{14}C concentrations slowly begin to decrease as ^{14}C decays to nitrogen-14 (^{14}N). Dilution of ^{14}C through geochemical processes, such as the dissolution of carbonates or CO_2 from rocks and soil, can substantially alter the original ^{14}C concentration (Lemay, 2002). ^{14}C concentrations in groundwater may be altered, therefore, by the introduction of nonradioactive carbon-12 (^{12}C) from exchange with carbon in rocks and soils that are millions of years old, resulting in apparent ^{14}C groundwater ages that are falsely old. Various types of geochemical modeling are used to correct for these effects to obtain better estimates of groundwater age (Plummer and others, 1994). Geochemical modeling to find corrected ages was not needed for the interpretations in this study; generalizations of the apparent age were made on the basis of the sample results. The age of groundwater is qualified as "apparent age" in this report because chemical processes affect the environmental tracers used to determine age. Musgrove and others (2010, p. 42) explain that "because

it is not possible to identify and account for all physical and chemical processes that might affect groundwater age-tracer results, the apparent age of groundwater is most appropriately reported."

Quality-Assurance and Quality-Control Procedures

Quality-control data were collected during sampling in 2014 and 2016 to assess the variability and bias that may exist within the sample-collection procedures and laboratory analyses (U.S. Geological Survey, variously dated). To test for this variability and bias, two field-blank samples, four sequential-replicate samples, and two matrix-spiked environmental samples were collected. All field-blank and sequential-replicate samples were analyzed for major ions, trace elements, nutrients, and organic compounds. Sequential-replicate samples also were analyzed for environmental tracers. Matrix-spike samples were analyzed only for organic compounds.

Field-Blank Analyses

Field-blank samples were collected and processed at two well locations prior to the collection of environmental samples at those locations to ensure that equipment cleaning conducted in the field between the collection of samples from different wells was adequate and that the collection, processing, or transporting procedures in the field did not contaminate the environmental samples. Field-blank results indicate that the sample collection and handling procedures did not introduce appreciable amounts of bias to the environmental samples, with possible exceptions for calcium, cobalt, lead, zinc, and aluminum—constituents that were not used for conceptual model development. Cobalt concentrations of 0.054 and 0.066 microgram per liter (µg/L) were detected in each of the field-blank samples. A lead concentration of 0.04 µg/L and a zinc concentration of 3.5 µg/L were detected in one field-blank sample. An aluminum concentration of 0.02 µg/L was detected in the other field-blank sample. Calcium was detected in both field-blank samples, but concentrations in field-blank samples were considered negligible (0.04 and 0.03 mg/L) compared to concentrations in all the environmental samples (greater than 30 mg/L). Four organic compounds (dicrotophos, chlorpyrifos, metolachlor, and methyl parathion) were detected in one field-blank sample; all detections were less than 0.03 µg/L. Of the four organic compounds detected in the field-blank sample, metolachlor was the only organic compound detected in environmental samples. The cause for low-level concentrations of some constituents in the field-blank samples is unknown, and the detection of metolachlor in one field-blank sample (0.006 µg/L) may indicate that false detections could occur in environmental samples and need to be considered during interpretation of the results.

Sequential-Replicate Analyses

Four sequential-replicate samples were collected to measure the variability in results of analyses originating from sampling procedures and analytical methods. To evaluate the potential variability introduced during sample collection, processing, or laboratory analysis, the analytical results measured in an environmental sample were compared with those measured in the associated replicate sample by computing the relative percent difference (RPD) for each constituent. The RPD was computed by using the following equation:

$$RPD = \frac{|C_1 - C_2|}{(C_1 + C_2)/2} \times 100 \qquad (1)$$

where

C_1 is the concentration from the environmental sample and

C_2 is the concentration from the replicate sample.

RPDs of 10 percent or less indicate good agreement between the paired results if the concentrations were sufficiently large compared to their associated laboratory reporting levels (LRLs) (Childress and others, 1999; Oden and others, 2011). An RPD was not computed if either of the paired results was reported as estimated or less than the detection limit. Most RPDs did not exceed 10 percent for constituents analyzed in the four sequential-replicate sample pairs collected during this study, indicating generally good agreement between the environmental and replicate sample concentrations. RPDs exceeded 10 percent for seven trace elements (cobalt, copper, iron, lead, manganese, zinc, and antimony) in at least one sequential-replicate sample pair and for orthophosphate in only one sequential-replicate sample pair. Differences between the concentrations in paired samples where each sample concentration is low can result in large RPD values, which was the case for some of the trace elements listed and orthophosphate. The constituents with RPD values in excess of 10 percent (trace elements and orthophosphate) were not relevant to the conceptual model development and are not discussed further in the report. RPDs did not exceed 10 percent for any organic constituents but did exceed 10 percent for tritium for two of the sequential-replicate pairs. Differences between tritium concentrations (0.6 and 0.9 TU) did not affect determination of relative ages in samples.

Matrix Spikes Analyses

A spiked environmental sample is an environmental-replicate sample to which a known volume containing known concentrations of target constituents is added in the field (Wilde and others, 2004; Martin and others, 2009). Water was collected from the well and processed following standard procedures to produce two samples (U.S. Geological Survey, variously dated; Shelton, 1994; Koterba and others, 1995). Spike solution was added to only one of the two water samples,

resulting in spiked and unspiked samples (the matrix spike and the "background" sample, respectively). Matrix spikes are usually collected to determine any matrix interference and the analyzing laboratory's ability to recover constituent concentrations (Zaugg and others, 1995; Menheer and Brigham, 1997; Mueller and others, 1997).

Unspiked and spiked environmental samples were used to assess bias and variability from degradation of organic compound concentrations during sample processing, storage, and analysis. Analytical recoveries of the spiked target constituents are expressed as percentages of expected (theoretical) concentrations. The percent recoveries of constituents in spiked environmental samples were compared to theoretical and laboratory recoveries to evaluate matrix interferences or degradation of organic compounds. Percent recovery is computed as follows:

$$\text{Percent recovery} = [(C_{spiked} - C_{unspiked}) \times 100] / C_{expected} \quad (2)$$

where

C_{spiked} is the measured concentration in the spiked environmental sample in micrograms per liter;

$C_{unspiked}$ is the measured concentration in the unspiked environmental sample in micrograms per liter; and

$C_{expected}$ is the theoretical concentration in the spiked environmental sample in micrograms per liter and is computed as follows:

$$C_{expected} = (C_{solution} \times V_{spike}) / V_{sample} \quad (3)$$

where

$C_{solution}$ is the concentration of constituent in the spike solution in micrograms per liter;

V_{spike} is the volume of spike added to the environmental sample in milliliters; and

V_{sample} is the volume of the environmental sample in milliliters.

Constituent concentrations less than the LRL were set to zero for the purpose of computing percent recovery.

A mixture of target constituents was added to one of the environmental-replicate samples for spike analysis. Two matrix-spike analyses were done for two different wells. Percent recoveries were computed for each of the constituents, with the optimum value being 100 percent (Mueller and others, 2015; Shoda and others, 2018). Depending on the constituent, overall percent recoveries for this study ranged from approximately 38.5 to 88.9 percent for the organic compounds detected in samples, with each organic constituent detected in this study having a different range in percent recovery. For example, prometryn, prometon, metolachlor, atrazine, and acetochlor had higher percent recoveries of 72.2–88.9 percent,

but deethylatrazine, cyfluthrin, and trifluralin had lower percent recoveries of 38.5–65.5 percent. If a selected constituent has a substantially high or low recovery, environmental sample results of the organic constituent could be affected, but reported concentrations of organic compounds were not adjusted to account for results of matrix-spike analyses. Because recoveries for deethylatrazine were consistently low in laboratory recovery spiked samples (around 53 percent), all concentrations for that constituent are reported as estimated. Concentrations of selected organic compounds measured in the unspiked environmental samples that were less than the respective LRL or that were not detected were considered irrelevant, and their recoveries were not evaluated in the matrix spike results.

Geochemical Characteristics

Groundwater chemistry can vary on the basis of water interacting with the surrounding rock in an aquifer and water mixing from different sources (Hem, 1985). To better understand general water quality and provide insights into groundwater-flow paths and recharge areas, water-quality samples were collected in the study area in 2014 and 2016 from 51 wells in Gaines, Terry, and Yoakum Counties in Texas (11 wells in Gaines County, 20 wells in Terry County, and 20 wells in Yoakum County) (table 2; fig. 3). The initial sampling design outlined a plan to collect an equal number of water-quality samples from each aquifer (Ogallala, Edwards-Trinity [High Plains], and Dockum aquifers) in the three counties. The aquifer designations of several wells were changed after comparing the sampling interval of the wells to the hydrogeologic framework developed in this study. Therefore, the resulting number of wells per each aquifer became uneven with 26 wells completed in the Ogallala aquifer, 12 wells completed in the Edwards-Trinity (High Plains) aquifer, 5 wells completed in the Dockum aquifer, and 8 wells completed in any combination of two or more of the aquifers in the study area (hereinafter referred as a "combination" of aquifers) (table 2; fig. 3). The uneven distribution of wells in the various aquifers in the study area was partly due to a lack of wells available for sampling and the predominance of wells in the Ogallala aquifer.

Physicochemical properties and other constituents were used to evaluate general water quality, aquifer interactions, and potential source areas of groundwater by examining and comparing hydrochemical facies, DS, nutrients, trace elements, organic compounds, and environmental tracers such as $^{87}Sr/^{86}Sr$, δD, $\delta^{18}O$, ^3H, and ^{14}C concentrations. All water-quality results were used in combination to identify the chemical characteristics of water in these counties and provide insight into potential groundwater-flow paths. The qualitative geochemical analysis does not include a quantitative evaluation of residence times in the aquifer nor does it include geochemical flow-path modeling of the groundwater system.

Table 3. U.S. Environmental Protection Agency primary and secondary drinking water standards, U.S. Geological Survey health-based screening levels, and the percent of samples that exceeded the designated standard or level for selected constituents analyzed in groundwater samples in Gaines, Terry, and Yoakum Counties, Texas, 2014 and 2016.

[MCL, maximum contaminant level; HBSL, health-based screening level; mg/L, milligram per liter; µg/L, microgram per liter; --, no value. MCLs from U.S. Environmental Protection Agency, 2020; HBSLs from U.S. Geological Survey, 2020c]

Constituent	Primary MCL standard	Secondary MCL standard	HBSL	Samples exceeding MCL or HBSL (percent)
Dissolved solids (mg/L)	--	500	--	92
Nitrate (mg/L)	10	--	--	35
Chloride (mg/L)	--	250	--	27
Fluoride (mg/L)	4.0	--	--	49
Sulfate (mg/L)	--	250	--	59
Arsenic (µg/L)	10	--	--	76
Strontium (µg/L)	--	--	4,000	29
Selenium (µg/L)	50	--	--	6

As a baseline indicator of the significance of the amount of constituent measured within the groundwater, oftentimes constituent concentrations are compared with U.S. Environmental Protection Agency (EPA) designated drinking water standards and USGS health-based screening levels (table 3) (U.S. Environmental Protection Agency, 2020; U.S. Geological Survey, 2020c). Arsenic is one of the constituents for which sample concentrations exceeded the primary maximum contaminant level of 10 µg/L in 76 percent of the samples collected in the study (table 3). Arsenic was not included in the conceptual model development but is a trace element often detected at concentrations exceeding 10 µg/L in the Ogallala aquifer. Arsenic is thought to be associated with historical arsenic acid use in agricultural settings but also can come from natural sources such as marine shale, saline lakes, volcanic-ash deposits, and iron-oxide minerals in the aquifer (Fahlquist, 2003; Scanlon and others, 2005; and Gurdak and others, 2009).

Hydrochemical Facies

The composition of groundwater principally is controlled by the composition of recharge water, water-rock interaction, and the mixing of water from different sources. The term "facies" refers to a classification scheme used to describe water in terms of the major cation and anion milliequivalents composition (Freeze and Cherry, 1979; Bartos and Ogle, 2002). A trilinear (Piper) diagram is a useful tool for evaluating the relative abundance of major cations and anions and classifying facies or water types (Piper, 1944). Hydrochemical facies are complex and varied within the aquifers in the study area, indicating possible groundwater interactions among the aquifers in the study area. Specific hydrochemical facies do not seem to be associated with any particular aquifer in the
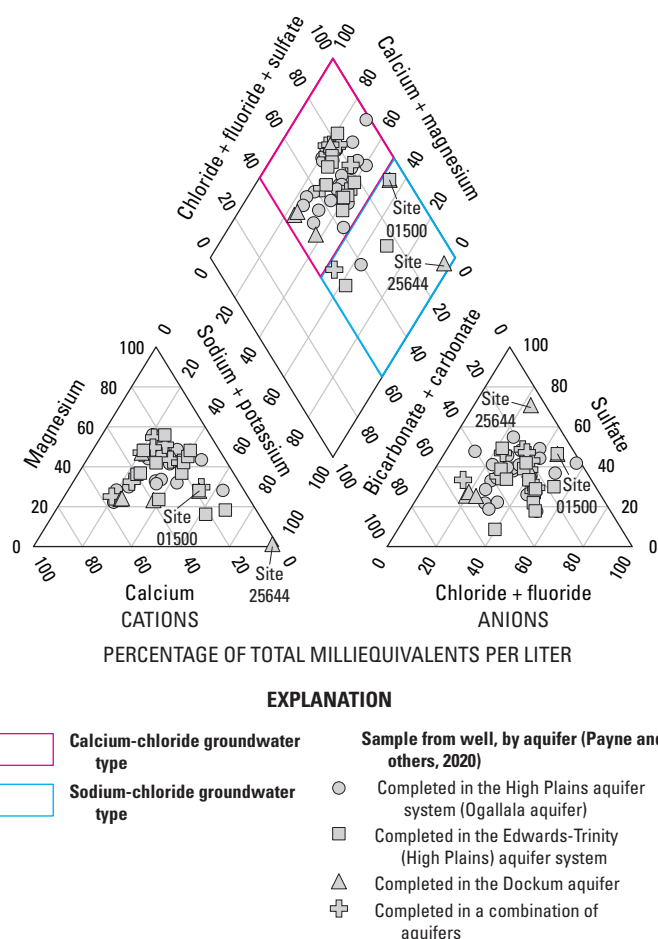
Figure 9. Relations between major cations and anions measured in water-quality samples from groundwater wells in Gaines, Terry, and Yoakum Counties, Texas, 2014 and 2016.

study area (fig. 9). Most of the samples were classified as calcium-chloride groundwater type. Seven samples were classified as sodium-chloride groundwater type.

Dissolved Solids

DS concentrations are a measure of how many dissolved constituents are in a sample. Sodium and chloride are often the primary constituents that contribute to elevated DS concentrations (Hem, 1985). In this report, DS concentrations of less than or equal to 1,000 mg/L are considered indicative of freshwater, whereas DS concentrations greater than 1,000 mg/L and less than 10,000 mg/L are considered indicative of brackish water (Winslow and Kister, 1956). DS concentrations in the groundwater samples collected in the study area range from 424 to 5,900 mg/L (Payne and others, 2020; fig. 10) with the median DS concentration of 1,020 mg/L (Payne and others, 2020). DS concentrations of less than 1,000 mg/L were measured in less than one-half (47 percent) the wells sampled in the study area. The EPA secondary drinking-water standard for DS concentrations is 500 mg/L for color, taste, and odor issues (table 3) (U.S. Environmental Protection Agency, 2020). The DS concentration exceeded 500 mg/L in 92 percent of the wells sampled. The highest DS concentrations (5,900 and 4,900 mg/L) were measured in two wells (sites 25644 and 01500, respectively) in Gaines County (fig. 10); the highest sodium (2,040 and 942 mg/L) and chloride (646 and 1,030 mg/L) concentrations were also measured in these same two wells (fig. 9) (Payne and others, 2020). Of the wells sampled in Terry County, 100 percent had DS concentrations greater than 500 mg/L, whereas 95 percent of the wells sampled in Gaines County and 85 percent of the wells sampled in Yoakum County had DS concentrations exceeding 500 mg/L.

Nutrients

Elevated nutrient concentrations in groundwater (predominantly in the forms of nitrate and nitrite) can result from surface-water infiltration in agricultural or municipal areas. Nutrient sources typically include livestock manure, septic systems, municipal treatment systems, or fertilizers (Dubrovsky and others, 2010). National background concentrations of nitrate, the most common form of nitrogen in groundwater, were estimated to be 1 mg/L (Dubrovsky and others, 2010). Nitrate plus nitrite concentrations in the groundwater samples collected in the study area ranged from less than the detection limit of 0.04 mg/L to 98.2 mg/L (Payne and others, 2020; fig. 11) with the median concentration at 7 mg/L (Payne and others, 2020). The concentration of nitrate plus nitrite exceeded the EPA primary maximum contaminant level of 10 mg/L in 35 percent of the samples from the study area (table 3). Nitrite concentrations in the study area were negligible with detectable concentrations (0.001–0.057 mg/L) in less than 30 percent of samples, indicating that most of the nitrogen in the groundwater is nitrate (Payne and others,

2020). The greatest percentage (60 percent) of wells sampled with nitrate plus nitrite concentrations greater than the drinking water standard for nitrate were in Terry County, whereas 27 percent were in Gaines County, and 15 percent were in Yoakum County (fig. 11). The pattern observed for nitrate plus nitrate concentrations (highest in Terry County, followed by Gaines and Yoakum Counties), is similar to the pattern observed for DS concentrations. There appears to be a relation between DS and nitrate plus nitrite concentrations (fig. 12), which may indicate that the elevated DS concentrations in the study area could be related to surface-water infiltration to the aquifers, similar to nutrient sources.

Organic Compounds

Organic compounds such as herbicides and insecticides detected in groundwater samples likely result from surface-water infiltration and anthropogenic (human) influences on groundwater in the study area. Groundwater samples were analyzed for 83 organic compounds, and the only organic compounds detected in this study were acetochlor, atrazine, metolachlor, prometon, prometryn, trifluralin, cyfluthrin, and deethylatrazine (Payne and others, 2020). All organic compounds detected are herbicides, except for cyfluthrin, an insecticide, and deethylatrazine, an atrazine degradate. Herbicides are commonly used in these counties because of the extensive agricultural land use in the region (fig. 3). All concentrations for these organic compounds were very low (less than 0.03 µg/L). Often groundwater samples collected from a given well will have detections of multiple organic compounds. In this study, three organic compounds were detected in the sample collected from one well (site 10061) (fig. 3, table 2), which was the greatest number of organic compounds detected in the samples collected from any well sampled for this study (Payne and others, 2020). Two organic compounds were detected in each of the samples collected from 10 wells (sites 01500, 04518, 04809, 10509, 10523, 12504, 18790, 20215, 20759, and 25865). At least one organic compound was detected in the samples collected from 26 of the 51 wells; metolachlor (detected in the samples from 16 wells) (fig. 13A) and deethylatrazine (detected in the samples from 12 wells) (fig. 14A) were the most commonly detected compounds (Payne and others, 2020).

