# Brackish Groundwater in the Woodbine Aquifer, Texas

Sara Sutton, P.G., Mark C. Robinson, P.G., Olga Bauer

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## Geoscientist Seal

The contents of this report (including figures, tables, and plates) document the work of the following licensed Texas geoscientists:

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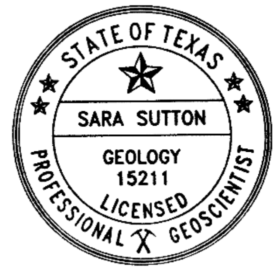


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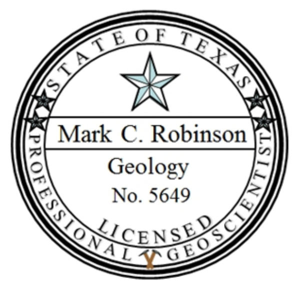


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# 1 Executive summary

The Texas Water Development Board (TWDB) Brackish Resources Aquifer Characterization System (BRACS) Program was established in 2009 to map and characterize the brackish portions of Texas aquifers to provide useful information and data to regional water planning groups and other entities interested in using brackish groundwater as a water supply. Both Texas industry and public water supply planners are looking at brackish groundwater to supplement stressed freshwater resources. Groundwater contains dissolved minerals, measured in units of milligrams per liter, and can be classified as fresh (0 to 1,000 milligrams per liter), brackish (1,000 to 10,000 milligrams per liter), or saline (greater than 10,000 milligrams per liter). The calculated volume of in-place brackish groundwater in the state is currently estimated at more than 3.3 billion acre-feet (including the Woodbine Aquifer). While this total volume may be constrained by other factors limiting long-term availability, brackish groundwater will be an important water supply source that can be used to help meet future water demands. Groundwater desalination strategies in the 2022 State Water Plan represent additional new groundwater supply for nine of the regional planning groups (TWDB, 2024a). Development of these strategies would create an additional supply volume of approximately 97,000 acre-feet per year estimated to be online by 2030, with an additional 157,000 acre-feet per year of groundwater recommended to be in service by 2070.

**Program description**

The goals of the BRACS Program are to 1) map and characterize the brackish parts of the major and minor aquifers of the state in greater detail using existing water well reports, geophysical well logs, and available aquifer data and 2) build datasets that can be used for groundwater exploration and replicable numerical groundwater flow models to estimate aquifer productivity. The BRACS Program uses the information produced from brackish aquifer studies to identify potential brackish groundwater production zones, which are areas that can produce brackish groundwater over 30- and 50-year periods without causing significant impacts to water availability or quality for existing users (Texas Water Code § 16.060).

Since the program was created in 2009, the TWDB has completed 17 brackish aquifer studies; eight of these completed studies are contract reports. There are five ongoing aquifer studies, three of which have been contracted, and four remaining aquifers that will need to be characterized by December 1, 2032. At the time of this report’s publication, the five brackish aquifer studies currently in progress are 1) the Edwards-Trinity (Plateau) Aquifer, 2) the Yegua-Jackson Aquifer,3) the Ellenburger-San Saba Aquifer, 4) the Hickory Aquifer. and 5) the Dockum Aquifer.

**Study area**

The Woodbine Aquifer study area encompasses approximately 15,000 square miles in northeast Texas, including all or parts of 29 counties listed in Section 4 of this report. The study area extends downdip to the south and east from the outcrop area, up to approximately 50 miles beyond the extent of the official TWDB-designated aquifer boundary, and several miles into and downdip of the Mexia-Talco Fault Zone (Figure 1-1).

Portions of regional water planning areas C, D, and G are included in the study area. Groundwater Management Area 8 occupies most of the study area, but limited portions of groundwater management areas 11 and 12 are included. There are six groundwater conservation districts within the Woodbine Aquifer study area. Groundwater from the Woodbine Aquifer is primarily used for municipal and irrigation purposes (TWDB, 2024a).

The 2022 State Water Plan indicates that annual groundwater supplies for the Woodbine Aquifer are projected to decrease 2.5 percent by 2070 (TWDB, 2024a). There are fourteen water user groups that list the development of groundwater from the Woodbine Aquifer as a recommended water strategy in the plan.

