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Changes Between Early Development (1930–60) and Recent (2005–15) Groundwater-Level Altitudes and Dissolved-Solids and Nitrate Concentrations In and Near Gaines, Terry, and Yoakum Counties, Texas

Pamphlet to accompany
Scientific Investigations Map 3355

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

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SALLY JEWELL, Secretary

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Suzette M. Kimball, Director

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Conversion Factors

Inch/Pound 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)

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

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Changes Between Early Development (1930–60) and Recent (2005–15) Groundwater-Level Altitudes and Dissolved-Solids and Nitrate Concentrations In and Near Gaines, Terry, and Yoakum Counties, Texas

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Abstract

Llano Estacado Underground Water Conservation District, Sandy Land Underground Water Conservation District, and South Plains Underground Water Conservation District manage groundwater resources in a part of west Texas near the Texas-New Mexico State line. Declining groundwater levels have raised concerns about the amount of available groundwater in the study area and the potential for water-quality changes resulting from dewatering and increased vertical groundwater movement between adjacent water-bearing units.

In 2014, the U.S. Geological Survey, in cooperation with Llano Estacado Underground Water Conservation District, Sandy Land Underground Water District, and South Plains Underground Water Conservation District, began a multiphase project to develop a regional conceptual model of the hydrogeologic framework and geochemistry of the Ogallala, Edwards-Trinity, and Dockum aquifers. 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 area. This report describes 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 were compiled and evaluated for the Ogallala, Edwards-Trinity, 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. Pertinent data were compiled from available sources for the study area and for a 5-mile buffer area around the study area to prevent gridding errors near the boundary. Geologic and well-construction data were used to determine or verify the aquifer in which each well was completed. Depending on the available data, the aquifer assignment (aquifer 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 completed aquifer reported for a given well by the data source.

Potentiometric-surface maps were created to depict changes in groundwater-level altitudes for the Ogallala and Edwards-Trinity aquifers. In addition to comparing groundwater-level altitudes and water quality from the early development and recent periods, hydrographs of groundwater-level altitudes were created, and changes in water quality for various periods between 1930 and 2015 were evaluated. Variance maps for each groundwater-level-altitude grid were used to evaluate the spatial data coverage and to identify areas with higher uncertainty because of spatially limited data availability for some of the aquifers.

For this report, existing dissolved-solids and nitrate concentration data were compiled and assessed for evidence of spatial patterns and changes over time. These data were compiled for samples collected from wells completed in the Ogallala, Edwards-Trinity, or Dockum aquifer during the early development period (1930–60) or the recent period (2005–15); temporal and spatial variations were assessed from depictions of the measured concentration values. Dissolved-solids and nitrate concentrations measured in samples from three wells completed in the Ogallala aquifer (well identifiers 11524, 11824, and 11825) for which long-term monitoring was done for various periods between 1950 and 2015 were also compiled and analyzed.

Groundwater-level altitudes of the Ogallala aquifer are generally higher in the northwestern part of the study area and lower in the southeastern part of the study area, varying by as much as 800 feet. Groundwater flow paths for the early development period generally trend from northwest to southeast across the study area. Compared to those for the early development period, local features in the potentiometric surface for the recent period are more pronounced, likely as a result of additional data coverage, increased groundwater withdrawals, and local flow paths that are more variable.

For the Edwards-Trinity aquifer potentiometric-surface map of the recent period, a general northwest to southeast flow gradient was also evident, with some subtle differences compared to the early development period. The Edwards-Trinity aquifer water-level-altitude change map between the early development and recent periods indicated similar spatial trends as in the Ogallala aquifer and indicated that groundwater-level altitudes declined over a large amount of the area for which sufficient data were available for reliably mapping changes.

During the recent period, median dissolved-solids concentrations of less than 1,000 milligrams per liter (mg/L) were predominantly measured in the western part of the study area, and median concentrations of more than 1,000 mg/L were predominantly measured in the eastern part of the study area. A general pattern of increasing nitrate concentrations from west to the northeast was evident in the study area. Nitrate concentrations measured in samples collected from 16 wells completed in the Ogallala aquifer for the recent period were equal to or greater than 10 mg/L, the primary drinking water standard for finished drinking water.

Introduction

Llano Estacado Underground Water Conservation District (LEUWCD), Sandy Land Underground Water Conservation District (SLUWCD), and South Plains Underground Water Conservation District (SPUWCD) (hereafter referred to collectively as the “UWCDs”) manage groundwater resources in a part of west Texas near the Texas-New Mexico State line (fig. 1). The UWCDs are responsible for managing the groundwater resources in their respective jurisdictions, which are in and near Gaines, Terry, and Yoakum Counties; the study area for this report is composed of the areas managed by the three UWCDs. An important source of water in the study area is the vast High Plains aquifer system, which extends from South Dakota to Texas (fig. 2). 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). Outside of Texas, additional geologic units of different ages are part of the aquifer system (valley fill, dune sand, the Arikaree Group, and the Brule Formation), so use of the more inclusive “High Plains” name for the aquifer system became common (Dugan and others, 1994). The Ogallala Formation is the only geologic unit of the High Plains aquifer system in Texas (Dugan and others, 1994). 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 (mostly from the Edwards-Trinity aquifer and augmented by lesser amounts from the Dockum aquifer) are an additional water source in the study area (fig. 1).