Twenty groundwater wells in Gaines, Terry, and Yoakum Counties were sampled for organic compounds during 2001–03 as part of previous studies done by the USGS (Fahlquist, 2003; Stanton and Fahlquist, 2006). The same detection limits for the analysis of metolachlor and deethylatrazine (the two most commonly detected organic compounds in this study) were used in this study as were used to analyze the samples collected during 2001–03 (Fahlquist, 2003; Stanton and Fahlquist, 2006). Metolachlor was not detected in groundwater samples collected from any of the wells sampled in these previous studies (fig. 13B), and deethylatrazine was detected in the samples from only three wells (fig. 14B). Even though the number of detections increased in samples collected in this study compared to the number of detections in
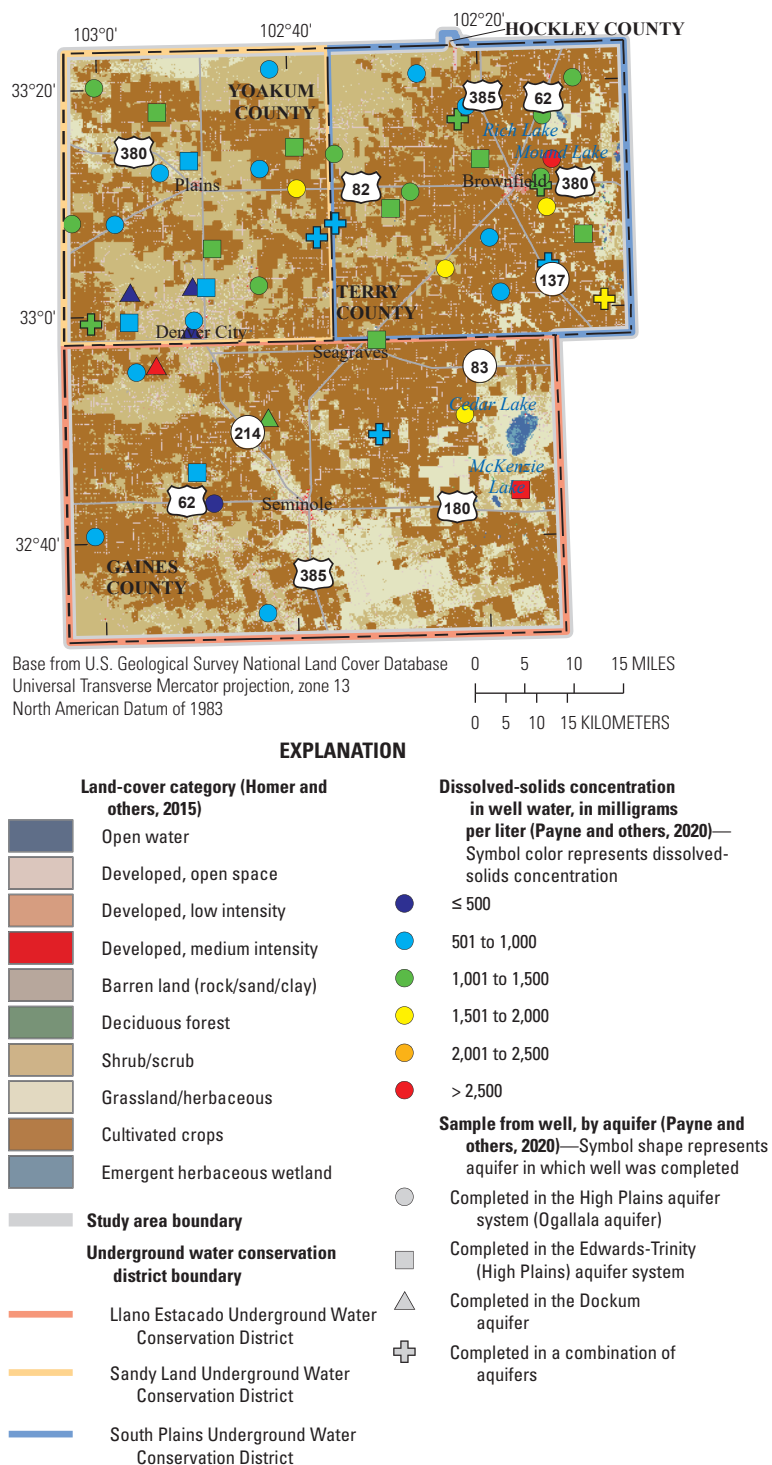
Figure 10.   Dissolved-solids concentrations in groundwater wells sampled in Gaines, Terry, and Yoakum Counties, Texas, 2014 and 2016.

Base from U.S. Geological Survey National Land Cover Database
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

EXPLANATION

Land-cover category (Homer and others, 2015)

- Open water
- Developed, open space
- Developed, low intensity
- Developed, medium intensity
- Barren land (rock/sand/clay)
- Deciduous forest
- Shrub/scrub
- Grassland/herbaceous
- Cultivated crops
- Emergent herbaceous wetland

Study area boundary

Underground water conservation district boundary

- Llano Estacado Underground Water Conservation District
- Sandy Land Underground Water Conservation District
- South Plains Underground Water Conservation District

Nitrate plus nitrite concentration in well water, in milligrams per liter (Payne and others, 2020)—Symbol color represents nitrate plus nitrite concentration

- < 5.0
- 5.1 to 10.0
- 10.1 to 15.0
- 15.1 to 20.0
- 20.1 to 25.0
- > 25.0

Sample from well, by aquifer (Payne and others, 2020)—Symbol shape represents aquifer in which well was completed

- Completed in the High Plains aquifer system (Ogallala aquifer)
- Completed in the Edwards-Trinity (High Plains) aquifer system
- Completed in the Dockum aquifer
- Completed in a combination of aquifers

Figure 11.   Nitrate plus nitrite concentrations in water-quality samples from groundwater wells in Gaines, Terry, and Yoakum Counties, Texas, 2014 and 2016.

Figure 12. Relation between dissolved-solids and nitrate plus nitrite concentrations in water-quality samples from groundwater wells in Gaines, Terry, and Yoakum Counties, Texas, 2014 and 2016.

samples collected in previous studies, detected concentrations remain very low (less than 0.03 µg/L). Similar to the pattern observed for DS and nutrient detections, the greatest number of detections for metolachlor and deethylatrazine were in samples collected in Terry County (fig. 13; fig. 14).

Environmental Tracers

Environmental tracers, such as $^{87}Sr/^{86}Sr$, δD and $\delta^{18}O$, ^{3}H, and ^{14}C in groundwater, are useful for understanding where and when groundwater recharge occurred in an aquifer system. The $^{87}Sr/^{86}Sr$ ratio can provide a useful tool for determining the source of dissolved constituents to water because the $^{87}Sr/^{86}Sr$ ratio undergoes negligible fractionation during rock-water interactions (Banner, 2004; Bumgarner and others, 2012). Therefore, water in specific geologic units are expected to have $^{87}Sr/^{86}Sr$ values that reflect the isotopic ratio of minerals in that specific aquifer unit (Kendall and McDonnell, 1998). Median $^{87}Sr/^{86}Sr$ values were computed for each aquifer for the groundwater samples collected in this study. The ranges and median values for $^{87}Sr/^{86}Sr$ were slightly different for the samples representing the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers (fig. 15) (Payne and others, 2020). The median $^{87}Sr/^{86}Sr$ values for samples collected from wells completed in the Ogallala, Edwards-Trinity (High

Plains), and Dockum aquifers were 0.70861, 0.70857, and 0.70866, respectively, whereas the median $^{87}Sr/^{86}Sr$ value for samples collected from wells completed in a combination of those aquifers was 0.70862. As may be expected, the median $^{87}Sr/^{86}Sr$ value for samples collected from wells completed in a combination of aquifers was between the median $^{87}Sr/^{86}Sr$ values for samples collected from wells completed in the Ogallala and Dockum aquifers and between median $^{87}Sr/^{86}Sr$ values from samples collected from wells completed in the Edwards-Trinity (High Plains) and Dockum aquifers, thereby supporting the mixed nature of the water in wells completed in a combination of aquifers. $^{87}Sr/^{86}Sr$ values for groundwater sampled from wells completed in the Edwards-Trinity (High Plains) aquifer in this study (0.70842–0.70866) were within the range of $^{87}Sr/^{86}Sr$ values reported in Bumgarner and others (2012) (0.70788 to 0.70979) for the same aquifer. According to Burke and others (1982), values for Permian- and Cretaceous-age carbonate and evaporite rocks are expected to range from 0.7068 to 0.7084, but Bumgarner and others (2012) state that the "additional sources of strontium (siliciclastics) with the interpreted complex stratigraphy and structural geology of the Pecos County region" may be contributing to the higher $^{87}Sr/^{86}Sr$ values. The range of $^{87}Sr/^{86}Sr$ values measured in samples from wells completed in the Dockum aquifer in this study (0.70847–0.70869) is within the range of $^{87}Sr/^{86}Sr$ values reported for the Dockum aquifer in Bumgarner and others (2012) (0.70743–0.70975). As with the Edwards-Trinity (High Plains) aquifer, the siliciclastic rocks of the Dockum aquifer may be contributing to the higher $^{87}Sr/^{86}Sr$ values observed by Bumgarner and others (2012). $^{87}Sr/^{86}Sr$ values representing water in the Ogallala aquifer in this study could not be compared to $^{87}Sr/^{86}Sr$ values reported by Bumgarner and others (2012) because the Ogallala aquifer is not present in the Pecos County region. Overall $^{87}Sr/^{86}Sr$ values in this study are similar to $^{87}Sr/^{86}Sr$ values reported in previous studies done near this study area.

Groundwater samples from the study area were analyzed for oxygen and hydrogen stable isotopes of water to help with the determination of recharge and flow paths. Oxygen and hydrogen stable isotopes of water are useful indicators of conditions present at the time and place of groundwater recharge (Faure, 1986; Uliana and others, 2007). The ratios of δD to $\delta^{18}O$ in groundwater samples can be used to evaluate the evaporation process along a flow path because evaporation causes the preferential loss of water molecules containing the lighter stable isotopes of hydrogen (hydrogen-1) and oxygen (oxygen-16) and therefore deviation from the GMWL (Witcher and others, 2004). Comparison of the ratios of δD to $\delta^{18}O$ values in groundwater samples collected in the study area to the GMWL can help determine changes to water chemistry from precipitation infiltrating into the groundwater system. All but one of the δD to $\delta^{18}O$ ratios for groundwater samples collected in this study plot are below the GMWL (fig. 16) because evaporation and rock-water interactions along flow paths can cause different δD and $\delta^{18}O$ values in groundwater samples compared to δD and $\delta^{18}O$ values in precipitation.

Base from U.S. Geological Survey National Land Cover Database
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

EXPLANATION

Land-cover category (Homer and others, 2015)

- Open water
- Developed, open space
- Developed, low intensity
- Developed, medium intensity
- Barren land (rock/sand/clay)
- Deciduous forest
- Shrub/scrub
- Grassland/herbaceous
- Cultivated crops
- Emergent herbaceous wetland

Study area boundary

Underground water conservation district boundary

- Llano Estacado Underground Water Conservation District
- Sandy Land Underground Water Conservation District
- South Plains Underground Water Conservation District

Metolachlor concentration detection in well water (Payne and others, 2020)—Symbol color represents detect or non-detect

- Detection of metolachlor in sample
- No detection of metolachlor in sample

Sample from well, by aquifer (Payne and others, 2020)—Symbol shape represents aquifer in which well was completed

- Completed in the High Plains aquifer system (Ogallala aquifer)
- Completed in the Edwards-Trinity (High Plains) aquifer system
- Completed in the Dockum aquifer
- Completed in a combination of aquifers

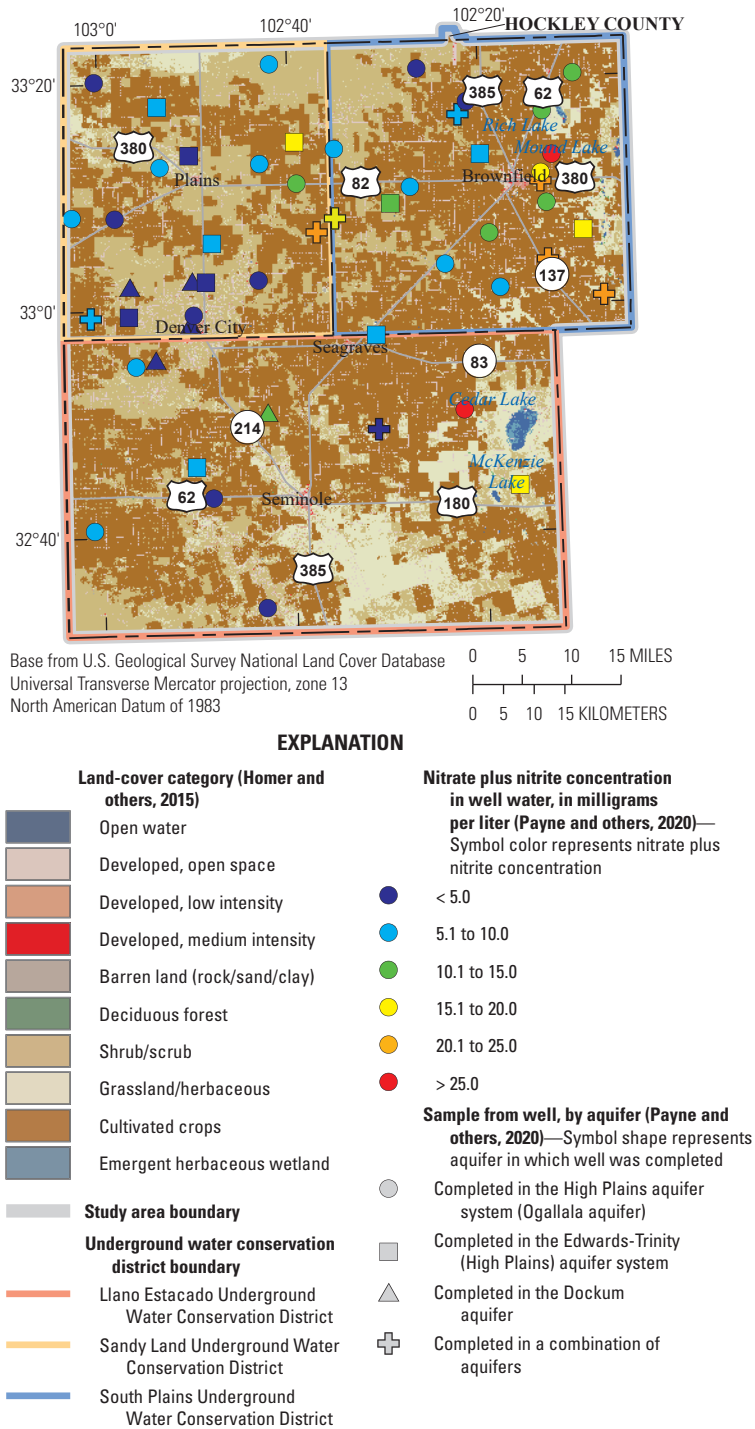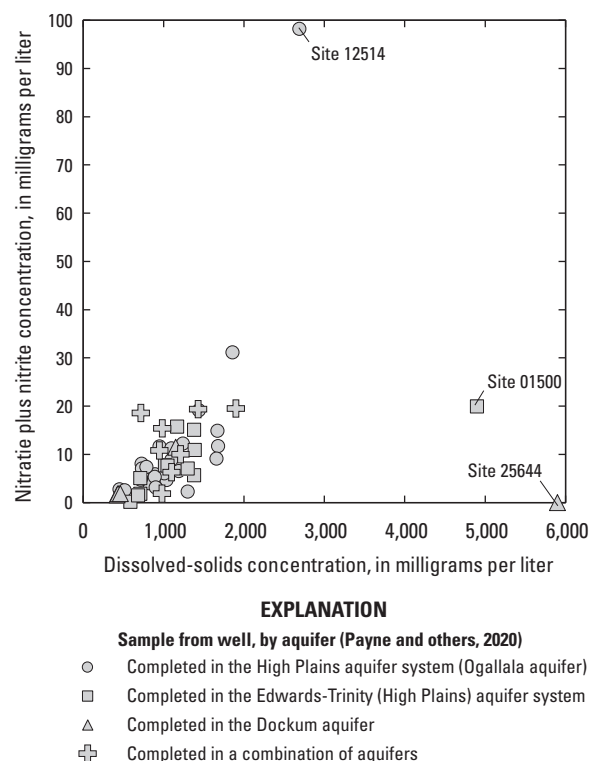**Figure 13.**   Metolachlor concentrations detected in water-quality samples from groundwater wells in Gaines, Terry, and Yoakum Counties, Texas, *A*, 2014 and 2016 and *B*, 2000–03 (Fahlquist, 2003; Stanton and Fahlquist, 2006).

Figure 14. Deethylatrazine concentrations detected in water-quality samples from groundwater wells in Gaines, Terry, and Yoakum Counties, Texas, *A*, 2014 and 2016 and *B*, 2000–03 (Fahlquist, 2003; Stanton and Fahlquist, 2006).

Figure 15. Strontium isotopic values in water-quality samples from groundwater wells in Gaines, Terry, and Yoakum Counties, Texas, 2014 and 2016.

δD to δ18O values in groundwater samples collected in this study do not have ratios specific to an aquifer (fig. 16), but a slight connection may exist between the δD to δ18O ratios and

geographic location, supporting a general groundwater-flow direction from west (Yoakum County) to east (Terry County). Heavier (higher) isotopic values of δD and δ18O, which can occur downgradient from flow paths, tended to be measured in the samples collected in Terry County (fig. 16). The lighter isotopic values measured in samples collected in a western part of the study area (Yoakum County) can be indicative of historically older waters within colder climate conditions (Gat and Gonfiantini, 1981; Jouzel and others, 1994).