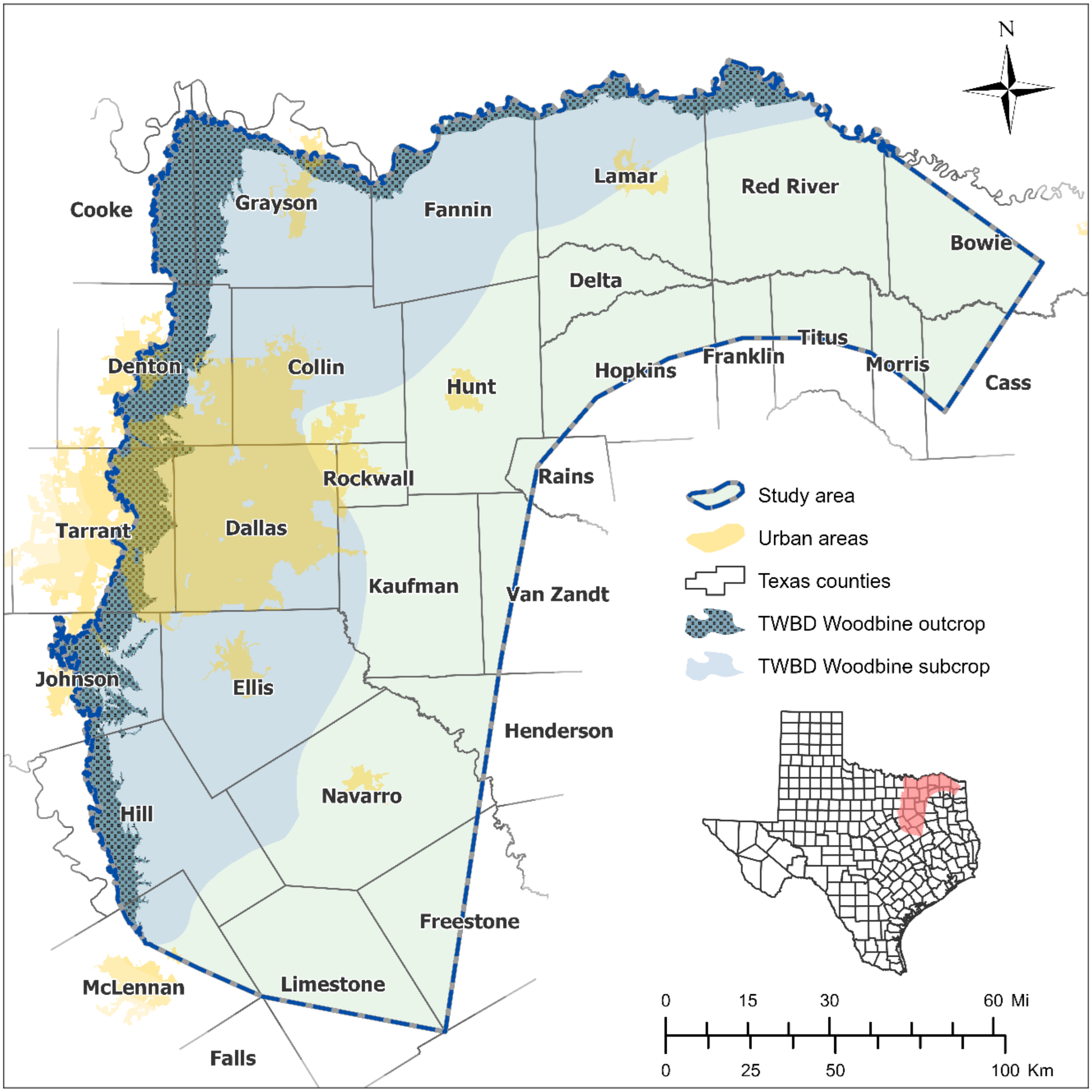


**Figure 1-1 Woodbine Aquifer study area.**

## Salinity distribution

A total of 329 wells were used for total dissolved solids concentration calculations and incorporated into the salinity distribution analysis along with 628 measured water quality samples. Figure 1-2 shows the salinity classes delineated to 1,000; 3,000; 10,000; and 35,000 milligrams per liter of total dissolved solids concentration.

The distribution of slightly saline (1,000 to 2,999 milligrams per liter) groundwater encompasses parts of 14 counties and covers the largest lateral extent of the five salinity classes within the study area. Localized pockets of slightly saline groundwater are present within the outcrop region where freshwater would generally be expected. The increased salinity in the outcrop area is likely due to elevated sulfate concentrations associated with the presence of lignite beds within the Woodbine Group (Baker, 1960; Baker and others, 1990). Structural complexities in the northwestern portion of the study area may also impact the distribution of slightly saline groundwater in this area.

Moderately saline (3,000 to 9,999 milligrams per liter) groundwater occupies a relatively narrow band west and north of the Mexia-Talco Fault Zone across parts of 13 counties in the study area. Moving down-dip, approaching the fault zone, salinity increases rapidly from very saline (10,000 to 34,999 milligrams per liter) to brine (greater than 35,000 milligrams per liter). Due to the limited sand content present in the far southern portion of the study area, salinity characterization was not performed, as denoted by a cutoff line.