Declining groundwater levels have raised concerns about the amount of available groundwater in the study area and the potential for water-quality changes resulting from dewatering and increased vertical groundwater movement between adjacent water-bearing units. Large groundwater withdrawals in localized areas can lower hydraulic heads and cause vertical flow in hydraulically connected aquifer units because groundwater moves from regions of high hydraulic head to low hydraulic head (Pischel and Gannett, 2015). Because groundwater quality generally decreases with depth, the upward groundwater movement within a given aquifer or between hydraulically connected aquifers can degrade water quality (Bartolino and Cunningham, 2003). Changes in water quality in the Ogallala aquifer and in the underlying Edwards-Trinity aquifer can occur as a result of 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 project to develop a regional conceptual model of the hydrogeologic framework and geochemistry of the Ogallala, Edwards-Trinity, and Dockum aquifers. This report describes the results of the first phase of the study, during which groundwater-level altitudes and selected water-quality data from in and near the study area were compiled and evaluated for the Ogallala, Edwards-Trinity, and Dockum aquifers.

Purpose and Scope

The primary purpose of this report is to document differences between early development (1930–60) and recent (2005–15) groundwater-level altitudes and selected water-quality constituents (dissolved-solids and nitrate concentrations) for the Ogallala, Edwards-Trinity, and Dockum aquifers. Potentiometric-surface maps are used to depict changes in groundwater-level altitudes for the Ogallala and Edwards-Trinity aquifers. Water-quality changes and spatial depictions of dissolved-solids and nitrate concentrations of the early development and recent periods are evaluated and described in this report. In addition to comparing groundwater-level altitudes and water quality from the early development and recent periods, hydrographs of groundwater-level altitudes and discussions of changes in water quality for various periods between 1930 and 2015 are provided. Few data were available for the Dockum aquifer, so observations regarding changes in groundwater-level altitudes and water quality pertaining to this aquifer were cursory compared to observations pertaining to the Ogallala and Edwards-Trinity aquifers.

Description of the Study Area

The study area (fig. 1) is bounded by the extents of the LEUWCD, SLUWCD, and SPUWCD management areas and consists of Gaines, Terry, and Yoakum Counties and part of Hockley County, Tex. The total study area covers approximately 3,227 square miles (mi^2), including 1,525 mi^2

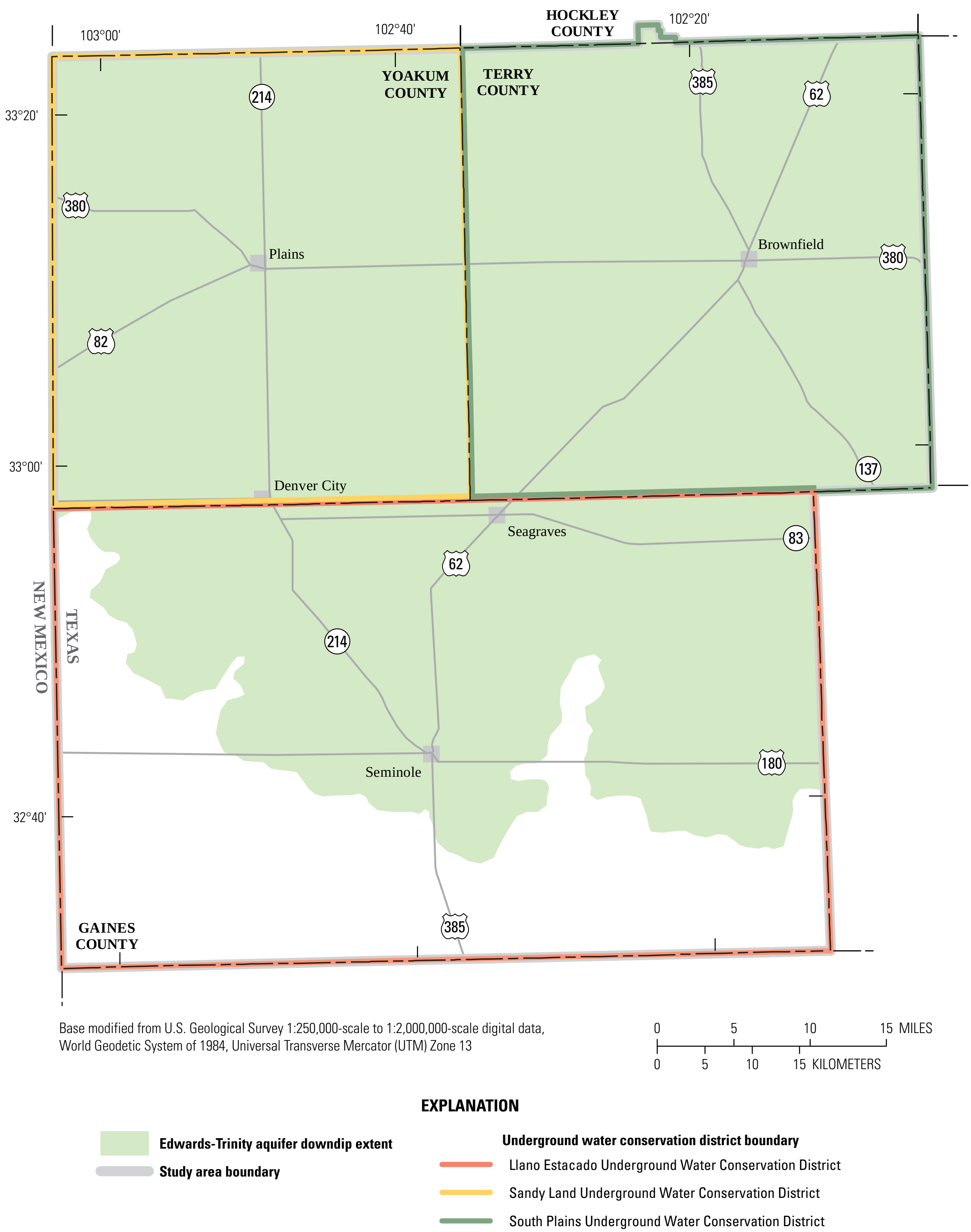

Figure 1. The study area composed of the areas of jurisdiction of Llano Estacado Underground Water Conservation District, Sandy Land Underground Water Conservation District, and South Plains Underground Water Conservation District and downdip extent of the Edwards-Trinity aquifer in and near Gaines, Terry, and Yoakum Counties, Texas.