Samples from groundwater wells in the study area were analyzed for 3H and 14C to gain insights regarding the age of the groundwater (Payne and others, 2020). By combining the results from 3H and 14C analyses and temporal variability of 3H deposition in precipitation, an apparent age can be assigned to the water from a given well (Michel and others, 2018; Lindsey and others, 2019). Water that generally has 3H concentrations greater than 1.5 TU and 14C concentrations greater than 60 pmc is considered modern and is less than about 70 years old (fig. 17). The groundwater sample collected from one well (site 20215) is an outlier for the general criteria for modern water; the 14C concentration measured in this sample is less than 60 pmc, possibly as a result of matrix interference during sample analysis (Plummer and others, 1994). Water that has 3H concentrations less than 0.15 TU is considered premodern and is more than several hundred years old. Water with 3H concentrations generally lower than 1.5 TU and 14C concentrations less than 80 pmc is considered a mixture of water less than about 70 years old and water more than several hundred years old (Michel and others, 2018; Lindsey and others, 2019). The evaluation of 3H and 14C concentrations measured in groundwater samples collected during this study indicates that a relation between the apparent ages of the groundwater and any specific aquifer does not appear to exist (fig. 17). The 3H and 14C concentrations have a slight connection with the spatial distribution of the groundwater samples, with the modern water frequently found in Terry County. Groundwater in the western part of the study area (western part of Gaines County and Yoakum County) seems to be older than water in the eastern part of the study area (eastern part of Gaines County and Terry County) (fig. 18). Given that groundwater in the eastern part of the study area is generally considered modern, or younger than 70 years old, groundwater would have been recently recharged, and land-use activities in the area could have had a great effect on groundwater quality. This recent recharge may explain the higher concentrations of nitrate and more frequent detections of metolachlor and deethylatrazine in Terry County.
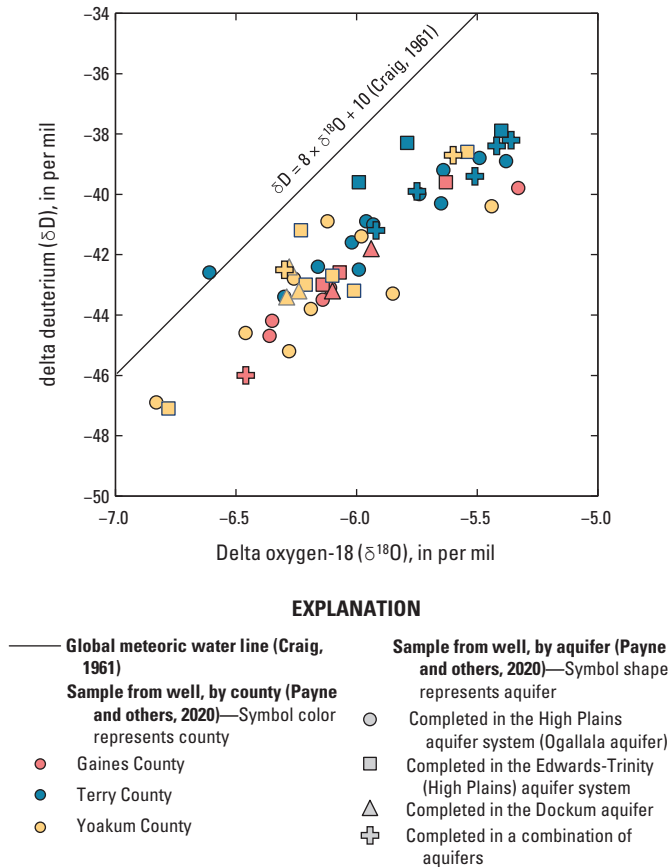
Figure 16. Relation between stable isotopes of hydrogen and oxygen in water-quality samples from groundwater wells in Gaines, Terry, and Yoakum Counties, Texas, 2014 and 2016.

Groundwater-Flow System

As explained in the "Purpose and Scope" section of this report, synoptic groundwater-level measurements were made within each of the aquifers to aid in the understanding of the groundwater-flow system. By carefully reviewing the well data to ensure each measurement was characterizing the correct aquifer, the groundwater measurement data were used to develop potentiometric-surface maps for each aquifer. Potentiometric-surface maps can be used to evaluate groundwater-level-altitude changes spatially and temporally, identify regional groundwater-flow paths and gradients, and compute vertical gradients between adjacent aquifer units (Freeze and Cherry, 1979; Fetter, 1988; Thomas and others, 2016).

Water-Level Measurements

Groundwater-level data were obtained during the dormant season, defined as November 2017 through April 2018 in this report, to represent the 2018 groundwater-level altitudes of the Ogallala, Edwards-Trinity (High Plains), and

Dockum aquifers. The dormant season is when groundwater withdrawals are typically lower compared to the rest of year because virtually all the groundwater is withdrawn for irrigation purposes during the growing season in the study area. Groundwater-level-altitude data collected during the dormant season were likely unaffected by drawdown and cones of depression from agricultural pumping (Heath, 1983). The water-level measurements within the Edwards-Trinity (High Plains) and Dockum aquifers were made by USGS personnel by using a calibrated steel tape or electric water-level tape in accordance with methods described in Cunningham and Schalk (2011). All groundwater-level measurements collected by the USGS were reviewed by USGS personnel and loaded into the NWIS (U.S. Geological Survey, 2020b). The groundwater levels measured for this report were complemented with additional compiled groundwater-level data collected from the Edwards-Trinity (High Plains) and Dockum aquifers during the same dormant season (Payne and others, 2020).

To ensure that recorded groundwater-level measurements were accurate, at least two groundwater-level measurements were made at each well while the well was not being pumped. If the two measurements did not agree within 0.02 ft, then one or more additional measurements were made. The measurement in which field personnel had the most confidence was used as the final value in the case where more than two measurements were made. After the groundwater-level-measurement data were collected, they were thoroughly evaluated and subsequently used for the construction of potentiometric-surface maps of groundwater-level altitudes. The groundwater-level measurements made or provided for this study are given in a companion data release (Payne and others, 2020).

Data Processing and Interpretation

Using geologic and well-construction data, the aquifer assignment (aquifer or aquifers in which a given well was completed) was determined on the basis of the following criteria, in order of priority: (1) the screened or open interval(s) of the well, (2) the total depth of the well, or (3) the aquifer of completion reported for a given well by the data source. Wells that were completed in a combination of aquifers were not used for the development of the potentiometric-surface maps. Thomas and others (2016) provide a detailed discussion on how the aquifer assignments were determined from these criteria.

Potentiometric-surface maps of groundwater-level altitudes were created to help assess spatial changes in groundwater across the study area and within each aquifer. The groundwater-level measurements were converted from depths below land surface to altitudes by subtracting the depths from the 3DEP (U.S. Geological Survey, 2017). Potentiometric-surface maps for the Edwards-Trinity (High Plains) and Dockum aquifers were created by using Oasis montaj (Seequent, 2020a), as described in Thomas and others (2016). Gridded surfaces of the groundwater-level altitudes

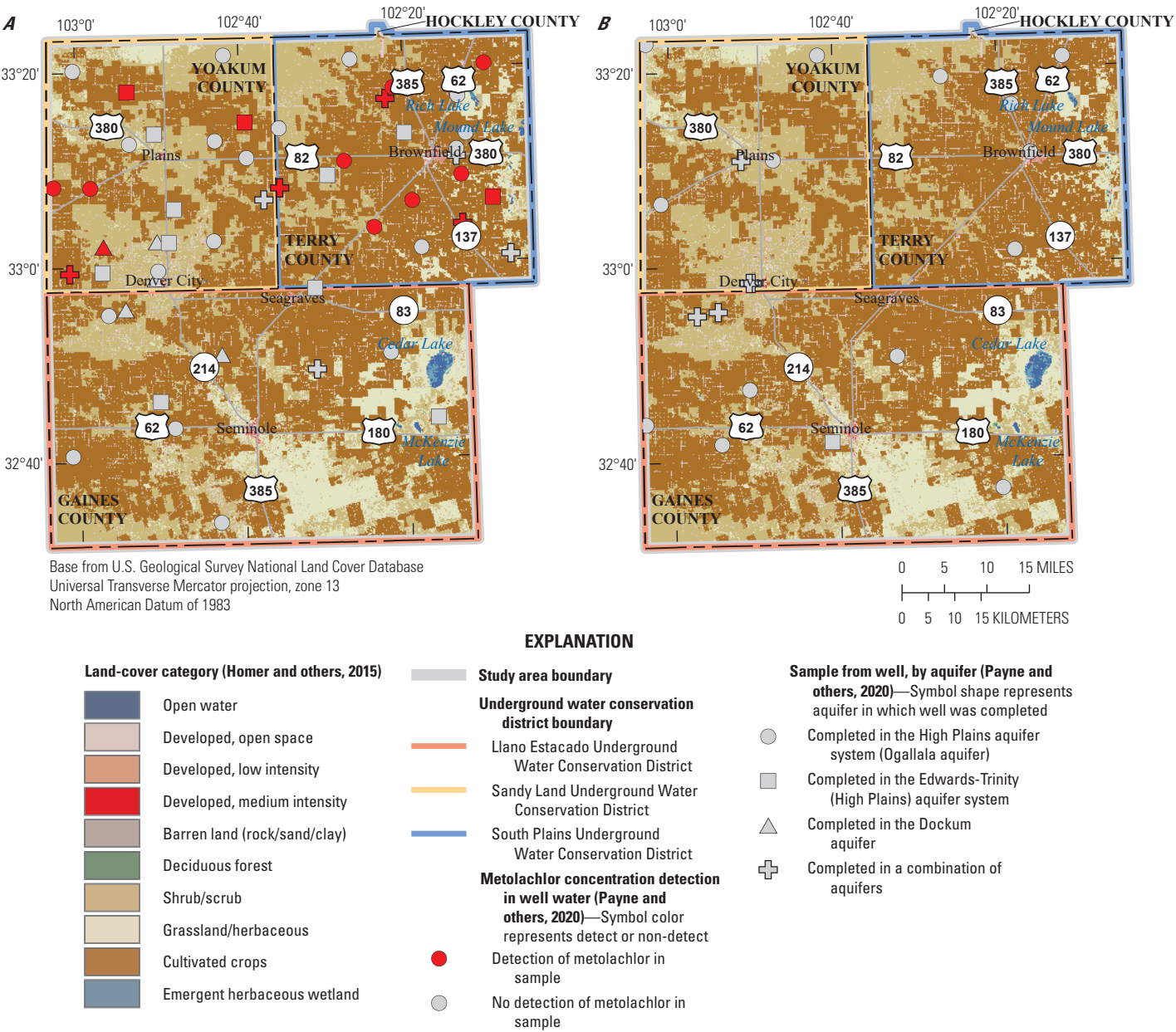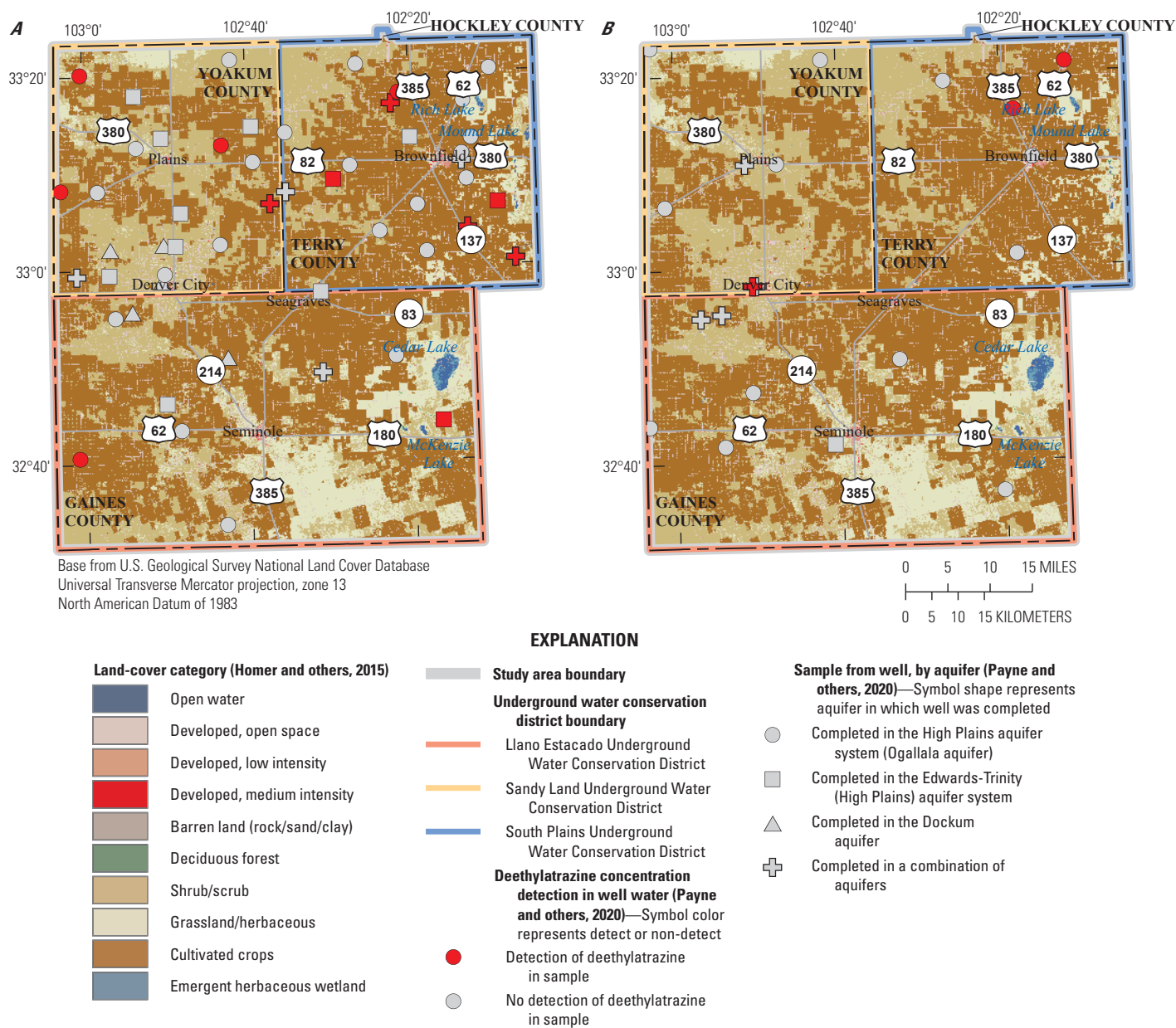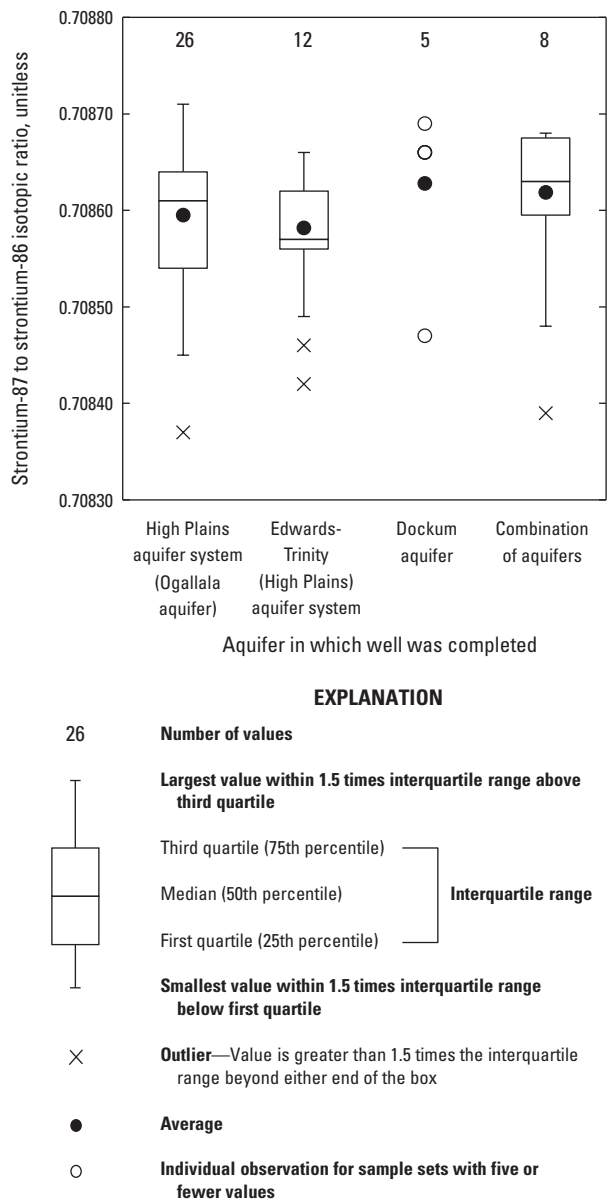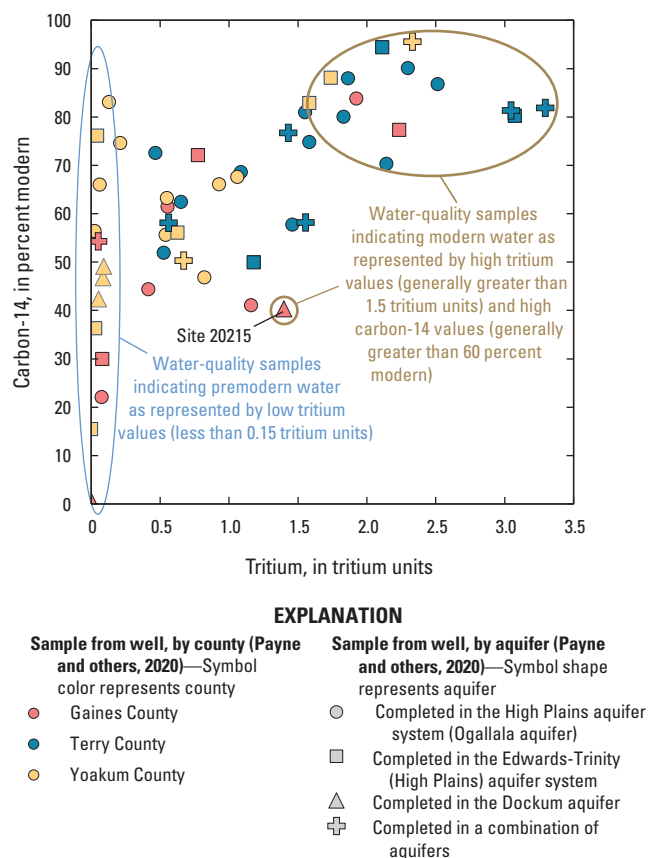**Figure 17.** Tritium and carbon-14 concentrations in water-quality samples from groundwater wells in Gaines, Terry, and Yoakum Counties, Texas, 2014 and 2016.

for the Edwards-Trinity (High Plains) and Dockum aquifers were prepared and reviewed for anomalies following methods described in Thomas and others (2016). In areas where anomalies were identified, groundwater-level altitudes were evaluated for consistency with nearby wells completed in the same aquifer. Outlying data were reviewed by comparing them with the original source data. If the original source data were deemed questionable, then the outlying data were removed. The potentiometric-surface map for the Ogallala aquifer was constructed by Brady and Bush (2018) using data collected by the UWCDs; the UWCDs also reviewed and maintained the data for the maps in machine-readable format. All of the data used to construct potentiometric surface maps for this study are provided in the companion data release for this report (Payne and others, 2020).