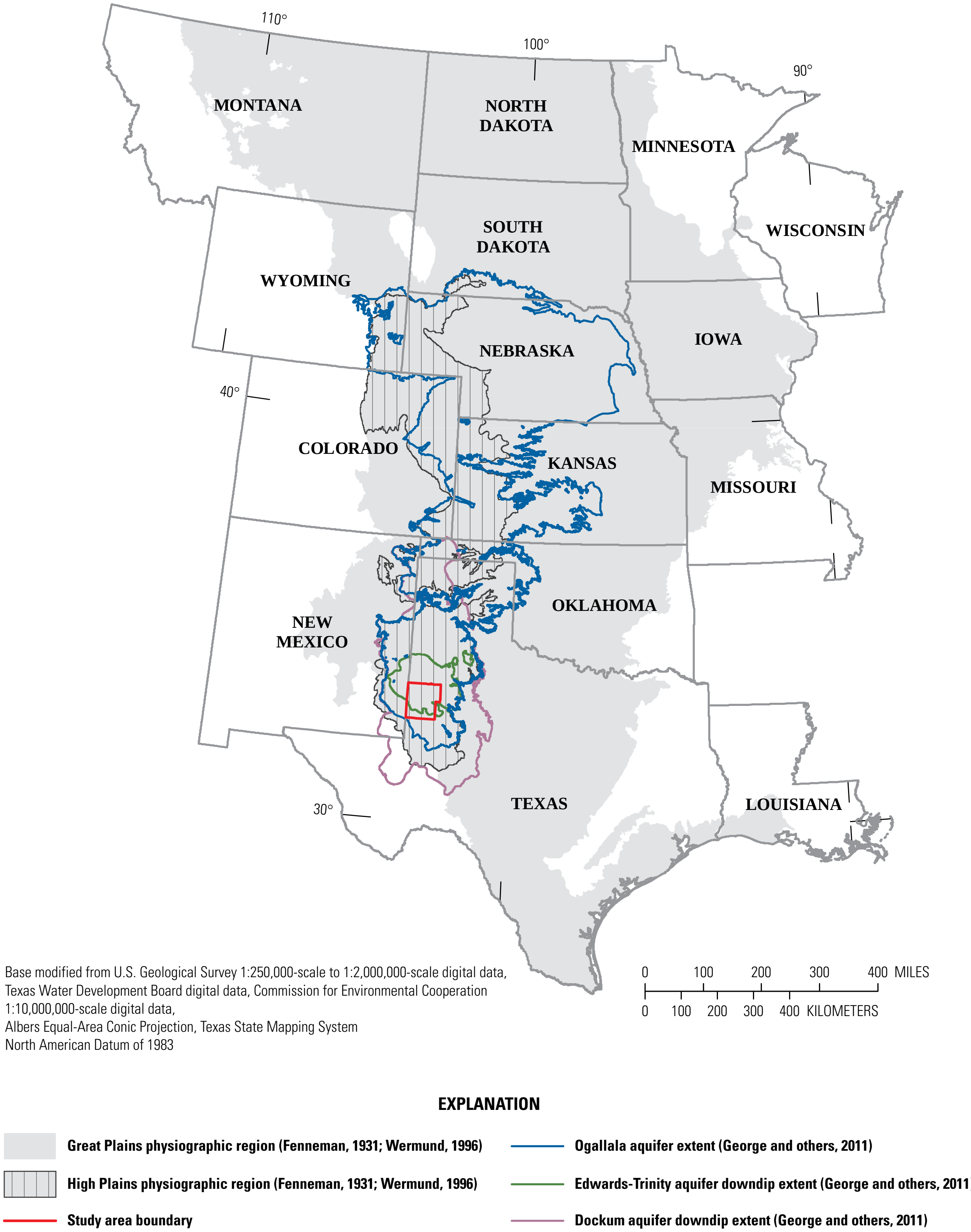

Figure 2. The location of the study area within the full, regional extent of the major aquifers and physiographic regions included in the study.

in LEUWCD, 798 mi^2 in SLUWCD, and 902 mi^2 in SPUWCD (Llano Estacado Underground Water Conservation District, 2015; Sandy Land Underground Water Conservation District, 2015; South Plains Underground Water Conservation District, 2015). The study area is in the Great Plains physiographic region (fig. 2) and consists of an elevated and relatively undissected plain (U.S. Geological Survey, 2015a). The population of the study area is slightly more than 38,000 (U.S. Census Bureau, 2015). The combination of minimal topographic relief, availability of groundwater for irrigation, and excellent soils makes this an important agricultural region in Texas (U.S. Geological Survey, 2015a).

The climate of the study area is semiarid (Larkin and Bomar, 1983). Precipitation in the study area averages approximately 18.8 inches each year, mostly in the form of rain; about 5.2 inches of snow falls each year (National Oceanic and Atmospheric Administration, 2015). The potential evapotranspiration greatly exceeds average annual precipitation; Larkin and Bomar (1983) reported average annual gross lake surface evaporation rates ranging from 75 to 79 inches for the study area. The average temperature for the study area is approximately 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, 2015).