Regional Groundwater Flow

Potentiometric-surface maps for the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers were evaluated for spatial variability in groundwater-level altitudes and

regional groundwater-flow paths and gradients (fig. 19). Groundwater-level altitudes for the aquifers are generally higher in the northwestern part of the study area and lower in the southeastern part of the study area. Groundwater-flow paths generally have a northwest to southeast direction across the study area in each of the aquifers.

Ogallala Aquifer

The 2018 groundwater-level altitudes for the Ogallala aquifer are generally higher in the northwestern part of the study area and lower in the southeastern part of the study area, differing by more than 800 ft (fig. 19A) (Thomas and others, 2016; Brady and Bush, 2018; Payne and others, 2020). Groundwater-flow paths in the Ogallala aquifer follow the regional trend from northwest to southeast. Groundwater in Yoakum County flows towards the east or southeast except for the southwest corner of the county west of Denver City, Tex., where some groundwater flows towards the south (fig. 19A). As groundwater flows from Yoakum County into Terry County, it flows towards the southeast or south; groundwater flows more towards the south approaching the central and eastern part of Terry County (fig. 19A). Groundwater flow in Gaines County is generally towards the southeast; in some areas, flow is slightly to the east or south (fig. 19A).

Edwards-Trinity (High Plains) Aquifer

The paucity of wells completed in the Edwards-Trinity (High Plains) aquifer made it difficult to obtain a dataset similar to that for the Ogallala aquifer. Because of the small dataset for the Edwards-Trinity (High Plains) aquifer, inferences drawn from the potentiometric surface for this aquifer are more qualitative compared to the inferences drawn from the potentiometric-surface of Ogallala aquifer.

The recent groundwater-level altitudes for the Edwards-Trinity (High Plains) aquifer were greater than 3,700 ft in the northwestern part of the study area (fig. 19B) (Thomas and others, 2016; Payne and others, 2020), and the lowest altitudes were about 3,000 ft along the southeastern extent of the aquifer within the study area. Groundwater-level altitudes decline to the southeast in the Edwards-Trinity (High Plains) aquifer, indicating that groundwater flows from northwest to southeast. Some localized groundwater-flow paths were observed. West of Denver City, Tex., groundwater flows towards the south before flowing towards the east, south of Denver City, Tex. (fig. 19B). Groundwater in the north-central part of the study area flows east from Yoakum County into Terry County, and then flows initially to the southeast towards Brownfield, Tex. (fig. 19B), before transitioning to a more easterly direction.
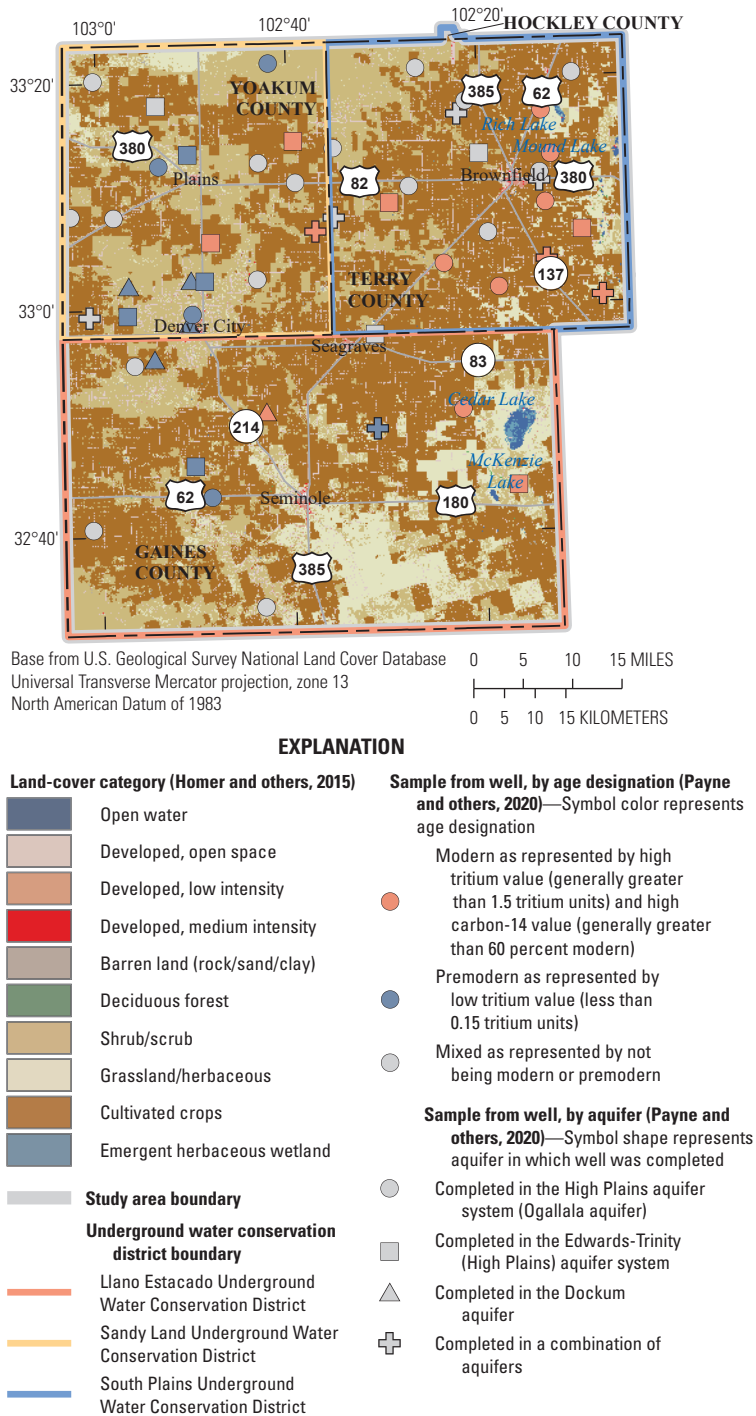
Figure 18. Relative ages of groundwater in Gaines, Terry, and Yoakum Counties, Texas, 2014 and 2016.

Figure 19. Potentiometric surfaces developed from groundwater-level altitudes measured during the dormant season (November 2017 through April 2018) in wells completed in *A*, the Ogallala aquifer (Brady and Bush, 2018), *B*, the Edwards-Trinity (High Plains) aquifer system, and *C*, the Dockum aquifer in and near Gaines, Terry, and Yoakum Counties, Texas.

Dockum Aquifer

The number of wells completed in the Dockum aquifer was substantially less than the number of wells completed in the Ogallala and Edwards-Trinity (High Plains) aquifers. Groundwater-level-altitude data were primarily from wells in Gaines County, with only a couple measurements in the northern part of the study area. The few data that were available were used to provide generalized insights regarding groundwater-flow gradients within the Dockum aquifer.

Similar to the Ogallala and Edwards-Trinity (High Plains) aquifers, groundwater-level altitudes for the Dockum aquifer were highest in the northwest of the data extent, at more than 3,700 ft, and lowest in the southeastern Gaines County, at about 2,900 ft (fig. 19C) (Thomas and others, 2016; Payne and others, 2020). This altitude difference indicates regional groundwater-flow paths for the Dockum aquifer are from the northwest to the southeast of the study area (fig. 19C).

Aquifer Hydraulic Properties

Understanding the hydraulic properties of an aquifer system is critical to characterizing the ability of the system to transmit (transmissivity and hydraulic conductivity) and store (specific yield) water (Lohman, 1979; Heath, 1983; Fetter, 1988). Transmissivity is defined as the rate at which water is transmitted horizontally through a unit width of an aquifer under a unit hydraulic gradient. The hydraulic conductivity, also called the coefficient of permeability, of an aquifer is the transmissivity divided by the aquifer thickness (or saturated thickness if unconfined). Higher hydraulic-conductivity values correlate with higher yields and less drawdown in a well (Heath, 1983). Specific yield is the volumetric fraction of the bulk aquifer volume that a given aquifer will yield when all the water is allowed to drain out of it under the forces of gravity (Bear, 1979). The lower the specific yield, the deeper the drawdown in a well for a given pumping rate (Heath, 1983). Total porosity, the fraction of the soil or rock volume that is occupied by pore space, is the void space of a rock or unconsolidated material and is equal to the specific yield (effective porosity) plus specific retention, or water retained because of capillary or other forces. In general, the total porosity is a measure of the total subsurface water content, effective porosity is the water held in larger pores available for production, and specific retention is water held in smaller pores too tight to produce. Historical aquifer-test data were used in conjunction with borehole EM flowmeter and nuclear magnetic resonance (NMR) measurements and surface geophysical TDEM sounding data collected for this study (fig. 2) to estimate transmissivity and total porosity, which were then used to estimate the hydraulic conductivity and specific yield of the aquifers. All aquifer-test data were in the form of single-well pumping tests rather than the traditional collection of multiple measurements involving several wells (Stallman, 1971).

Data Compilation

Hydraulic-property data were compiled for the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers in and near Gaines, Terry, and Yoakum Counties. A 5-mile buffer was created around the study area to prevent gridding errors near the study area boundary. Aquifer-test data collected at more than 1,950 groundwater wells were compiled from databases maintained by the USGS (U.S. Geological Survey, 2020b), the Texas Water Development Board (Texas Water Development Board, 2020c; Texas Water Development Board, 2020d; Texas Water Development Board, 2020e), and SPUWCD (South Plains Underground Water Conservation District, written commun., 2020) and data from Payne and others (2020). Transmissivity of a well was estimated using Driscoll's equation for an unconfined aquifer (Driscoll, 1986, appendix 16D). Driscoll's equation is

$$T = 1{,}500 \times Q/s \qquad (4)$$

where

T	is transmissivity in gallons per day per foot of drawdown;
Q	is well yield or pumping rate in gallons per minute; and
s	is drawdown at any point in the vicinity of a well discharging at a constant rate in feet.

Transmissivity values were estimated from the historical aquifer-test data that had both a pump rate or yield and a drawdown, using the methods outlined in Bumgarner and others (2012).

Data Collection

Aquifer tests are done to assess the hydraulic properties of water-bearing and associated rocks (Stallman, 1971). Seven single-well aquifer tests were completed with ambient and pumping borehole EM flowmeter measurements made by the USGS in March 2017 (table 4) (Payne and others, 2020; U.S. Geological Survey, 2020a). Additionally, borehole NMR measurements were made at six wells by the USGS in April 2018 (table 4) (Payne and others, 2020; U.S. Geological Survey, 2020a). Borehole EM induction data were collected at the same wells where the borehole NMR measurements were made (some borehole EM induction logs were made prior to the measurements in August 2012) (table 4). Borehole geophysical tools used in the data collection for this study were interfaced to a Century System VI, a Mount Sopris Matrix, or a Vista Clara Javelin Wireline log-acquisition system. Limitations, calibration procedures, and algorithms of the logging tools are described by the manufacturers (Century Geophysical Corporation, 2020; Mount Sopris Instruments, 2020; Vista Clara Inc., 2020).

Table 4.   Selected well completion information, aquifer designation, borehole geophysical method, and measurement date for borehole geophysical data collected from wells in and near Gaines, Terry, and Yoakum Counties, Texas.

[USGS, U.S. Geological Survey; bls, below land surface; EM, electromagnetic; NMR, nuclear magnetic resonance; OGLL, High Plains aquifer system (Ogallala aquifer); ETHP; Edwards-Trinity (High Plains) aquifer system; DOCK, Dockum aquifer; COMB, Combination; --, no value]

Site identifier	USGS well number	County	Well depth (feet bls)	Screened or open interval (feet bls)	Aquifer in which the well is completed	Aquifer designation	Geophysical method	Measurement date
02099	324151102175901	Gaines	210	--	DOCK	DOCK	EM induction, NMR	2/12/2014, 4/6/2018
02207	325034102215501	Gaines	80	--	OGLL	OGLL	EM induction	2/12/2014
02342	324006102223901	Gaines	132	--	DOCK	DOCK	EM induction	4/3/2013
02408	324035102243801	Gaines	118	58–118	OGLL	OGLL	EM induction	4/3/2013
02455	324000102223501	Gaines	118	--	OGLL	OGLL	EM induction	4/3/2013
02508	324025102242001	Gaines	116	--	OGLL	OGLL	EM induction	4/3/2013
02985	323840102275101	Gaines	187	145–187	OGLL; DOCK	COMB	EM induction	4/3/2013
03074	323246102333401	Gaines	130	50–130	OGLL	OGLL	EM induction	4/4/2013
03698	323247102335501	Gaines	145	--	OGLL	OGLL	EM induction	4/4/2013
04563	323254102314501	Gaines	124	50–124	OGLL; DOCK	COMB	EM induction	4/4/2013
05090	325431102215901	Gaines	108	78–108	OGLL; ETHP	COMB	EM induction	4/4/2013
06427	324337102315801	Gaines	163	--	DOCK	DOCK	EM induction	4/4/2013
10091	331615102351001	Terry	119	--	OGLL	OGLL	EM induction, EM flowmeter	8/21/2012, 3/16/2017
10118	331756102213501	Terry	370	110–160, 330–370	OGLL; ETHP	COMB	EM induction	3/28/2012
10446	330554102081101	Terry	260	60–260	ETHP	ETHP	EM induction, EM flowmeter	3/29/2012, 3/18/2017
10793	325755102232901	Terry	270	100–270	OGLL; ETHP	COMB	EM induction	3/29/2012
11025	324659102423401	Gaines	207	107–207	OGLL; ETHP	COMB	EM induction	8/23/2012
11071	324623102321401	Gaines	211	86–211	OGLL; ETHP	COMB	EM induction	4/4/2013
11111	325033102192701	Gaines	82	--	OGLL	OGLL	EM induction	4/4/2013
11349	324243102245701	Gaines	117	26–117	OGLL; ETHP	COMB	EM induction	4/2/2013
11520	323720102245701	Gaines	125	--	DOCK	DOCK	EM induction	4/2/2013
11541	323455102285901	Gaines	127	--	DOCK	DOCK	EM induction	4/3/2013
11542	323402102260401	Gaines	149	--	OGLL	OGLL	EM induction	4/2/2013
11642	330037102071801	Terry	250	210–250	ETHP; DOCK	COMB	EM induction	8/22/2012
11643	330037102073801	Terry	210	170–210	ETHP	ETHP	EM induction, EM flowmeter	8/22/2012, 3/20/2017
11644	331410102281601	Terry	358	155–358	ETHP; DOCK	COMB	EM induction, EM flowmeter	8/21/2012, 3/17/2017
11650	323243102452501	Gaines	1,720	920–1,720	DOCK	DOCK	EM induction	8/23/2012

Table 4. Selected well completion information, aquifer designation, borehole geophysical method, and measurement date for borehole geophysical data collected from wells in and near Gaines, Terry, and Yoakum Counties, Texas.—Continued

[USGS, U.S. Geological Survey; bls, below land surface; EM, electromagnetic; NMR, nuclear magnetic resonance; OGLL, High Plains aquifer system (Ogallala aquifer); ETHP; Edwards-Trinity (High Plains) aquifer system; DOCK, Dockum aquifer; COMB, Combination; --, no value]

Site identifier	USGS well number	County	Well depth (feet bls)	Screened or open interval (feet bls)	Aquifer in which the well is completed	Aquifer designation	Geophysical method	Measurement date
11657	323922102430701	Gaines	184	104–184	OGLL; ETHP; DOCK	COMB	EM induction	8/23/2012
11659	324000102555501	Gaines	213	--	DOCK	DOCK	EM induction	8/23/2012
11702	325419102550601	Gaines	265	145–265	OGLL; ETHP; DOCK	COMB	EM induction, EM flowmeter	8/23/2012, 3/22/2017
11708	325535102351001	Gaines	175	115–175	OGLL; ETHP	COMB	EM induction	8/23/2012
11715	325812102190401	Terry	250	90–150, 210–250	OGLL; ETHP	COMB	EM induction, EM flowmeter	8/22/2012, 3/19/2017
11771	331045102133901	Terry	340	80–100, 300–340	OGLL; ETHP	COMB	EM induction, NMR	8/22/2012, 4/6/2018
11801	331954102260401	Terry	406	366–406	ETHP; DOCK	COMB	EM induction	8/22/2012
20887	331511102250101	Terry	383	343–383	ETHP; DOCK	COMB	EM induction	8/22/2012
22528	331409102304201	Terry	174	134–174	OGLL	OGLL	EM induction, NMR	4/5/2018, 4/5/2018
31080	324752102384001	Gaines	238	--	ETHP	ETHP	EM induction, NMR	4/4/2018, 4/4/2018
32047	324700102525601	Gaines	227	--	ETHP	ETHP	EM induction, NMR	4/4/2018, 4/4/2018
32266	330319102413501	Yoakum	268	--	ETHP	ETHP	EM induction, NMR	4/5/2018, 4/5/2018
32749	330631102455801	Yoakum	372	--	ETHP	ETHP	EM induction, EM flowmeter	3/21/2017, 3/21/2017

Borehole geophysical data collection by the USGS followed ASTM borehole geophysical standard procedures (American Society of Testing and Materials, 2004; American Society of Testing and Materials, 2007; American Society of Testing and Materials, 2010). During collection, the data were recorded in binary formats by their appropriate log-acquisition system and were converted to, and archived as, Log American Standard Code for Information Interchange Standard (LAS) files (Canadian Well Logging Society, 2020) for tabular data and presented as chart logs in Portable Document Format (PDF). The LAS, PDF, original binary, and image files of the borehole data are available on the USGS GeoLog Locator (U.S. Geological Survey, 2020a).

Borehole Electromagnetic Flowmeter

The EM flowmeter measures the rate and direction of vertical flow in a borehole by using the principle of Faraday's law of induction. Comprehensive descriptions of the theory and application of EM flowmeter are presented in Kaufman and Dashevsky (2003) and Kaufman and Itskovich (2017). The EM flowmeter data were collected in the boreholes at various stationary locations throughout the water column and by raising and lowering the EM flowmeter through the length of the water column, following a methodology similar to that described in Thomas and others (2012). Stationary and moving EM flowmeter data were collected during ambient and stressed, or pumping, conditions. When possible, EM flowmeter data were collected at the same depths during ambient and stressed conditions.

Borehole Nuclear Magnetic Resonance Sounding

Borehole NMR is a non-invasive geophysical technique that directly measures water content in the subsurface by detecting the behavior of water responding to magnetic fields applied by the borehole geophysical tool (Kenyon and others, 1995). NMR data were used to define properties of the aquifers and to measure total porosity, effective porosity, and specific retention in the study area. The principles and applications of the NMR method are summarized by Weichman and others (2000), Legchenko and others (2006), Plata and Rubio (2008), Walbrecker and others (2009), Walsh and others (2013), and Kass and others (2014).