Hydrogeologic Setting

The Ogallala aquifer is the largest aquifer in the United States and is composed primarily of poorly sorted gravel, sand, silt, and clay deposits (Texas Water Development Board, 2015a). The late Miocene- to early Pliocene-age Ogallala aquifer consists of heterogeneous sequences of gravel and coarse-grained sand in the lower portion and grades upward into sand, silt, and clay (Peckham and Ashworth, 1993). Dissolved-solids concentrations in the Ogallala aquifer vary from less than 600 to more than 6,000 milligrams per liter (mg/L) within Gaines County (Llano Estacado Underground Water Conservation District, 2015). In many areas, groundwater moves vertically between the Ogallala Formation and the underlying Cretaceous- and Triassic-age formations (fig. 3) (Ashworth and Hopkins, 1995). The Cretaceous-age Edwards-Trinity aquifer is a minor aquifer (George and others, 2011) that underlies the Ogallala aquifer (fig. 3) except in the southern part of the study area. Water-bearing units in the Edwards-Trinity aquifer include the sandstone of the Trinity Group and limestone of the overlying Edwards Group (fig. 3). Groundwater from the Edwards-Trinity aquifer is typically slightly saline (1,000–3,000 mg/L) and contains more dissolved solids than does groundwater from the overlying Ogallala aquifer (George and others,

Geologic and hydrogeologic units within the spatial extent of the Edwards-Trinity aquifer			
Era	**Period**	**Series or group**	**Hydrogeologic unit**
Cenozoic	Tertiary	Late Miocene to Pliocene	Ogallala aquifer
Mesozoic	Cretaceous	Fredericksburg Group	Edwards-Trinity aquifer
		Trinity Group	
	Triassic	Dockum Group	Dockum aquifer

Geologic and hydrogeologic units outside the spatial extent of the Edwards-Trinity aquifer			
Era	**Period**	**Series or group**	**Hydrogeologic unit**
Cenozoic	Tertiary	Late Miocene to Pliocene	Ogallala aquifer
Mesozoic	Triassic	Dockum Group	Dockum aquifer

Figure 3. Geologic and hydrogeologic units in and near Gaines, Terry, and Yoakum Counties, Texas. (Series and groups modified from Knowles and others, 1984; hydrogeologic units modified from Clark and others, 2014.)

2011). Most of the dissolved-solids concentrations are between 1,000 and 2,000 mg/L (George and others, 2011). The Dockum aquifer is composed of the Triassic-age Dockum Group (fig. 3) and underlies the Ogallala and Edwards-Trinity aquifers throughout much of the High Plains physiographic region (fig. 2). The Dockum Group is composed of sandstone, siltstone, mudstone, and shale that were originally deposited in fluvial and lacustrine environments (McGowen and others, 1979). Groundwater in the Dockum aquifer is characterized by decreasing quality with depth, mixed geochemistry, high concentrations of dissolved solids and other constituents that exceed secondary drinking water standards (U.S. Environmental Protection Agency, 2016), and high concentrations of sodium that may negatively affect irrigated land (Bradley and Kalaswad, 2003).

Data Compilation

Readily available digital groundwater data (geologic, well-construction, groundwater-level-altitude, and selected water-quality data) for the study area were compiled to assess temporal and spatial changes in groundwater resources in and near Gaines, Terry, and Yoakum Counties from 1930 to 2015. Pertinent data were compiled from available sources for the study area and for a 5-mile buffer area around the study area to prevent gridding errors near the boundary.

Groundwater-level-altitude and water-quality data were compiled from various agencies. More than 19,000 groundwater-level-altitude measurements collected from more than 1,800 wells were obtained from databases maintained by the USGS (U.S. Geological Survey, 2015b), the Texas Water Development Board (TWDB) (Texas Water Development Board, 2015b), and the three UWCDs (LEUWCD, written commun., 2015; SPUWCD, written commun., 2015; SLUWCD, written commun., 2015) (tables 1–3). More than 4,400 dissolved-solids and nitrate concentration samples from 1,500 wells were also compiled from the three UWCDs (LEUWCD, written commun., 2015; SPUWCD, written commun., 2015; SLUWCD, written commun., 2015), the National Water Information System (NWIS) (U.S. Geological Survey, 2015b), and the TWDB (Texas Water Development Board, 2015b) (tables 4–9).

Discrete water-quality data were compiled for the study area from databases maintained by the TWDB, LEUWCD, SLUWCD, and SPUWCD. Data obtained from the TWDB were downloaded for each county in the study area and for a 5-mile buffer area surrounding the study area from the TWDB groundwater database (https://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp). Groundwater-level-altitude and dissolved-solids and nitrate concentration data were evaluated by the authors and are presented in tables in this report.

Nitrate values reported by the TWDB as nitrate (nitrate as NO_3) were converted to nitrate values as nitrogen (nitrate as N) by multiplying NO_3 values by 0.2259. These values were converted so that the TWDB data could be directly compared with other compiled nitrate data and because the maximum contaminant level for nitrate in finished drinking water is for nitrate as N (concentrations of constituents measured in untreated groundwater samples are often compared to maximum contaminant levels [MCLs] for drinking water as a point of reference; U.S. Environmental Protection Agency, 2016). Additional information on TWDB data, metadata, and quality-control procedures can be found at http://www.twdb.texas.gov/groundwater/faq/faqgwdb.asp. Methods of analysis for data in the TWDB groundwater database are not indicated in the datasets; however, analyzing and collecting agencies are identified, as well as whether the ion balance was good or poor (when a complete chemical analysis of major ions is conducted, good ion balance is an indicator that analytical methods have been performed satisfactorily [Hem, 1985]).

Since their establishments, the UWCDs have collected various types of groundwater data to monitor changes in groundwater levels and water quality for the primary aquifers in their jurisdictions. These data were provided electronically by each district for their respective jurisdictions to the USGS for inclusion in this study. Data were analyzed by various analytical chemistry methods including colorimetric and spectrophotometric methods (SLUWCD, written commun., 2015). These data are reviewed and maintained in machine-readable format by the UWCDs. Nitrate concentration values provided by the UWCDs were reported as nitrate as N.