The NMR geophysical tool used for this investigation was a wireline Javelin JPX-350 developed by Vista Clara Inc. (Vista Clara Inc., 2020). The tool is approximately 15 feet long and has a diameter of 3.5 inches. The diameter of sensitivity of the instrument ranges from 10 to 15 inches from the center of the tool; the well construction must be considered so as not to include the annular space in the measurement. Because the NMR instrument detects water content through the manipulation of magnetic fields, any metallic material within the immediate vicinity of the instrument, such as steel casing or centralizers will also render the measurements from the tool unusable in that area. Open-hole wells with a diameter of 4 to 8 inches were targeted for data collection. Because few open-hole wells were available in the study area, polyvinyl chloride (PVC) cased wells were primarily used for the NMR data collection.

For this study, continuous data collection techniques were utilized; vertical resolution is spread out across the traveled distance of the logging tool throughout the depth of the well during data collection, which was done by using traversal rates of about 100 to 160 feet per hour as recommended by the tool manufacturer (Vista Clara Inc., 2020). Vertical resolution for the NMR logs in this study ranges from 1.5 to 5.0 feet. The logging tool measured the magnitude and rate of the T_2 decay, the signal response associated with the T_2 relaxation time. The T_2 relaxation time is a time constant that is associated with the decay of the magnetized field in the direction perpendicular to the background field (Dlubac and others, 2013). The magnitude of the T_2 decay is directly proportional to the amount of water in the measurement area (Hull and others, 2019). The rate of the T_2 decay indicates the relative pore size distribution in the measurement area, with faster T_2 decays related to smaller pore size. The data collection methods are similar to those described in Hull and others (2019).

Borehole Electromagnetic Induction

EM induction tools measure conductivity in air- or water-filled wells and are effective in open-hole or PVC-cased wells. Explanation of how conductivity values are computed from EM induction tools is provided by Keys (1997). The measurement of conductivity commonly is reciprocated to provide logs with curves of resistivity and conductivity (Keys, 1997). A Century Geophysical Corporation 9510 or a Century Geophysical Corporation 9512 EM induction conductivity probe was calibrated and used to the manufacturer's specifications (Century Geophysical Corporation, 2020). Evaluation of the induction data from the Century Geophysical Corporation 9510 tool revealed lower than expected values, so the instrument was recalibrated. The original values from the Century Geophysical Corporation 9512 EM induction tool and the recalibrated values from the Century Geophysical Corporation 9510 EM induction tool were used find a correlation between resistivity and total porosity from the borehole NMR. The borehole EM induction results were systematically corrected to a temperature of 77 °F (25 °C).

Methods

After data compilation and collection, the data needed to be processed further to obtain the desired aquifer properties of hydraulic conductivity and specific yield. The compiled historical aquifer-test data and the borehole EM flowmeter data were used to estimate the hydraulic conductivity, and the borehole NMR was used to estimate hydraulic conductivity and specific yield. The surface geophysical TDEM data were used to estimate the specific yield.

Compiled Data

Hydraulic-conductivity values were estimated from the historical aquifer-test data. If a groundwater-level measurement was made in conjunction with the historical aquifer-test data, that groundwater-level measurement was used with the well completion data to determine the saturated thickness of the aquifer. The saturated thickness obtained during the aquifer test can be described by one of four scenarios: (1) the well opening, or screened interval, is contained within the saturated part of the aquifer making the saturated thickness the length of the well opening, or screened interval; (2) the water table is above the well opening, or screened interval, and the base of the aquifer is within the well opening, or screened interval, making the saturated thickness the difference between the altitude of the top of the well opening and the altitude of the base of the aquifer; (3) the water table is within the well opening, or screened interval, and the base of the aquifer is below the well opening, or screened interval, making the saturated thickness the difference between the altitude of the water table and the altitude to the bottom of the well opening, or screened interval; and (4) the entire saturated part of the aquifer is contained within the well opening, or screened interval, making the saturated thickness the difference between the water-table altitude and the altitude of the base of the aquifer. The hydraulic conductivities were computed by dividing the transmissivity by the saturated thickness determined from one of the four scenarios. In the case of the second and fourth scenarios, there

would be an influence from another geologic formation, so the hydraulic conductivities were noted to come from a combination of aquifers and were not used for the analysis.

If the historical aquifer-test data did not include a groundwater-level measurement, the date of the aquifer test was used to estimate the groundwater-level at the time of the test. First, all the historical groundwater-level measurements at the aquifer-test wells were evaluated. If a groundwater-level measurement made within 1 year prior to or after the aquifer-test date was available (wells are typically measured annually in the study area, so the closest temporal measurements should be about 1 year apart), that groundwater-level measurement was used to estimate the saturated thickness for the aquifer-test data. If there were no groundwater-level measurements within this 2-year timeframe for the well, then a median groundwater-level altitude was computed on the basis of measurements made for the 10 nearest wells. The median groundwater-level altitude was then used to estimate the saturated thickness for the aquifer-test data. The hydraulic-conductivity value was then computed by using this estimated saturated thickness value.

Some of the historical aquifer-test data were collected over multiple years from the same wells, resulting in multiple hydraulic-conductivity values for these wells. In theory, hydraulic conductivity should not change over time as long as the physical conditions of the soil and water do not change (Kirkham, 2014), but in practice, the hydraulic conductivity can change slightly over time because of chemical and physical processes such as ion exchange processes, changes in chemical concentrations in the water, swelling of clay, and migration of clay particles (Hillel, 2008). In most cases, when there were multiple hydraulic-conductivity values for a given well, most of the hydraulic-conductivity values were relatively similar (within about one order of magnitude). Although the hydraulic-conductivity values were relatively similar, the hydraulic-conductivity values collected most recently were used in the final analysis for wells where aquifer tests were completed over multiple years. Because hydraulic conductivity is not expected to change appreciably over time, a dataset with a large time range should not skew the results.

Borehole Flowmeter

To process the borehole EM flowmeter data and compute different zones of transmissivity and hydraulic heads for the open section of the borehole, the Flow-Log Analysis of Single Holes (FLASH) numerical model was used (Day-Lewis and others, 2011), which is similar to the numerical model used in Thomas and others (2012). FLASH produces multilayered models utilizing the Thiem equation to create an analytical solution for steady-state flow in a borehole (Day-Lewis and others, 2011). FLASH generates numerical borehole flow data representing the theoretical flow that would be measured in a borehole given a specified number of transmissive zones and head values for parts of the aquifer not affected by nearby pumping. Several hydraulic properties, including total

transmissivity or radius of influence (the distance for which the well can affect or be affected by its surroundings), are entered into FLASH to solve the multilayered model and compute the output values (transmissivities and hydraulic heads) for each transmissive zone. For this study, an estimated total transmissivity, based on the difference in measured drawdown between ambient and pumping conditions and computed using Driscoll's equation, was used to model the radius of influence (Driscoll, 1986, appendix 16D).

The total transmissivity for an aquifer was obtained by adding the transmissivity from each modeled zone within the aquifer. The total transmissivity was then divided by the saturated thickness of the aquifer, using the groundwater-level measurement made prior to flowmeter data collection, to get a hydraulic-conductivity value for the aquifer.

Borehole Nuclear Magnetic Resonance

The NMR method, which measures the response of the water molecules directly, was used to estimate the hydraulic conductivity and the specific yield of the aquifer simultaneously. The NMR data were processed using the manufacturer's software (Vista Clara Javelin ProPlus version 3.7). Frequency measurements containing greater than 15-percent residual noise were removed. The T_2-decay data from the resulting frequency measurements were filtered using an impulse noise filter and were adjusted by removing the ambient noise, collected with an external reference coil, measured concurrently at the land surface. Depth-averaging over three measurements was applied to smooth the data and dampen the effects of any suspicious measurements. The four frequency measurements for each log in the study were "noise-stacked," meaning that they were combined in proportion to their relative noise. After the frequency data were combined, the resultant T_2 decay was modeled with a multiexponential decay curve. The modeling results produce a pore-size distribution model shown as a fraction of the total water content, which is the sum of the mobile-, capillary-, and bound-water fractions. The mobile-, capillary-, and bound-water fractions (fractions of the total porosity) were determined by using empirically derived cutoff values of T_2 relaxation times (Straley and others, 1997). Software defaults for capillary- and bound-water are 33 and 4 milliseconds, respectively, and are generally accepted as robust cutoff values (Timur, 1969; Walsh and others, 2013; Behroozmand and others, 2015).

Hydraulic-conductivity values were estimated from the NMR data by using the Schlumberger-Doll research equation (Kenyon and others, 1988). Because the borehole NMR method is not limited to the open section of the well, the average hydraulic-conductivity value for the saturated part of the aquifer, regardless of well opening or screened interval, was used to represent the hydraulic conductivity of the aquifer at the well location. The average mobile-water fraction of the total porosity for the saturated part of the aquifer, regardless of well opening or screened interval, was used to represent the specific yield of the aquifer at the well location.

Time-Domain Electromagnetic Soundings

A set of processes was needed to convert bulk resistivity from the TDEM to specific yields. Resistivity was related to total porosity by using Archie's equation to form a regression between the borehole EM induction and borehole NMR data, and specific yield was estimated from total porosity by applying a factor found from the borehole NMR data. Fluid resistivity is needed for Archie's equation, so historical specific conductivity values from water-quality data were used to estimate the fluid resistivity throughout the study area.

Resistivity and Total Porosity Regression Equation

Because of the relatively extensive spatial extent of the TDEM data relative to other data types that can be used to derive specific yield, the inverse modeling results of the TDEM data were used to provide a rough estimate of the specific yield throughout the study area. In order for TDEM data to provide useful specific yield estimates, a meaningful correlation must exist between bulk resistivity and total porosity. The total porosity, as opposed to the effective porosity, was used for statistical analysis because the TDEM soundings measure bulk resistivity of the subsurface, which would include all components of the total porosity. Archie (1952) shows a relation between porosity (Φ) and the formation factor (F) of the subsurface, which is the bulk resistivity of the subsurface divided by the fluid resistivity. For the scenario where the subsurface is filled with water only (as opposed to hydrocarbons or other fluids), Archie's equation reduces to

$$F = \frac{a}{\Phi^m} \qquad (5)$$

where

a is the tortuosity factor and

m is the cementation exponent; both constants are unitless.

Using Archie's equation, the borehole NMR total porosity results, the borehole EM induction results, and the fluid conductivity (inverse of resistivity) results were used to determine the relation between the formation factor (the borehole EM induction divided by the fluid resistivity) and total porosity. Fitting a non-linear curve using the power equation to the borehole NMR porosity and the formation factor, a regression equation was found for each hydrogeologic unit in the study area (fig. 20). The hydrogeologic unit was used in the analysis instead of the individual aquifers because of the contrast of geologic material between the Trinity and Fredericksburg Groups. The goodness-of-fit of the regression models, as indicated by the R-squared (coefficient of determination; R^2) values (Helsel and others, 2020), of the Dockum Group (R^2 value of 0.2133), Fredericksburg Group (R^2 value of 0.3892), and Ogallala Formation (R^2 value of 0.2566) are fair considering Archie's equation was developed for a clean, consolidated sand. The fit of the regression model of the Trinity Group (R^2 value of 0.0791) is poor. A different regression equation should be used to estimate the total porosity for all geologic formations within the study area considering the effect of clays and carbonates on estimating the porosity from resistivity (Crain, 2019). However, because of the lack of a sediment grain-size analysis to provide estimates of tortuosity factor and cementation exponent, and because of the lack of additional information to fulfill the variables found in equations such as the Waxman-Smits equation (Waxman and Smits, 1968) or others listed in Kadhim and others (2013), the relation derived from the Archie's equation was used for a rough estimate of total porosity in the study area. Computing the estimated total porosity values from the regression equations and comparing them with the measured total porosity values from the borehole NMR, the resulting correlation fit is fair (0.1896) with the expected one-to-one relation between the measured and the estimated results (fig. 21).

Effective Porosity and Total Porosity Regression

Effective porosity values were estimated by using regression models developed between the total porosity and the mobile-water fraction of the total porosity measured from the borehole NMR results. Fitting a straight line to the total porosity and the mobile-water fraction of the total porosity, a linear regression equation was computed for each geologic formation in the study area (fig. 22). The goodness-of-fit values of the regression models of the Dockum Group (R^2 value of 0.6872), Trinity Group (R^2 value of 0.6877), and Ogallala Formation (R^2 value of 0.5140) are good; the fit of the Fredericksburg Group (R^2 value of 0.0160) is poor. The slope of the regression equation of the Fredericksburg Group was near 0 (0.0847), indicating a near constant value of effective porosity for all measured total porosity values. Therefore, the estimated effective porosity for the Fredericksburg Group was set as 0.01 on the basis of the average effective porosity values from the borehole NMR results after removing high effective porosity outliers (greater than 0.05) from the dataset.

Absolute differences between the measured mobile-water fraction of the total porosity and the estimated effective porosity were plotted against formation factor. The lower the formation factor, the higher the variability (fig. 23). When the formation factor is less than 4, the maximum variability (disregarding outliers represented as the highest 5 percent of values) in the differences between the measured mobile-water fraction of the total porosity and the estimated effective porosity was about 0.15 (unitless), whereas when the formation factor is equal to or greater than 4, the maximum variability (disregarding the highest 5 percent of values) in the differences between the measured mobile-water fraction of the total porosity and the estimated effective porosity was about 0.05 (unitless). Generally, the more accurate estimates of effective porosity are in locations where the formation factor is higher. For formation factors of less than 4, the preponderance of fine-grained sediments such as silts and clays can make it hard to distinguish between fine-grained sediments and saturated sediments with low fluid resistivity. The lack of ability to distinguish between fine-grained sediments and saturated sediments with

EXPLANATION

—— **Dockum Group regression**	$\Phi = 0.2642F^{-0.379}$	$R^2 = 0.2133$
—— **Trinity Group regression**	$\Phi = 0.2616F^{-0.272}$	$R^2 = 0.0791$
—— **Fredericksburg Group regression**	$\Phi = 0.2026F^{-0.281}$	$R^2 = 0.3892$
—— **Ogallala Formation regression**	$\Phi = 0.2176F^{-0.240}$	$R^2 = 0.2566$

Measurement from borehole geophysical data, by hydrogeologic unit (U.S. Geological Survey, 2020a)

○ Dockum Group
○ Trinity Group
○ Fredericksburg Group
○ Ogallala Formation
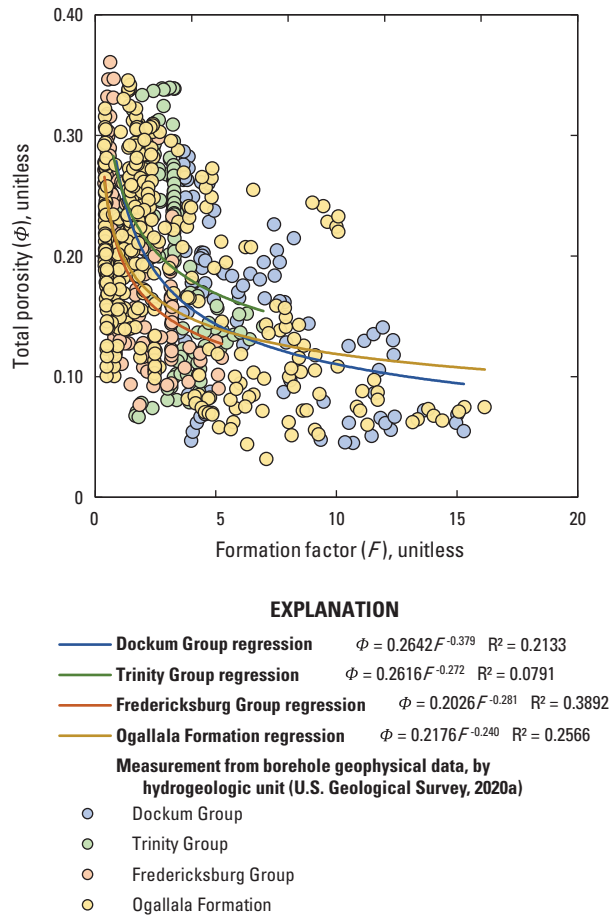
Figure 20. Relation between the borehole nuclear magnetic resonance total porosity and the formation factor computed from the borehole electromagnetic induction and fluid conductivity logs for wells in Gaines, Terry, and Yoakum Counties, Texas, 2012–18. (R^2 is the coefficient of determination.)

low fluid resistivity results in less accuracy with a low formation factor. The formation factor was used to estimate the variability of the effective porosity (effective porosity variability values) for the study area aquifers. The effective porosity variability values represent a value range (plus or minus) from the estimated effective porosity at any location.

Application of Regression Equations to the Time-Domain Electromagnetic Sounding Data

The TDEM resistivity soundings were temperature corrected by comparing the inverse modeling results with the borehole EM induction logs. TDEM inverse modeling results were also corrected for the geothermal gradient (Nathenson and Guffanti, 1988). The temperature at depth was estimated by using a surface temperature set as the monthly average air temperature during the month that the data were collected (National Oceanic and Atmospheric Administration, 2020) and a subsurface gradient of 77 °F per 3,280 ft (25 °C per 1 kilometer) (Nathenson and Guffanti, 1988). The inverse

EXPLANATION

Measurement (U.S. Geological Survey, 2020a) and estimate from borehole geophysical data, by hydrogeologic unit

○ Dockum Group
○ Trinity Group
○ Fredericksburg Group
○ Ogallala Formation
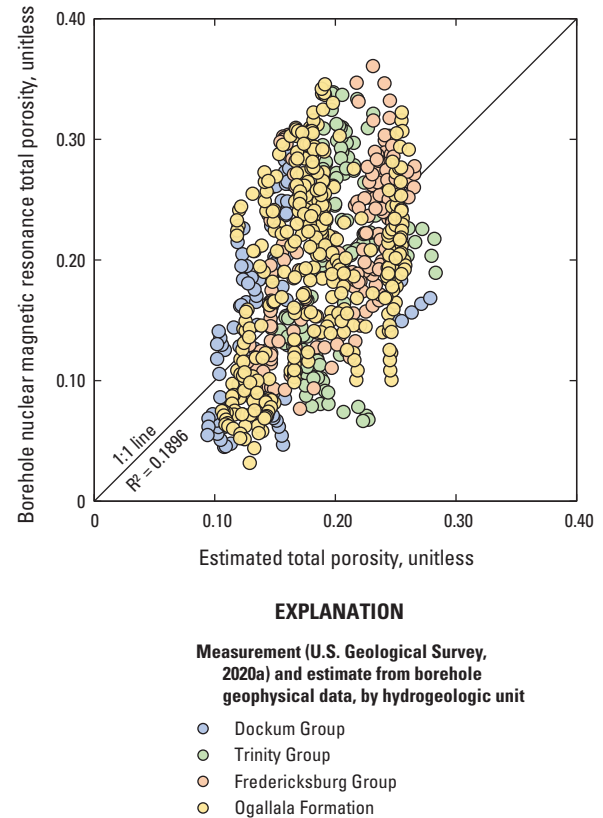
Figure 21. Relation between the borehole nuclear magnetic resonance total porosity and the estimated total porosity from the formation factor computed from the borehole electromagnetic induction and fluid conductivity logs for wells in Gaines, Terry, and Yoakum Counties, Texas, 2012–18. (R^2 is the coefficient of determination.)

modeling results of the TDEM soundings were adjusted according to Arps equation (Arps, 1945; Arps, 1956) using these temperatures.

The borehole EM induction results were compared to the nearest temperature corrected inverse modeling results of the TDEM soundings to ensure that the results from the TDEM soundings could be used to estimate effective porosity from a regression model of the borehole EM induction results. This comparison showed that the median difference between the borehole EM induction and the temperature corrected inverse modeling results of the TDEM was about -0.7 ohm-meters (ohm-m). The interquartile range of the differences was -13.9 to 8.9 ohm-m. The interquartile range shows that there is some variability between the borehole EM induction and the temperature corrected inverse modeling results of the TDEM soundings, but the regression fit is considered reasonable by the authors. The observed variability is most likely a result of the high vertical resolution of the borehole EM induction with depth relative to the bulk resistivity with depth from the TDEM soundings. At higher resistivities (where most of the variability is observed), the effect on the effective porosity is minimal (plus or minus 0.05).
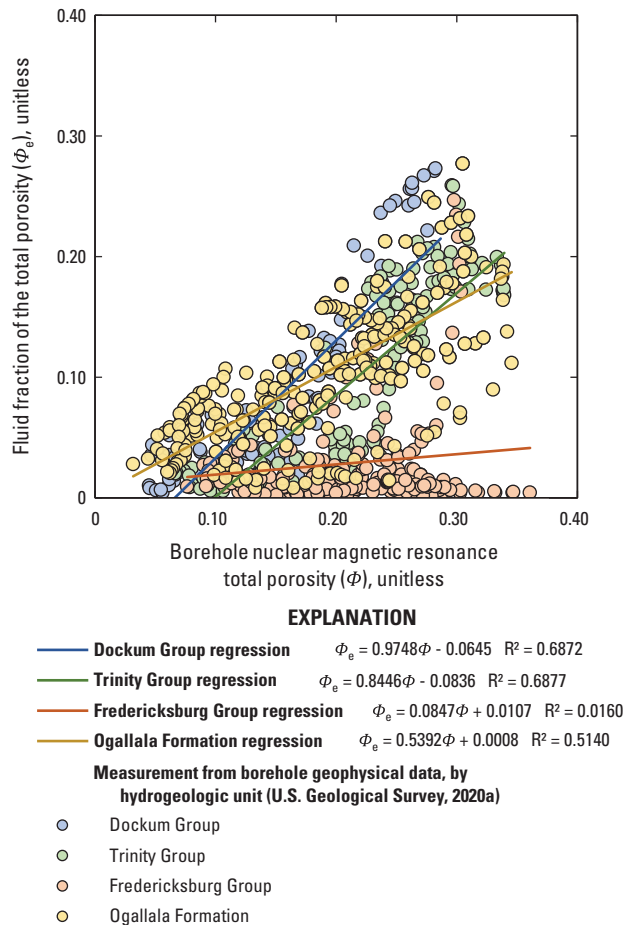
Figure 22. Relation between the borehole nuclear magnetic resonance total porosity and fluid fraction of the total porosity for wells in Gaines, Terry, and Yoakum Counties, Texas, 2012–18. (R^2 is the coefficient of determination.)

Figure 23. Relation between the absolute difference of the mobile-water fraction of the borehole nuclear magnetic resonance total porosity with the estimated effective porosity and the formation factor for wells in Gaines, Terry, and Yoakum Counties, Texas, 2012–18.

A fluid resistivity is needed to compute the formation factor at each TDEM location. Specific conductance values compiled using the historical water-quality data (Payne and others, 2020) were used to estimate the fluid resistivity throughout the study area. All specific conductance values measured during the time period of this study were used. An analysis of historical specific conductance values with depth showed that there was very little variability as a function of depth within the top 500 ft below land surface at any given location. There was more variability as a function of geographic location than depth, an assertion confirmed with the specific conductance measurements made in conjunction with the water-quality sampling and the borehole fluid conductivity data collected during this study. Because of the lack of change with depth, a grid of the specific conductance values at less than a depth of 500 ft was used to represent fluid resistivity throughout the study area. The median specific conductance value for each well was computed, and then a grid was developed by using the kriging method as described in Thomas and others (2019, p. 8); a larger 16,400-ft by 16,400-ft (5,000-m by 5,000-m)

cell size was used, although a cell size of 1,640 ft by 1,640 ft (500 m by 500 m) was used in other surfaces in this report because of the coarse spacing of the data available for this analysis. The grid was sampled for the specific conductance value at each TDEM sounding location; the specific conductance value was converted to a fluid resistivity value and used to compute the formation factor from the inverse modeling results of the TDEM sounding data.

Effective porosity and effective porosity variability values were estimated by using the formation factor computed from the inverse modeling results of the TDEM sounding data. Values greater than the water-table altitude (at the time of TDEM data collection) were ignored in the analysis. A depth-weighted average of the effective porosity and effective porosity variability values was computed from the inverse modeling results of the TDEM sounding data for each aquifer in each TDEM sounding. The estimated effective porosity and effective porosity variability were used to estimate the specific yield and the specific yield variability values for the study area aquifers. The specific yield variability represents a value range (plus or minus) from the estimated specific yield at any location.

Hydraulic Conductivity, Specific Yield, and Specific Yield Variability

The hydraulic-conductivity values computed for each aquifer from historical aquifer-test, borehole EM flowmeter, and borehole NMR data were gridded for the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers (fig. 24). The same was done for the specific yield and specific yield variability values for each aquifer; specific yield was computed from the borehole NMR and the inverse modeling results of the surface geophysical TDEM sounding data (fig. 25). The kriging method as described in Thomas and others (2019, p. 8) was used with a 16,400-ft by 16,400-ft (5,000-m by 5,000-m) cell size for the hydraulic conductivity grids and a 1,640-ft by 1,640-ft (500-m by 500-m) cell size for the specific yield grids to account for the spacing of the data, especially the lack of hydraulic-conductivity values for Edwards-Trinity (High Plains) and Dockum aquifers.

Ogallala Aquifer

The hydraulic-conductivity values of the Ogallala aquifer range from about 0.55 to about 350 feet per day (ft/d) (Payne and others, 2020). The median of the hydraulic-conductivity values is 5.7 ft/d with most (70 percent) of the values between 1.00 and 9.99 ft/d; values within the range of 1.00–9.99 ft/d are mostly concentrated in Terry County. The largest areas with high hydraulic-conductivity values are west of Brownfield, Tex., in Terry County and southeast of Plains, Tex., in Yoakum County (fig. 24A). The lowest hydraulic-conductivity values are in Terry County, south of Brownfield, Tex., near the border with Gaines County. A large area of low hydraulic conductivity (1.00 to 9.99 ft/d) stretches from northern Terry County to Seminole, Tex.

The estimated specific yield values of the Ogallala aquifer range from 0.03 to 0.13 (unitless) with the specific yield variability ranging from 0.03 to 0.15 (Payne and others, 2020). The median of the specific yield values is 0.09 with most (59 percent) of the specific yield values between 0.09 and 0.12. About one-half the specific yield variability values are greater than 0.10. The highest specific yield values are in Terry County, west and southeast of Brownfield, Tex. (fig. 25A). The lowest specific yield values are in Gaines County, westnorthwest of Seminole, Tex., contained within an area of relatively low specific yields stretching from eastern Gaines County northeast towards the border of Gaines County with both Terry and Yoakum Counties. Generally, specific yield variability is relatively high in the northeastern and eastern parts of the study area and relatively low to the west and southwest. There is evidence of some correspondence between specific yield and specific yield variability values, in that lower specific yield variability is generally observed in areas where specific yield is higher.

Edwards-Trinity (High Plains) Aquifer

The hydraulic-conductivity values for the Edwards-Trinity (High Plains) aquifer range from about 0.03 to about 270 ft/d (Payne and others, 2020). The median of the hydraulic-conductivity values is 4.7 ft/d with most (65 percent) of the values between 1.00 and 9.99 ft/d. The highest hydraulic-conductivity values are in southeastern Yoakum County near the border with Terry County, and southern Yoakum County near Denver City into northwest Gaines County (fig. 24B). There are also high hydraulic-conductivity values east of Brownfield, Tex., and in northeast of Seminole, Tex. The lowest hydraulic-conductivity values are in Terry County northwest of Brownfield, Tex., and in Yoakum County southeast of Plains, Tex.

The estimated specific yield values of the Edwards-Trinity (High Plains) aquifer range from 0.01 to 0.28 with the specific yield variability ranging from 0.05 to 0.15 (Payne and others, 2020). The median specific yield value for the Edwards-Trinity (High Plains) aquifer within the study area is 0.07, and most (56 percent) of the specific yield values are between 0.05 and 0.08. Almost all the study area (95 percent) has specific yield variability values greater than 0.10 and a median value of 0.15. The highest specific yield values are in the north-central part of Yoakum County (fig. 25B). The lowest specific yield values are in eastern Gaines and Yoakum Counties and around Rich Lake in Terry County. The specific yield variability values are relatively high throughout the entire study area except in central Gaines County near borehole NMR data collection wells. This lower specific yield variability near the borehole NMR-logged wells is on account of the higher accuracy of the borehole NMR method relative to the regression method used to process the TDEM inverse modeling results.

Dockum Aquifer

There were substantially fewer hydraulic-conductivity values computed for wells completed only in the Dockum aquifer (27 wells) compared to wells completed only in the Ogallala (380 wells) or Edwards-Trinity (High Plains) (74 wells) aquifers. The available data were used to provide generalized insights regarding hydraulic properties of the aquifer. The hydraulic-conductivity values of the Dockum aquifer range from about 0.25 to about 240 ft/d (Payne and others, 2020). Most (52 percent) of the hydraulic-conductivity values are between 1.00 and 9.99 ft/d with a median value of 2.8 ft/d. The highest hydraulic-conductivity value was measured in Gaines County south of Cedar Lake (fig. 24C). The lowest hydraulic conductivity also was measured in Gaines County, in the southeast corner of the county. Other low hydraulic-conductivity values were measured in the northeast corner of the study area around Brownfield, Tex.

Base modified from U.S. Geological Survey 1:250,000-scale to 1:2,000,000-scale digital data,
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

EXPLANATION

Estimated hydraulic conductivity, in feet per day
- 0.100 to 0.999
- 1.00 to 9.99
- 10.0 to 99.9
- ≥ 100

Study area boundary
Edwards-Trinity (High Plains) aquifer system downdip extent
Underground water conservation district boundary
- Llano Estacado Underground Water Conservation District
- Sandy Land Underground Water Conservation District
- South Plains Underground Water Conservation District

Hydraulic conductivity from well, in feet per day (Payne and others, 2020)
- < 0.100
- 0.100 to 0.999
- 1.00 to 9.99
- 10.0 to 99.9

Figure 24.   Hydraulic-conductivity values computed from historical aquifer test, borehole electromagnetic flowmeter, and borehole nuclear magnetic resonance data for A, the Ogallala aquifer, B, the Edwards-Trinity (High Plains) aquifer system, and C, the Dockum aquifer in and near Gaines, Terry, and Yoakum Counties, Texas.
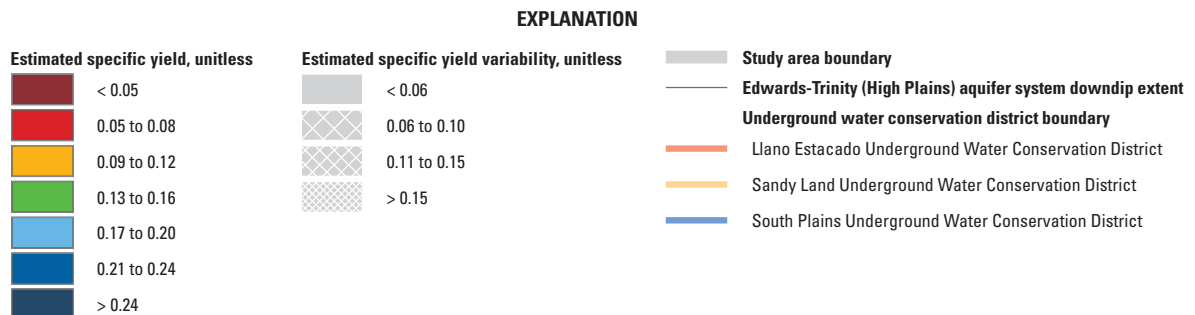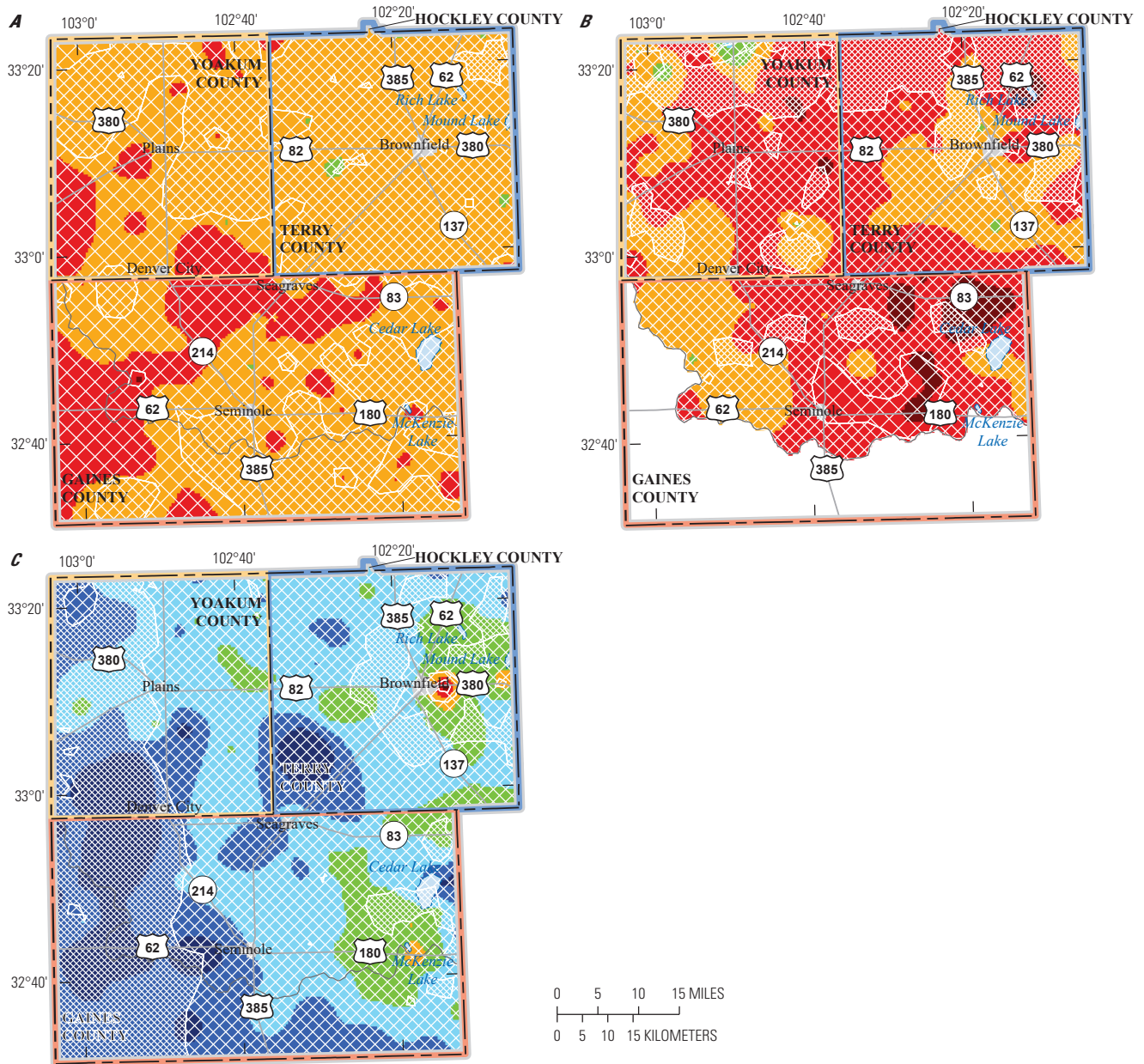
Figure 25. Estimated specific yield and specific yield variability values computed from borehole nuclear magnetic resonance and inverse modeling results of the time-domain electromagnetic data for *A*, the Ogallala aquifer, *B*, the Edwards-Trinity (High Plains) aquifer system, and *C*, the Dockum aquifer in and near Gaines, Terry, and Yoakum Counties, Texas.

The estimated specific yield values for the Dockum aquifer range from 0.03 to 0.44 with the specific yield variability ranging from 0.06 to 0.15 (Payne and others, 2020). Most (67 percent) of the specific yield values are between 0.17 and 0.24, and most of those values (37 percent of total) are between 0.17 and 0.20. The median specific yield value for the Dockum aquifer is 0.19. Similar to the specific yield variability values in the Edwards-Trinity (High Plains) aquifer, almost all of the study area (99 percent) has specific yield variability values greater than 0.10 with about one-third of the total values (34 percent) being greater than 0.15. The median specific yield variability is 0.15. The highest specific yield values are in the western part of the study area (northwest corner of Gaines County), whereas the lowest specific yield values are in the eastern part of the study area (east of Brownfield and east of Seminole) (fig. 25C). In general, the specific yield values decrease from west to east. The specific yield variability values are relatively high throughout the entire study area except near Brownfield, Tex., where borehole NMR data were collected. The high specific yield variability is expected in the Dockum aquifer because of the lower measured formation factors in the aquifer as a result of more clays causing a low bulk resistivity compared to the fluid resistivity.

Conceptual Model

A regional conceptual model was built by combining the results from the hydrogeologic framework, geochemistry, groundwater-flow system, and aquifer hydraulic properties analyses. In conjunction with the analysis of the hydrogeologic framework for each of the geologic units, a combined analysis was done for the Trinity and Fredericksburg Groups and Ogallala Formation (units that constitute the Ogallala and Edwards-Trinity (High Plains) aquifers that contain most of the groundwater used in the study area). The combined thickness of the Trinity and Fredericksburg Groups and Ogallala Formation is generally greatest in the north-central part of the study area and thinnest in the southeastern part of the study area (fig. 26). In Gaines and Terry Counties, the thickness of the combined Trinity and Fredericksburg Groups and Ogallala Formation generally decreases from the northwest corners of the counties to the southeast corners, whereas in Yoakum County, the combined thickness decreases from the northeast corner to the southwest corner of the county.