Because the data were collected and processed during a period of many years (1930–2015) by various agencies using several different methods and standards, limitations of the data are not well known. Data values flagged by the reporting agency as containing possible errors were removed from the dataset and not included in interpretations; for example, any data downloaded from the TWDB flagged as “unsatisfactory” were removed.

To help identify and evaluate outliers, data from nearby wells were compared with each other. When an outlier was identified, the value was reviewed; that is, the original data source was checked to confirm that no typographical errors occurred and that the well location was verified. Outliers were removed if review of the original data source indicated that errors occurred during collection or analysis or if the value varied from previous data collected at the same well or nearby wells by more than an order of magnitude. For example, a maximum nitrate concentration value of 314 mg/L reported for a sample collected in 2008 in Terry County was an extreme outlier; previous nitrate concentrations measured in 1996 and 2004 in samples collected from the same well were 21.4 and 28.4 mg/L, respectively. The original laboratory report was obtained and reviewed to ensure that there was not a typographical error and that the correct value was used from the laboratory analysis. Because this value was an extreme outlier and more than an order of magnitude greater than previously reported data, it was removed from the dataset and not used in interpretations.

Some compiled results from SLUWCD were presented as a measured concentration of 0.0 mg/L. Because a spectrophotometer instrument was used to analyze these data, 0.0 is a possible answer, as spectrophotometers do not have an analytically derived reporting limit. Spectrophotometers have an optimal detection level that should not be confused with a reporting limit. The spectrophotometric method used in this instance had an optimal range of 0.23–13.5 mg/L of nitrate as N (Amber Blount, SLUWCD, written commun., 2015). A review by the USGS indicated that the data seemed reasonable (within an acceptable range and comparable to nearby data) and could not be classified as erroneous; therefore, 0.0 mg/L concentrations should be considered a nondetect result.

Data Processing and Interpretation

Geologic and well-construction data (compiled along with the groundwater data) were used to determine or verify the aquifer in which each well was completed. Depending on the available data, the aquifer assignment (aquifer 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 completed aquifer reported for a given well by the data source. Screened or open intervals and total depths of the wells were compared to the geologic information for areas near the well to determine or verify the correct aquifer assignment for each well. For wells with screened or open interval information, the aquifer was assigned on the basis of the geologic unit in which the screened or open interval was completed. If the well had multiple screened or open intervals, the top of the uppermost screened or open interval and the bottom of the lowermost screened or open interval were used to determine the correct aquifer assignment. Wells with screened or open intervals completed in multiple aquifers were flagged and not included in the report. If no screened or open interval was reported for a well, then the total depth of the well was used to determine the aquifer assignment, with the assumption that the well was cased to the bottom depth of the well and the opening of the well was at or near the base of the well. For wells without screened interval, open interval, or total depth information, the aquifer assignment reported by the data source was used. Groundwater data were compared with data obtained from nearby wells that had the same aquifer assignment to ensure that they were representative of the assigned aquifer.

Potentiometric-surface maps of groundwater-level altitudes and maps showing representations of water quality were created to help assess temporal and spatial changes in groundwater across the study area and within each aquifer. To help evaluate water-level data, the mean groundwater-level altitude during 1930–60 (hereinafter referred to as the “early development period”) for each well was determined for the dormant season, defined as November through April in this report. (The dormant season is when groundwater withdrawals are typically lower compared to the rest of year because most 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 relatively unaffected by drawdown and cones of depression (Heath, 1983). The mean dormant season groundwater-level altitude for each well during 2005–15 (hereinafter referred to as the “recent period”) was used to make a potentiometric-surface map representing the recent period groundwater-level altitudes in the study area. Using mean data for relatively long time periods helped to ensure sufficient data coverage and that the data are not biased by a single-year event such as extreme drought or wet period in the study area.

Because groundwater levels are measured as depth to water below land surface and because hand-held Global Positioning System devices (commonly used for reported elevations) typically have poor vertical accuracy, groundwater-level altitudes were calculated by subtracting the depth to water below land surface from a digital elevation model in order to provide consistency and improve accuracy. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (National Aeronautics and Space Administration, 2015) was used to determine the land-surface altitude across the study area.

Groundwater-level-altitude data consist of x and y values (latitude and longitude coordinates) and one or more z values (measured groundwater-level altitudes). The process of gridding interpolates x, y, and z data spatially. The resultant dataset is referred to as a “grid” (Geosoft, 2015). To help evaluate the accuracy of groundwater-level-altitude data, histograms were produced of the groundwater-level altitudes to identify anomalous data that could indicate inaccurate well information, data collection issues, or incorrect aquifer assignment for the completed interval of a well. A few groundwater-level-altitude values were excluded either because they were flagged as potentially erroneous by the reporting agency or because they differed greatly from groundwater-level-altitude values obtained from nearby wells completed in the same aquifer. Potentiometric-surface maps for the Ogallala and Edwards-Trinity aquifers were created by using Oasis montaj (Geosoft, 2015). There were insufficient data to create potentiometric-surface maps for the Dockum aquifer.

Kriging algorithms in Oasis montaj were used to determine the most probable value at each grid node (2,000 meters [m] by 2,000 m) on the basis of a statistical analysis of the entire dataset for each grid (Isaaks and Srivastava, 1989). This kriging method was chosen in part because of its utility for assessing clustered data such as well fields or multiple measurements for a single well. Variance maps automatically developed during the kriging process were used to evaluate the uncertainty in the potentiometric-surface contours. Generally, as the distance between data points becomes greater, correlation between points lessens, and uncertainty in areas between points increases (Isaaks and Srivastava, 1989). These variance maps were used to clip (that is, exclude beyond a certain spatial extent) the final potentiometric-surface grids to certain areas such that only those data with acceptable uncertainty values were retained.