The groundwater geochemical results were evaluated further to spatially identify groups of similar groundwater samples. Groundwater samples were grouped on the basis of similarities found in the physicochemical properties, major ions, trace elements, nutrients, organic compounds, and selected stable isotopes and age tracers. This grouping of the groundwater is done to provide an overall summary of the geochemical results as it pertains to the study area. Three groundwater groups were identified in the study area as shown in table 5 (fig. 27).

The first groundwater group (Group 1) contains most (61 percent) of the groundwater wells sampled with all but one well in the northern half of the study area (fig. 27). The water in Group 1 is considered modern as shown by the tritium and carbon-14 concentrations and confirmed with high concentrations of nitrate plus nitrite and frequent detections of organic compounds (table 5). This group has the lowest strontium stable isotope ratios within the study area, which also indicates recent recharge because the groundwater has not had much time for isotopic exchange associated with water-rock interaction. Groundwater wells in Group 1 are primarily screened in either the Ogallala aquifer or Edwards-Trinity (High Plains) aquifer; only one well is screened in the Dockum aquifer (fig. 27). Recent recharge, affected by land-use activities, may explain the younger age, higher concentrations of nitrate plus nitrite, and more frequent detections of organic compounds for wells in Group 1.

Groundwater wells in the Group 2 are typically in the southwestern and northwestern parts of the study area (fig. 27). The groundwater in Group 2 is some of the oldest groundwater, as shown by the tritium and carbon-14 concentrations, and has the lowest DS concentrations in the study area (table 5). The relatively old age of the groundwater in Group 2 is supported by high strontium stable isotope ratios, which are indicative of an extended period of isotopic exchange associated with water-rock interactions. The hydrogen and oxygen stable isotope ratios in conjunction with tritium and carbon-14 concentrations indicate that the groundwater in Group 2 may have recharged during the Pleistocene period. Samples collected from 3 of the 5 wells completed in the Dockum aquifer have characteristics of groundwater in Group 2 (fig. 27).

The last group (Group 3) is likely a mixture of groundwater from Group 1 or Group 2 (or both) with a third, highly mineralized groundwater. The groundwater in Group 3 has the highest DS concentrations in the study area and has some geochemical characteristics similar to those in Group 1 and Group 2 (table 5). Some of the samples in Group 3 have similar characteristics to the groundwater in Group 2, including some of the oldest groundwater in the study area, as indicated by tritium and carbon-14 concentrations, in addition to the highest calcium concentrations. Some of the samples in Group 3 are more similar to the groundwater in Group 1, having some of the highest nutrient concentrations in the study area in addition to being more modern, as indicated by the tritium and carbon-14 concentrations. Groundwater from Group 3 is also the most highly mineralized groundwater in the study area and typically is present near the southwest corner of Yoakum County and northwest corner of Gaines County, near Brownfield, Tex., in Terry County, and near Cedar Lake in Gaines County (fig. 27). The highly mineralized groundwater is from an unknown source but is interpreted to be from a deep saline source, as indicated by the sample at site 25644, which has the highest DS concentration in the study area and the deepest screened interval at greater than 1,800 feet below land surface (Payne and others, 2020). Additional information is needed to confirm that this highly mineralized groundwater is from a deep source.
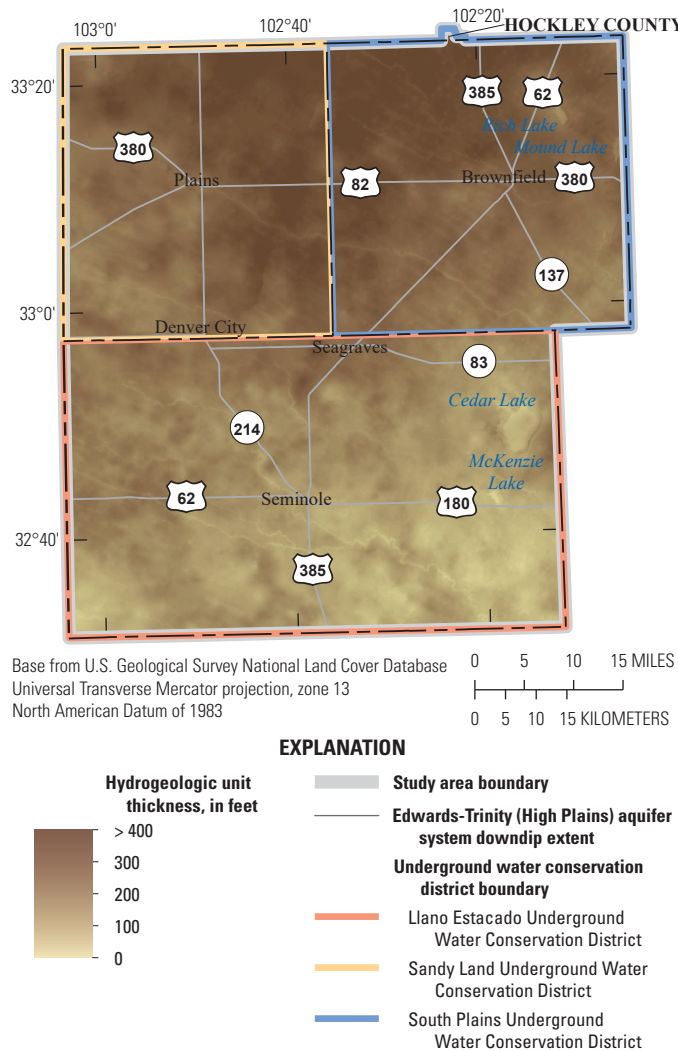
Figure 26. Combined hydrogeologic unit thickness of the Trinity and Fredericksburg Groups and Ogallala Formation in and near Gaines, Terry, and Yoakum Counties, Texas.

The results from the groundwater-flow system analysis were used to further assess the paleochannel analysis. The results of the paleochannel analysis from the trend-removal grids and hydrology toolset analysis (fig. 7) and the groundwater-flow paths determined from the potentiometric maps (fig. 19) exhibit similar results for groundwater-flow directions, especially for the Ogallala aquifer, for which more groundwater-level data were available (fig. 7C; fig. 19A). Results of a comparison of the two methods indicate that the groundwater flows preferentially through low-altitude areas of each aquifer, which correspond to the paleochannels. The groundwater-flow paths in the Ogallala aquifer tend to closely approximate the mapped paleochannels. The tendency for groundwater-flow paths and paleochannels to correspond indicates that within the study area, the groundwater flows preferentially along the paleochannels, especially within the Ogallala aquifer where dewatering of the aquifer results in a greater influence of the base structure on the flow of groundwater. There are some localized areas where the mapped paleochannels are different from the groundwater-flow paths in the Ogallala aquifer. The paleochannel analysis identified a few channels oriented towards the east that did not align with groundwater-flow paths, including some channels that cross the border between Yoakum and Terry Counties between Plains and Brownfield, Tex., and other channels that are northwest of, and east of, Seminole, Tex. (fig. 7C; fig. 19A). Instead, the groundwater-flow paths generally continued southeast in most of these locations, which is consistent with the general groundwater flow of the study area. Because of the lack of groundwater-level data for the Edwards-Trinity (High Plains) aquifer, the groundwater-flow path results (fig. 19B) are not detailed enough to compare to the paleochannel analysis results (fig. 7A), but the groundwater-flow paths did have the same general direction as the paleochannels found at the
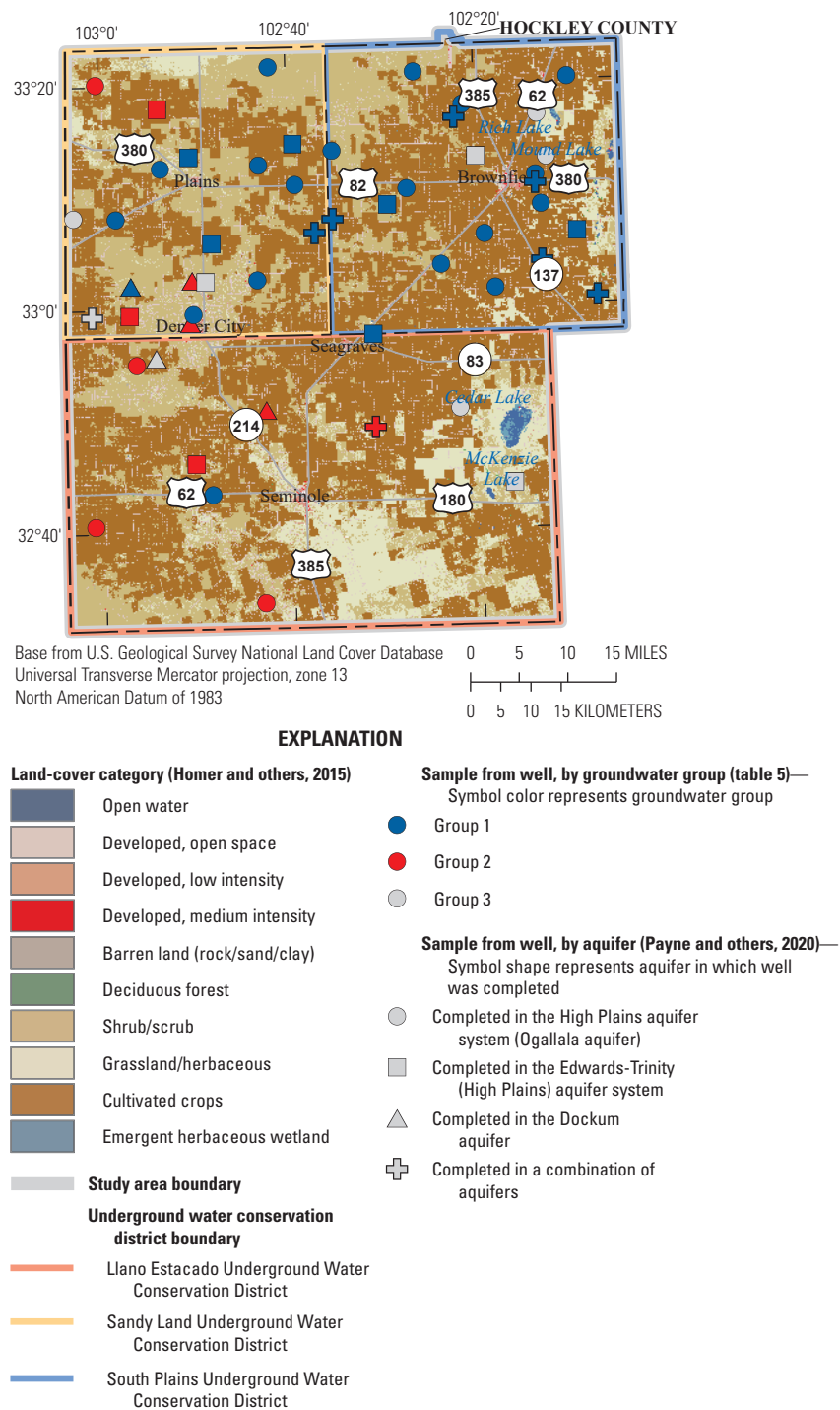
Figure 27.   Groundwater groups for the water-quality samples collected in Gaines, Terry, and Yoakum Counties, Texas, 2014 and 2016.

Table 5. Description of groundwater groups and median water-quality results for groundwater groups from water-quality samples collected in Gaines, Terry, and Yoakum Counties, 2014 and 2016.

[mg/L, milligram per liter; µg/L, microgram per liter; δD, delta deuterium; δ18O, delta oxygen-18; 87Sr/86Sr, strontium-87 per strontium-86; pCi/L, picocurie per liter]

	Description of groups		
Groundwater group:	Group 1	Group 2	Group 3
Site identifier for wells (table 2) within groundwater group	04518, 04809, 05380, 06260, 07706, 08956, 09493, 10676, 10748, 11642, 11771, 12504, 14388, 18745, 18790, 19639, 20759, 20903, 21524, 23705, 24005, 24915, 25865, 25883, 27256, 27272, 27287, 27488, 27811, 28275, 28367	09503, 09781, 10061, 10509, 10639, 20215, 21325, 25208, 25317, 26701, 27727	01500, 03060, 08389, 10523, 12514, 15747, 25644, 26458, 27974
Total samples in groundwater group	31	11	9
Number of samples from wells completed in the High Plains aquifer system (Ogallala aquifer)	18	4	4
Number of samples from wells completed in the Edwards-Trinity (High Plains) aquifer system	6	3	3
Number of samples from wells completed in the Dockum aquifer	1	3	1
Number of samples from wells completed in a combination of aquifers	6	1	1
	Median results for water-quality constituents		
Dissolved solids dried at 180 degrees Celsius, water, filtered (mg/L)	1,010	820	1,380
Major ions			
Bicarbonate, water, filtered, inflection-point titration method, field (mg/L)	268	216	297
Calcium, water, filtered (mg/L)	72.6	100	73.0
Chloride, water, filtered (mg/L)	152	198	322
Fluoride, water, filtered (mg/L)	4.35	2.82	3.47
Magnesium, water, filtered (mg/L)	88.5	55.2	55.3
Potassium, water, filtered (mg/L)	12.2	4.35	7.15
Sodium, water, filtered (mg/L)	108	83.5	265
Sulfate, water, filtered (mg/L)	284	125	426
Nitrate plus nitrite, water, filtered (mg/L as nitrogen) [number of non-detects]	8.02 [0]	4.66 [0]	10.5 [1]
Deethylatrazine, water, filtered, recoverable (µg/L) [number of non-detects]	E0.006 [23]	E0.008 [9]	E0.021 [7]
Metolachlor, water, filtered, recoverable (µg/L) [number of non-detects]	0.006 [18]	0.006 [10]	0.004 [7]
δ18O, water, unfiltered (per mil)	-5.96	-6.14	-5.94
δD, water, unfiltered (per mil)	-41.2	-43.1	-40.3
87Sr/86Sr, water, unfiltered	0.70859	0.70863	0.70860
Tritium, water, unfiltered (pCi/L)	3.50	1.34	3.80
Carbon-14, water, filtered (percent modern)	74.57	44.36	67.60

base of the Trinity Group. The paleochannel analysis was not performed for the Dockum Group, so a comparison between the paleochannels of the Dockum Group and the groundwater-flow paths within the Dockum aquifer was not possible.

Saturated thickness for the Ogallala and the combined Ogallala and Edwards-Trinity (High Plains) aquifers can be estimated by computing the diff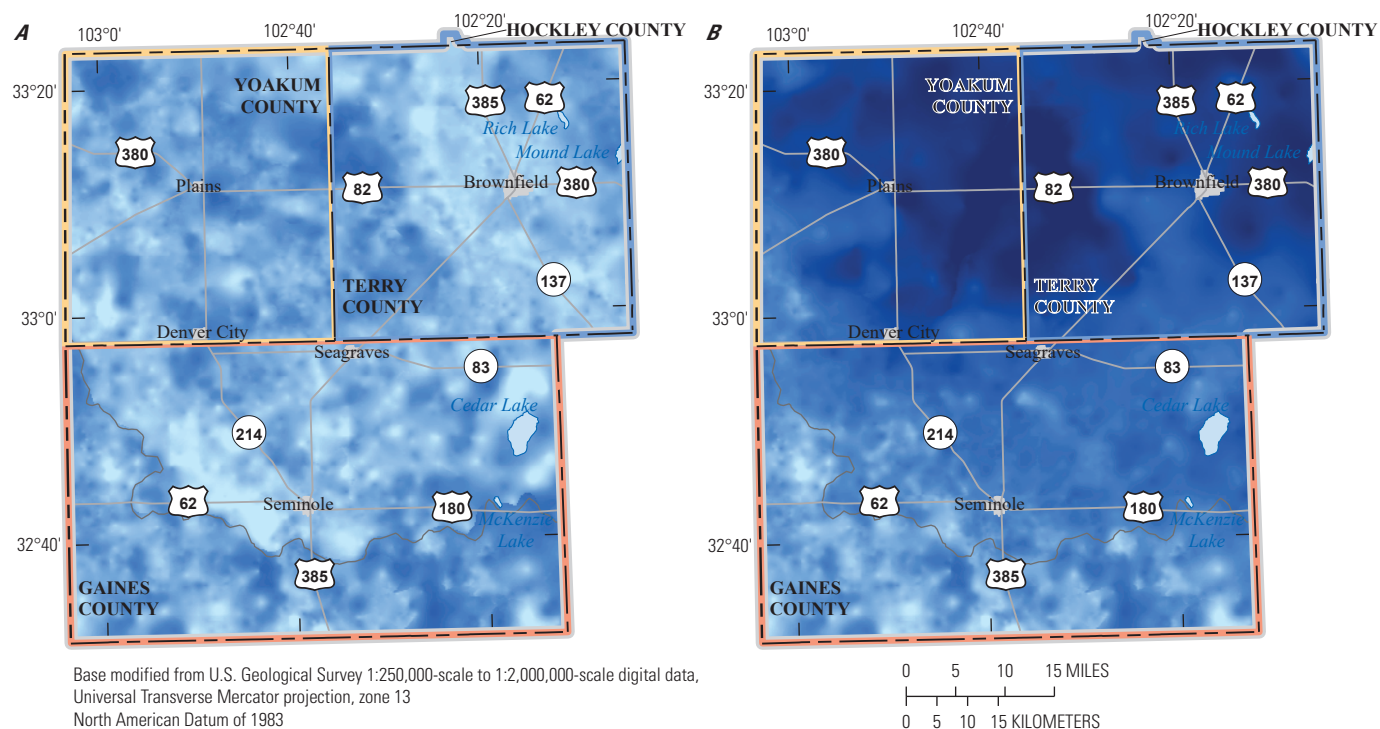erence between the altitude of the water table and the altitude of the base of the aquifer at a given location (fig. 28). The saturated thickness of the Ogallala aquifer can vary substantially in a relatively small area in response to substantial spatial variations in the base of the Ogallala Formation (fig. 28A). The Ogallala aquifer is unsaturated in localized areas in the study area; unsaturated areas are generally present near the southern extent of the Edwards-Trinity (High Plains) aquifer, with the largest unsaturated area west of Seminole, Tex. The saturated thickness of the Ogallala aquifer is thickest (more than 125 feet) southeast of Seminole and west of Brownfield, Tex., near the border between Terry and Yoakum Counties. Although the saturated thickness varies locally, regionally thinner sections in the Ogallala aquifer extend from north-central Terry County to the southeast and from the southwest corner of Yoakum County to south-central Gaines County. Regionally thicker sections of the saturated part of the Ogallala aquifer are in the north-central part of the study area from northeast Yoakum County to the southwest corner of Terry County and in the southeast corner of Gaines County.