Groundwater-level-altitude grids were reviewed for anomalies. In areas where anomalies were identified, groundwater-level altitudes were evaluated for consistency with nearby wells completed in the same aquifer. After the initial grids were completed, a few additional data determined to be anomalous were also excluded from the revised grids. To generate temporal groundwater-level-change grids for the Ogallala and Edwards-Trinity aquifers, the gridded surfaces for the early development period were subtracted from the gridded surfaces for the recent period.

Over time, the quality of groundwater can change as a result of chemical reactions among the constituents dissolved in the water, reactions between these constituents and dissolvable minerals in the rocks through which the water flows (water-rock interaction), and mixing of water from different sources with varying chemistry (Elango and Kannan, 2007; Bumgarner and others, 2012). The distribution of dissolved solids and nitrate concentrations are useful indicators of groundwater quality in west Texas (Reeves and Miller, 1978). When multiple samples from a given well were collected and analyzed for dissolved-solids and nitrate concentrations during early development or recent periods, median concentrations were calculated. Dissolved-solids and nitrate concentration values were plotted spatially to depict how the concentrations of these constituents varied throughout the study period during a given period (early development or recent periods) and to depict changes in concentrations between these two periods. Dissolved-solids and nitrate concentrations can change over time as a direct result of processes related to agriculture, such as evaporation of irrigation water and the application of fertilizers that introduce minerals in the near-surface soil (Hudak and others, 2000). Because there is a strong and positive correlation between dissolved-solids concentrations and salinity, the concentrations of dissolved solids are used to evaluate the salinity of water (Winslow and Kister, 1956). Dissolved solids were of particular interest because of the extensive agriculture in the study area; elevated salinity can inhibit or prevent the growth of crops (Fipps, 2003). Nitrates, generally found in fertilizers and manure, can be a health concern in potable water supplies (Dozier and others, 2008), and excess nitrates not absorbed by the crops or vegetation can migrate in excess irrigation water down to the water table, increasing nitrate concentrations in groundwater (Hudak and others, 2000).

To avoid the possibility of introducing a short-term bias associated with droughts or excessively wet periods and to ensure sufficient data coverage, median concentrations for water-quality data were calculated for both the early development and recent periods. Additionally, before median concentrations were calculated, data were spatially evaluated to identify anomalous areas that could indicate inaccurate well information, errors in data collection, or data records in which the incorrect aquifer was assigned for a given well. All data were reviewed to identify any obvious typographical errors. The remaining suspect data were not used in the development of the water-quality maps. Early development and recent period water-quality maps for the Ogallala and Edwards-Trinity aquifers were compared to evaluate changes in groundwater quality from the early development period to the recent period.

Groundwater-Level Altitudes in the Ogallala, Edwards-Trinity, and Dockum Aquifers from 1930 to 2015

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. Groundwater-level-altitude data were compiled for the Ogallala and Edwards-Trinity aquifers within the study area and gridded to evaluate groundwater-level changes for each aquifer. Variance maps for each groundwater-level-altitude grid were used to evaluate the spatial data coverage and to identify and remove areas with higher uncertainty caused by spatially limited data availability for some aquifers (tables 1–3).

Ogallala Aquifer

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, varying by as much as 800 feet (ft). For the early development and recent periods, the highest groundwater-level altitudes (about 3,750 ft above the North American Vertical Datum of 1988 [NAVD 88]) were in the northwestern corner of the study area (figs. 4 and 5, sheet 1). Groundwater flow paths for the early development period generally trend from northwest to southeast across the study area.

In the Ogallala aquifer, patterns in groundwater-level altitudes and flow paths for the recent period are diverse relative to the early development period. Compared to those for the early development period, local features in the potentiometric surface for the recent period are more pronounced (figs. 4 and 5, sheet 1), likely as a result of additional data coverage, increased groundwater withdrawals, and local flow paths that are more variable. As shown on the recent period map (fig. 5, sheet 1), groundwater in the northwestern corner of the study area flows east or southeast until near the border of Terry and Yoakum Counties, where groundwater then either flows east into Terry County or southeast. Groundwater near the border of Terry and Yoakum Counties changes direction and flows south near the town of Brownfield, Tex. Northwest of the town of Denver City, Tex., groundwater flows southeast, whereas groundwater to the southwest of Denver City generally flows south from Denver City and then east-southeast near the town of Seminole, Tex. Groundwater flow in the southwestern corner of the study area is generally to the east and then to the southeast (fig. 5, sheet 1).

Groundwater-level-altitude changes of the Ogallala aquifer between the early development and recent periods (fig. 6, sheet 1) indicate that groundwater-level altitudes declined primarily in western Gaines County, southwestern Yoakum County, central Terry County, and in the central part of the study area near the city of Seagraves, Tex., with the greatest declines occurring in northwestern Gaines County. Areas with increased groundwater-level altitudes were primarily observed in eastern Gaines County, eastern Yoakum County, and parts of both eastern and western Terry County (fig. 6, sheet 1). The greatest increases in groundwater-level altitudes occurred near the border of Yoakum and Terry Counties northeast of Plains, Tex. Within the areas with reliable data coverage, the groundwater-level-altitude change ranged from a 174-ft decline in northwestern Gaines County to a 66-ft rise northeast of Plains (fig. 6, sheet 1).

Hydrographs of selected wells across the study area (fig. 6, sheet 1; table 10) show groundwater-level altitudes varying temporally in the Ogallala aquifer. The hydrograph from well 11392, located in the southeastern part of the study area, shows increasing groundwater-level altitudes from around 1979 to early 1987 but then relatively stable groundwater-level altitudes through 2012 (fig. 6, sheet 1). The hydrograph from well 10128, located in the northeastern part of Terry County, shows relatively stable groundwater-level altitudes from 1960 to 2013 (fig. 6, sheet 1). Hydrographs of wells 10577 and 11171, in western Gaines County, show varying rates of generally declining groundwater-level altitudes from the early 1960s to 2015.

Edwards-Trinity Aquifer

Evaluation of the variance maps for the early development and recent periods indicated that the data coverage across the study area was poor for the Edwards-Trinity aquifer (figs. 7 and 8, sheet 1) compared to the data coverage for the Ogallala aquifer. Because of the smaller dataset, the discussion of the potentiometric-surface maps prepared for the Edwards-Trinity aquifer is more generalized compared to the discussion of those for the Ogallala aquifer. For the early development and recent periods, the highest groundwater-level altitudes for the Edwards-Trinity aquifer were about 3,800 ft in the northwestern part of the study area (figs. 7 and 8, sheet 1), and the lowest altitudes were about 3,000 ft along the southeastern extent of the aquifer within the study area. Groundwater-level altitudes declined to the southeast for the Edwards-Trinity aquifer, indicating that groundwater flows from northwest to southeast.

For the Edwards-Trinity potentiometric-surface map of the recent period, a general northwest to southeast flow gradient was also evident, with some subtle differences compared to the early development period (figs. 7 and 8, sheet 1). For example, north of Plains, the groundwater flows east and then southeast in eastern Terry County. West of Plains, the groundwater generally flows south and then flows southeast in Gaines County. Near Denver City, groundwater flows to the southeast before flowing slightly more to the south, east of Seminole.

Because of the limited dataset for the early development and recent periods, the potentiometric-surface change is shown for limited areas (those for which adequate data were available) and is generalized. The map showing Edwards-Trinity aquifer water-level-altitude change between the early development and recent periods (fig. 9, sheet 1) indicated similar spatial trends as those in the Ogallala aquifer; groundwater-level altitudes declined over a large amount of the area for which sufficient data were available. Water levels in these areas declined a maximum of 61 ft, with the greatest decline occurring southwest of Denver City. Some increases in the groundwater-level altitudes were mapped north and east of Plains in Yoakum County, in northeastern and southeastern parts of Terry County, and in localized parts of far eastern Gaines County (fig. 9, sheet 1).

Hydrographs of selected wells across the study area showed varying temporal groundwater-level altitudes. The hydrographs from wells 10223, 10621, and 10741 depict an overall decline in groundwater-level altitudes from around 1960 to 2015, whereas the hydrograph from well 10071 depicts a slight increase in groundwater-level altitudes from 1968 to 2015 (fig. 9, sheet 1; table 10). The hydrograph from well 10621, west of Denver City, shows a relatively consistent general pattern of declining groundwater-level altitudes, whereas the other three hydrographs show greater variations in groundwater-level altitudes during the period of record (fig. 9, sheet 1). The hydrograph from well 10223, west of Brownfield, depicts the most pronounced variation in groundwater-level-change patterns, with declining groundwater-level altitudes from early development to the late 1960s, increasing altitudes into the late 1980s, and then declining altitudes through recent conditions (fig. 9, sheet 1).

Dockum Aquifer

Groundwater-level-altitude data were available from only a few wells completed in the Dockum aquifer. The available data were used to provide additional generalized insights regarding groundwater flow gradients and temporal and spatial changes in the Ogallala and Edwards-Trinity aquifers (table 3).

Similar to those for the Ogallala and Edwards-Trinity aquifers, groundwater-level altitudes for the Dockum aquifer were highest to the northwest of the data extent, at more than 3,500 ft, and lowest to the southeastern part of Gaines County, at about 3,000 ft. This gradient indicates a regional groundwater flow path for the Dockum aquifer, from the northwest to the southeast of the study area. Compiled early development and recent groundwater-level altitude data were primarily from wells in Gaines County in the southern part of the study area, with only a few measurements in the northern part of the study area. Generalized grids of groundwater-level-altitude changes indicate that a decline of about 100 ft occurred from the early development to recent periods.

Changes in Dissolved-Solids and Nitrate Concentrations in the Ogallala, Edwards-Trinity, and Dockum Aquifers from 1930 to 2015

For this report, existing dissolved-solids and nitrate concentration data were compiled and assessed for evidence of spatial patterns and changes over time (tables 4–9). These data were compiled for samples collected from wells completed in the Ogallala, Edwards-Trinity, or Dockum aquifers during the early development period or the recent period; temporal and spatial variations were assessed from depictions of the measured concentration values. Often, more than one dissolved-solids or nitrate sample was available for a given well during the early development or recent period, so median concentrations were calculated for each well with multiple samples per time period. Dissolved-solids and nitrate concentrations measured in samples from three wells completed in the Ogallala aquifer (wells 11524, 11824, and 11825) where long-term monitoring was done for various periods between 1962 and 2014 were also compiled and analyzed (table 11).

Ogallala Aquifer

Dissolved-solids concentration data representing the early development period were available for only 24 samples collected from 22 wells completed in the Ogallala aquifer (table 4). Dissolved-solids concentrations measured in these 23 samples ranged from 433 mg/L in southwestern Gaines County, southwest of Seminole, to about 2,380 mg/L in eastern Terry County, southeast of Brownfield (fig. 10, sheet 2). In general, dissolved-solids concentrations appeared to increase from west to east.