The saturated thickness of the combined Ogallala and Edwards-Trinity (High Plains) aquifers are laterally persistent compared to the Ogallala aquifer alone (fig. 28B). This is a result of the larger aquifer thickness incorporated into the overall saturated thickness of the combined aquifer system. The saturated thickness of the combined Ogallala and Edwards-Trinity (High Plains) aquifers ranges from less than 10 feet along the far southern edge of the study area to more than 350 feet north and east of Brownfield, Tex., and along the border between Terry and Yoakum Counties. In general, the saturated part of the combined Ogallala and Edwards-Trinity (High Plains) aquifers is thinnest in the south and southwest of the study area where the thickness of the Fredericksburg and Trinity Groups are the thinnest or not present.

The volume of water stored within the saturated thickness depends on many factors, including the aquifer extent, specific yield, and saturated thickness of the hydrogeologic unit (Gutentag and others, 1984). Using the estimated saturated thickness and the estimated specific yield grids, the water volumes of the Ogallala, Edwards-Trinity (High Plains), and the combined Ogallala and Edwards-Trinity (High Plains) aquifers were estimated (table 6). The available water in the Edwards-Trinity (High Plains) aquifer (16.6 million acre-feet) is almost double the available water in the Ogallala aquifer (8.8 million acre-feet) in the study area. The semiconfined nature of the Edwards-Trinity (High Plains) aquifer may result in this value being an underestimate because more water

may be retained in the aquifer as a result of increased pressure in the aquifer from confining conditions. Although the Edwards-Trinity (High Plains) aquifer contains more available groundwater than the Ogallala aquifer, retrieving the groundwater from the Edwards-Trinity (High Plains) aquifer is more difficult because of the relatively low hydraulic conductivity and specific yield values compared to the Ogallala aquifer. Overall, the available water within the combined Ogallala and Edwards-Trinity (High Plains) aquifers is about 6.6, 10.2, and 8.6 million acre-feet for Gaines, Terry, and Yoakum Counties, respectively.

Because of the high variability associated with the specific yield values (the specific yield range is determined from the specific yield and the specific yield variability values), the resulting computed values for available groundwater in storage are highly variable as well. Within the Ogallala and Edwards-Trinity (High Plains) aquifers, the minimum volume of groundwater in storage (computed using the specific yield minus the specific yield variability) is 0 million acre-feet (table 6). The maximum volume of storage (computed using the specific yield plus the specific yield variability) for the Ogallala aquifer is about 19.2 million acre-feet for the study area and about 8.6, 5.6, and 5.0 million acre-feet for Gaines, Terry, and Yoakum Counties, respectively. These maximum values match closely to the total estimated recoverable storage volumes computed by Kohlrenken and others (2013) (table 6). The maximum storage volume for the Edwards-Trinity (High Plains) aquifer is about 50.4 million acre-feet for the study area and about 8.1, 23.6, and 18.7 million acre-feet for Gaines, Terry, and Yoakum Counties, respectively (table 6). These maximum storage values are much greater than those reported by Kohlrenken and others (2013); the estimated average storage values for the Edwards-Trinity (High Plains) aquifer are relatively close to those in Kohlrenken and others (2013). Overall, the maximum estimated storage of the combined Ogallala and Edwards-Trinity (High Plains) aquifers is 69.6 million acre-feet with about 16.7, 29.2, and 23.7 million acre-feet of groundwater storage in Gaines, Terry, and Yoakum Counties, respectively (table 6). The high specific yield variability can be attributed to many factors, such as the bulk measurement of resistivity from TDEM soundings, the fairly low goodness-of-fit for the regression models between the total porosity and formation factor (from bulk resistivity and estimated fluid resistivity), and the estimated fluid resistivity across the study area. The high specific yield variability could be reduced substantially with additional NMR data throughout the study area. Tortuosity and cementation data (from Archie's Law) could also help reduce the specific yield variability by optimizing the regression model between total porosity and formation factor. Additional specific conductance data throughout the study area could provide better fluid resistivity values to compute formation factors to use in the regression models.

Base modified from U.S. Geological Survey 1:250,000-scale to 1:2,000,000-scale digital data,
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

EXPLANATION

Aquifer saturated thickness,
in feet

> 300
225
150
75
0

Study area boundary

Edwards-Trinity (High Plains) aquifer system downdip extent

Underground water conservation district boundary

Llano Estacado Underground Water Conservation District

Sandy Land Underground Water Conservation District

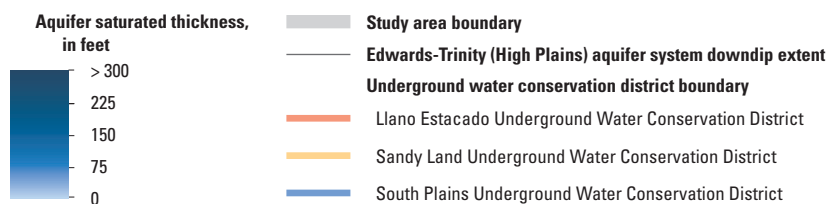South Plains Underground Water Conservation District

Figure 28.   Saturated thickness of *A*, the Ogallala aquifer and *B*, the combined Ogallala aquifer and the Edwards-Trinity (High Plains) aquifer system in and near Gaines, Terry, and Yoakum Counties, Texas

Table 6.   Estimated groundwater storage volumes (minimum, maximum, and average) computed from the estimated saturated thickness and estimated specific yield and specific yield variability values computed from borehole nuclear magnetic resonance and inverse modeling results of the time-domain electromagnetic data for the High Plains aquifer system (Ogallala aquifer), Edwards-Trinity (High Plains) aquifer system, and the combined Ogallala aquifer and Edwards-Trinity (High Plains) aquifer systems in and near Gaines, Terry, and Yoakum Counties, Texas.

[LEUWCD, Llano Estacado Underground Water Conservation District; SPUWCD, South Plains Underground Water Conservation District; SLUWCD, Sandy Land Underground Water Conservation District]

District (County)	Aquifer	Estimated groundwater storage volumes (million acre-feet)			Total estimated recoverable groundwater storage volumes from Kohlrenken and others (2013) (million acre-feet)
		Minimum	Maximum	Average	
LEUWCD (Gaines County)	High Plains aquifer system (Ogallala)	0.1	8.6	4.0	11.0
	Edwards-Trinity (High Plains) aquifer system	0.0	8.1	2.6	3.1
	High Plains aquifer system (Ogallala) and Edwards-Trinity (High Plains) aquifer system	0.1	16.7	6.6	14.1
SPUWCD (Terry County and part of Hockley County)	High Plains aquifer system (Ogallala)	0.0	5.6	2.4	5.3
	Edwards-Trinity (High Plains) aquifer system	0.0	23.6	7.8	3.3
	High Plains aquifer system (Ogallala) and Edwards-Trinity (High Plains) aquifer system	0.0	29.2	10.2	8.6
SLUWCD (Yoakum County)	High Plains aquifer system (Ogallala)	0.0	5.0	2.4	2.2
	Edwards-Trinity (High Plains) aquifer system	0.0	18.7	6.2	2.5
	High Plains aquifer system (Ogallala) and Edwards-Trinity (High Plains) aquifer system	0.0	23.7	8.6	4.7
Study area (Gaines, Terry, and Yoakum Counties and part of Hockley County	High Plains aquifer system (Ogallala)	0.1	19.2	8.8	18.5
	Edwards-Trinity (High Plains) aquifer system	0.0	50.4	16.6	8.9
	High Plains aquifer system (Ogallala) and Edwards-Trinity (High Plains) aquifer system	0.1	69.6	25.4	27.4

Summary

Llano Estacado Underground Water Conservation District (LEUWCD), Sandy Land Underground Water Conservation District (SLUWCD), and South Plains Underground Water Conservation District (SPUWCD) (hereinafter referred to collectively as the "UWCDs") manage groundwater resources in a part of west Texas near the Texas-New Mexico State line. The High Plains aquifer system (hereinafter referred to as the "Ogallala aquifer"), that in Texas is contained within the Ogallala Formation, is the shallowest aquifer in the study area and is the primary source of water for agriculture and municipal supply in the areas managed by the UWCDs. Groundwater withdrawals from deeper aquifers (primarily from the Edwards-Trinity (High Plains) aquifer system, hereinafter referred to as the "Edwards-Trinity [High Plains] aquifer," augmented by lesser amounts from the Dockum aquifer) provide additional water sources in the study area. The Edwards-Trinity (High Plains) aquifer is contained within the Trinity and Fredericksburg Groups. The Dockum aquifer, a relatively minor source of water in the study area, is contained in the Dockum Group which was evaluated as a single unit.

Groundwater levels have been documented to decline (more than 50 feet [ft]) in Texas since 1938 with declines occurring overall in the Ogallala aquifer soon after the beginning of substantial irrigation with groundwater from the aquifer (about 1950). The potential for continual declines of the groundwater in the Ogallala aquifer in the study area has raised concerns about the amount of available groundwater. Also of concern are the potential changes in water-quality resulting from dewatering and increased vertical groundwater movement between adjacent water-bearing units. Because the Ogallala aquifer and underlying aquifers are hydraulically connected in some locations, groundwater-level declines in the Ogallala aquifer and in the underlying Edwards-Trinity (High Plains) aquifer can result in changes in the water quality when mixed with the upward movement of deeper, relatively more saline groundwater. In 2014, the U.S. Geological Survey (USGS), in cooperation with the UWCDs, began a multiphase study to refine the understanding of the hydrogeologic framework, geochemistry, groundwater-flow system, and hydraulic properties to be included in the development of a regional conceptual model for the Ogallala, Edwards-Trinity (High Plains), and the Dockum aquifers.

The conceptual model helped in the understanding of the quantity and quality of the groundwater within the Ogallala, Edwards-Trinity (High Plains), and to a lesser extent the Dockum aquifers within the study area. The hydrogeologic framework was used to assess the vertical and lateral extents of hydrogeologic units, bed orientation, unit thickness, and location and orientation of paleochannels. The geochemistry helped to better understand general water quality and provide insight into groundwater-flow paths and recharge sources as well as mixing pathways. The groundwater-flow system analysis aided in evaluating the spatial groundwater-level-altitude changes and identifying regional groundwater-flow paths and gradients. The aquifer hydraulic properties, including hydraulic conductivity and specific yield, were estimated to better understand the ability of groundwater to move through the aquifer system and quantify the volume of available water in storage.

The analysis for the hydrogeologic framework consisted mostly of the compilation and review of available data; additional geophysical data were collected in selected areas to improve the spatial coverage across the study area and to reduce uncertainty regarding hydrogeologic unit extents. In general, the Trinity and Fredericksburg Groups and Ogallala Formation exhibit a slight regional dip (dip angle of about 0.14 degrees) to the southeast with dip directions becoming more to the south with each successively overlying unit (105, 110, and 125 degrees for the bases of the Trinity and Fredericksburg Groups and Ogallala Formation, respectively). The highest altitudes for each of the groups are in the northwest corner of the study area, and the lowest altitudes for each group are in the southeastern to eastern parts.

Paleochannel orientation varied over geologic time as formations were deposited and eroded. Paleochannels eroded into the Dockum Group as represented by the bases of the Trinity Group and Ogallala Formation (where the Trinity Group is not present) generally have a west to east direction. Paleochannels eroded into the Trinity Group, as represented by the base of the Fredericksburg Group, generally have a west to east direction. Paleochannels eroded into the Dockum (where the Fredericksburg Group is not present) and Fredericksburg Groups, as represented collectively by the base of the Ogallala Formation, generally have a northwest to southeast direction. Deep paleochannels (trend-removal value less than -25 ft) were found to be eroded into the Dockum Group, as represented by the base of the Trinity Group (north border of Terry County); eroded into the Trinity Group, as represented by the base of the Fredericksburg Group (north border of Terry County); and eroded into the Dockum (where the Fredericksburg Group is not present) and Fredericksburg Groups, as represented collectively by the base of the Ogallala Formation (southwest corner of the study area and near the northwest corner of Terry County). Moderately deep paleochannels (trend-removal value between -10 and -25 ft) were found in the central part of the study area eroded into the Dockum, Trinity, and Fredericksburg Groups, which may provide possible pathway links (as shown by some of the stream paths from the hydrology toolset analysis) between deeper paleochannels.

Relative to the other geologic units assessed for this study (the Trinity and Fredericksburg Groups and Ogallala Formation), the Dockum Group was found to have a much greater average thickness (approximately 2,115 feet), with the thickest parts of the Dockum Group in the western part of the study area and thinnest in the eastern part of the study area. Within the study area, the thicknesses of the Trinity and Fredericksburg Groups and Ogallala Formation vary locally, depending on the presence of erosional features such as paleochannels. In general, the Trinity and Fredericksburg

Groups thin to the south and are not present in the southern part of Gaines County, whereas the Ogallala Formation becomes thinner from west to east. The combined thickness of the Trinity and Fredericksburg Groups and Ogallala Formation (units that comprise the Ogallala and Edwards-Trinity [High Plains] aquifers that contain most of the groundwater used in the study area) is generally greatest in the north-central part of the study area and thinnest in the southeastern part of the study area.

Water-quality samples were collected from 51 wells throughout the study area to better understand general water quality and to provide insight into groundwater-flow paths and recharge areas. Groundwater samples were spatially grouped on the basis of similarities found in the physicochemical properties, major ions, trace elements, nutrients, organic compounds, and selected stable isotopes and age tracers. Three groundwater groups were identified in the study area. The first groundwater group (Group 1), represented mostly by groundwater from the Ogallala and Edwards-Trinity (High Plains) aquifers in the northern half of the study area, contains most (61 percent) of the groundwater wells sampled, and the groundwater is considered to be recent recharge, affected by land-use activities, as explained by the younger age, higher concentrations of nitrate plus nitrite, and more frequent detections of organic compounds. Groundwater wells in the second groundwater group (Group 2) are typically in the southwestern and northwestern parts of the study area, and the groundwater is considered to have been recharged during the Pleistocene period, as explained by the relatively old age of the groundwater, high strontium stable isotope ratios, and hydrogen and oxygen stable isotope ratios. The last group (Group 3) is likely a mixture of groundwater from Group 1 or Group 2 (or both) with a third, highly mineralized groundwater as explained by having the highest dissolved-solids concentrations in the study area and having some similarities to geochemical characteristics of groundwater from Groups 1 and 2. The highly mineralized groundwater is from an unknown source but is interpreted to be from a deeper saline source; in order to confirm this interpretation additional information is needed.

A groundwater-flow system analysis was done to understand the flow of groundwater throughout the aquifer system. Groundwater-level altitudes for the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers are generally higher in the northwestern part of the study area and lower in the southeastern part of the study area. Groundwater generally flows in a northwest to southeast direction across the study area in each of the aquifers. The results from the groundwater-flow system analysis were used to further assess the paleochannel analysis. The groundwater-flow paths closely resemble the mapped paleochannels, indicating that within the study area, the groundwater flows preferentially along the paleochannels, especially within the Ogallala aquifer where dewatering of the aquifer results in a greater effect of the base structure on the flow of groundwater.

Saturated thickness for the Ogallala and the combined Ogallala and Edwards-Trinity (High Plains) aquifers was estimated by computing the difference between the altitude of the water table and the altitude of the base of the aquifer at a given location. The Ogallala aquifer is unsaturated in localized areas in the study area. Unsaturated areas are generally near the southern extent of the Edwards-Trinity (High Plains) aquifer, with the largest unsaturated area west of Seminole, Tex. The saturated thickness of the Ogallala aquifer is thickest (more than 125 feet) southeast of Seminole and west of Brownfield, Tex., near the border between Terry and Yoakum Counties. The saturated thickness of the combined Ogallala and Edwards-Trinity (High Plains) aquifers is laterally persistent compared to the Ogallala aquifer alone. The saturated thickness of the combined Ogallala and Edwards-Trinity (High Plains) aquifers ranges from less than 10 feet along the far southern edge of the study area to more than 350 feet north and east of Brownfield, Tex., and along the border between Terry and Yoakum Counties.

To estimate the hydraulic properties for the aquifer system, available historical data were compiled and supplemented with the collection of borehole and surface geophysical data. The hydraulic-conductivity values varied greatly within the study area (ranging from about 0.03 to about 350 feet per day), and often large variations were found in the same area. Terry County contained the highest and lowest hydraulic conductivity values for the Ogallala aquifer, while Yoakum County contained the highest and lowest hydraulic conductivity values for the Edwards-Trinity (High Plains) aquifers. The highest hydraulic-conductivity values for the Dockum aquifer were in Gaines Counties whereas the lowest hydraulic-conductivity values were in Terry County. The median hydraulic conductivity value in each aquifer decreased with depth (5.7, 4.7, and 2.8 feet per day for the Ogallala, Edwards-Trinity [High Plains], and Dockum aquifers, respectively). Overall, the Ogallala aquifer has the highest hydraulic-conductivity values, whereas the Dockum aquifer has the lowest values in the study area. The estimated specific yield values within the study area ranged from 0.01 to 0.36 with the median value in each aquifer being 0.09, 0.07, and 0.19 for the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers, respectively. The specific yield variability ranged from 0.03 to 0.15 with more variability observed at deeper depths. The higher specific yield values are generally in the western parts of the study area except in the Ogallala aquifer where the higher specific yield values are in the east. The Ogallala aquifer has the lowest specific yield range and the least specific yield variability among the three aquifers, whereas the Dockum aquifer has the highest specific yield range and the greatest specific yield variability.

Using the estimated saturated thickness and the estimated specific yield grids, the water volumes of the Ogallala, Edwards-Trinity (High Plains), and the combined Ogallala and Edwards-Trinity (High Plains) aquifers were estimated. The available water in the Edwards-Trinity (High Plains) aquifer (16.6 million acre-feet) is almost double the available water in the Ogallala aquifer (8.8 million acre-feet) in the study area.

Overall, the available water within the combined Ogallala and Edwards-Trinity (High Plains) aquifers is about 6.6, 10.2, and 8.6 million acre-feet for Gaines, Terry, and Yoakum Counties, respectively. Because of the high variability associated with the specific yield values, the resulting computed values for available groundwater in storage are highly variable as well. Within the Ogallala and Edwards-Trinity (High Plains) aquifers, the minimum volume of groundwater in storage is very near 0 million acre-feet. The maximum volume of storage for the Ogallala aquifer is about 19.2 million acre-feet for the study area and about 8.6, 5.6, and 5.0 million acre-feet for Gaines, Terry, and Yoakum Counties, respectively, whereas the maximum storage volume for the Edwards-Trinity (High Plains) aquifer is about 50.4 million acre-feet for the study area and about 8.1, 23.6, and 18.7 million acre-feet for Gaines, Terry, and Yoakum Counties, respectively. Overall, the maximum estimated storage of the combined Ogallala and Edwards-Trinity (High Plains) aquifers is 69.6 million acre-feet with about 16.7, 29.2, and 23.7 million acre-feet of groundwater storage in Gaines, Terry, and Yoakum Counties, respectively. The high specific yield variability could be reduced substantially with additional nuclear magnetic resonance, tortuosity and cementation, and specific conductance data throughout the study area.

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