Compared to those for the early period, considerably more dissolved-solids concentration data were available for the recent period from wells completed in the Ogallala aquifer (1,700 samples collected from 355 wells). During the recent period, median dissolved-solids concentrations of less than 1,000 mg/L (the upper limit for freshwater indicated by Winslow and Kister, 1956) were predominantly measured in the western part of the study area, and median dissolved-solids concentrations of more than 1,000 mg/L were predominantly measured in the eastern part of the study area (fig. 11, sheet 2). For samples collected from wells completed in the Ogallala aquifer, dissolved-solids concentrations in the recent period ranged from 73 mg/L in northeastern Yoakum County, northeast of Plains, to about 8,000 mg/L in southeastern Gaines County, southeast of Seminole (table 4). All samples with median dissolved-solids concentrations higher than 3,000 mg/L were collected from wells in the far eastern part of the study area (fig. 11, sheet 2). A dissolved-solids concentration between 3,000 and 10,000 mg/L represents moderately saline water (Winslow and Kister, 1956); water with a dissolved-solids concentration greater than 3,000 mg/L is generally considered too salty to drink (Alley, 2003) and can reduce yields from salt-sensitive crops (Fipps, 2003).

Nitrate concentrations measured in 21 samples collected from 19 wells completed in the Ogallala aquifer were compiled for the early development period (table 5). Nitrate concentrations during this period ranged from 0.63 mg/L in northern Gaines County, near Seagraves, to 9.71 mg/L in southern Gaines County, southwest of Seminole; nitrate concentrations of more than 2.5 mg/L were measured in wells in the eastern part of the study area (fig. 12, sheet 2).

For the recent period, nitrate concentrations compiled from 1,271 samples collected from 345 wells completed in the Ogallala aquifer (fig. 13, sheet 2) ranged from 0.0 mg/L in Yoakum County to 23.0 mg/L in northern Gaines County, northeast of Seminole (table 5). A few elevated nitrate concentrations of more than 10 mg/L were widely distributed throughout the study area (fig. 13, sheet 2). Elevated nitrate concentrations were measured (Amber Blunt, SLUWCD, written commun., 2015) primarily in the east-central part of the study area, but there were not any spatial patterns evident for nitrate concentrations. The nitrate concentrations measured in samples collected from 16 wells completed in the Ogallala aquifer for the recent period were equal to or greater than 10 mg/L, the primary drinking water standard for finished drinking water (U.S. Environmental Protection Agency, 2016). This report documents nitrate concentrations in raw ambient groundwater prior to drinking water treatment; the quality of finished drinking water distributed through municipal water-supply systems can differ greatly from the quality of raw drinking water.

To gain a better understanding of temporal changes in water quality, data were compiled from three wells completed within the Ogallala aquifer with long-term water-quality monitoring (more than 25 years of dissolved-solids and nitrate concentration data) (fig. 14, sheet 2; table 11). Dissolved-solids concentration data for these selected wells indicate various water-quality changes. Relatively stable dissolved-solids concentrations ranging from about 680 to about 790 mg/L were measured in the samples from well 11524 (the median concentration was 707 mg/L). Dissolved-solids concentrations measured in samples from well 11824 were variable, ranging from about 470 to about 1,340 mg/L (fig. 14, sheet 2). In the samples collected from well 11825, dissolved-solids concentrations increased from about 420 mg/L in 1975 to 1,030 mg/L in 2008.

In general, the data obtained from these three selected wells with long-term monitoring records indicate that nitrate concentrations increased during the sampling period (table 11). The largest increase in nitrate was measured in samples from well 11824, from 0.2 mg/L in 1990 to 16.1 mg/L in 2013. Maximum increases in nitrate concentrations of about 4.0 mg/L and 7.2 mg/L were measured for the other two wells (wells 11825 and 11524, respectively).

Edwards-Trinity Aquifer

For wells completed in the Edwards-Trinity aquifer, few dissolved-solids concentration data were available for either the early development period (15 samples from 14 wells) or the recent period (18 samples from 12 wells) (table 6). Because of the small number of wells with available dissolved-solids concentration data, the only apparent pattern in dissolved-solids concentrations was a general increase in concentrations from west to east (figs. 15 and 16, sheet 2). Median dissolved-solids concentration values measured in samples from wells completed in the Edwards-Trinity aquifer for the early development period ranged from about 430 mg/L in south-central Yoakum County, near Denver City, to about 2,810 mg/L in central Gaines County, southeast of Seminole (fig. 15, sheet 2). Dissolved-solids concentrations for the recent period ranged from 535 mg/L in northwestern Gaines County, northwest of Seminole, to about 1,900 mg/L in central Gaines County, near Seminole (fig. 16, sheet 2).

For wells completed in the Edwards-Trinity aquifer, few nitrate concentration data were available for either the early development period (13 samples from 12 wells) or the recent period (18 samples from 12 wells) (table 7). Because of the scant number of data values and relatively consistent low concentrations, patterns in nitrate concentrations were not readily apparent. Nitrate concentrations measured in samples from wells completed in the Edwards-Trinity aquifer for the early development period ranged from 0.01 mg/L in south-central Yoakum County, near Denver City, to 2.71 mg/L in south-central Yoakum County (fig. 17, sheet 2). Nitrate concentrations for the recent period were in general appreciably higher compared to those measured in the early development period and ranged from 0.0 mg/L in eastern Gaines County, east of Seminole, to 7.16 mg/L in north-central Gaines County, near Seminole (fig. 18, sheet 2).

Dockum Aquifer

Few dissolved-solids concentration data existed for either the early development period (8 samples from 4 wells) or the recent period (3 samples from 2 wells) for samples collected from wells completed in the Dockum aquifer (table 8). Few nitrate concentration data from wells completed in the Dockum aquifer were obtained for either the early development period (3 samples from 3 wells) or the recent period (3 samples from 2 wells) (tables 8 and 9). Dissolved-solids concentrations measured from wells completed in the Dockum aquifer ranged from 427 mg/L in northwestern Gaines County, just southwest of Denver City, to about 13,430 mg/L in far northeastern Gaines County, northeast of Seminole. Nitrate concentrations measured from wells completed in the Dockum aquifer ranged from 0.6 mg/L in eastern Terry County, east of Brownfield, to 10.9 mg/L in northwestern Gaines County.

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