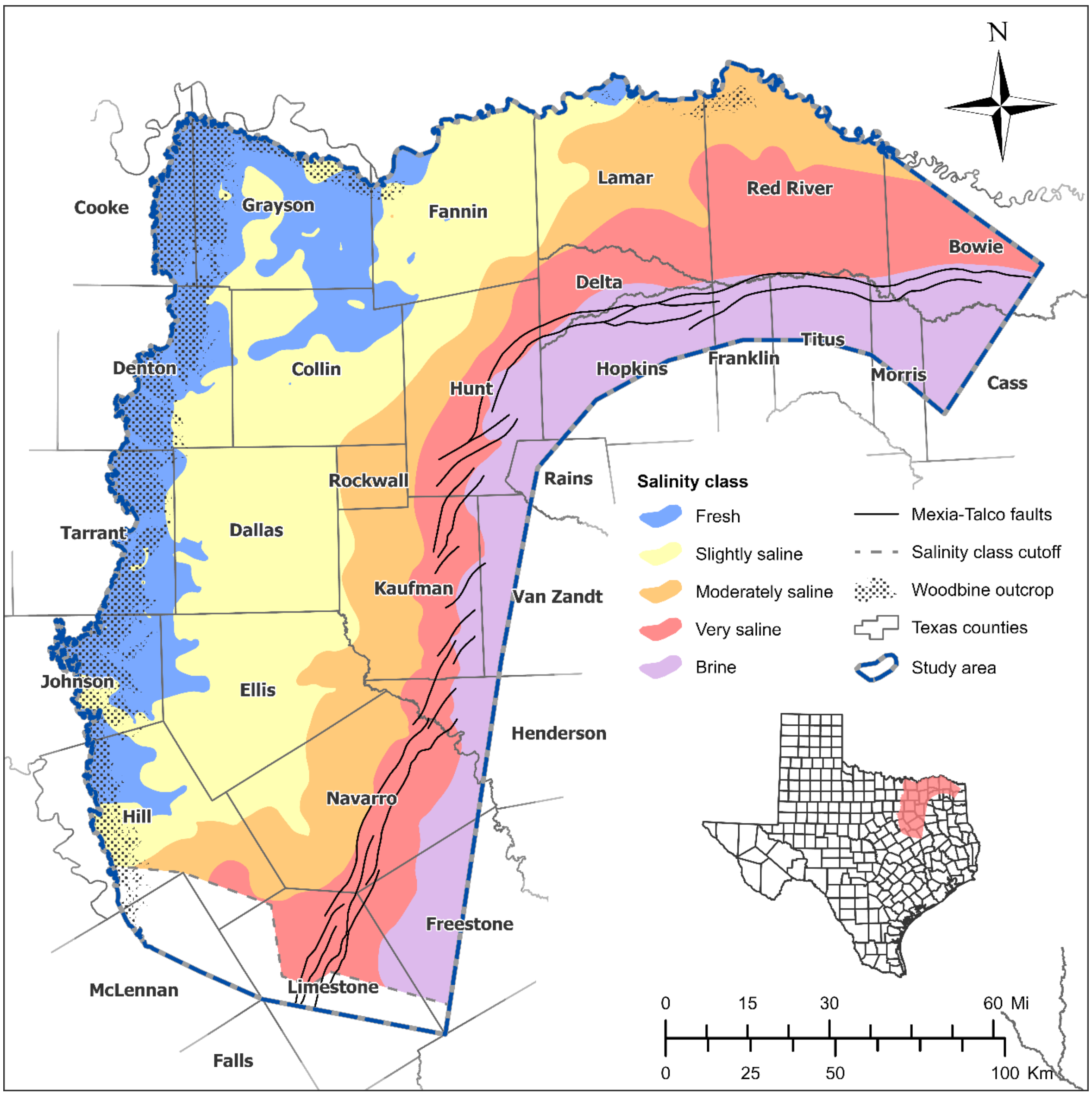


**Figure 1-2 Woodbine Aquifer salinity map.**

## Brackish groundwater volumes

We estimate that the Woodbine Aquifer has a total in-place brackish aquifer storage volume of approximately 120.4 million acre-feet with total dissolved solids concentrations between 1,000 and 9,999 milligrams per liter (Table 1-1). The in-place total brackish storage volume is the sum of 72.7 and 47.7 million acre-feet of slightly saline and moderately saline groundwater, respectively. Total volume of groundwater with salinity ranging from 1,000 milligrams per liter to 34,999 milligrams per liter is estimated to be approximately 170 million acre-feet.

**Table 1-1 Total estimated brackish storage volume in the Woodbine Aquifer per salinity class (in millions of acre-feet).**

| Salinity zone | Slightly saline | Moderately saline | Total brackish volume | Very saline | Total volume including very saline |
|---|---|---|---|---|---|
| **Total** | 72.7 | 47.7 | **120.4** | 49.5 | **169.9** |

## Important note

The in-place aquifer storage volumes calculated in this study are estimates to provide insight into the magnitude and distribution of this important resource. We recommend that site-specific studies be conducted to support projects and efforts that will incorporate brackish groundwater resources into water resources planning.

The TWDB uses the information produced from this study to identify potential brackish groundwater production zones, which are areas that can produce brackish groundwater over 30- and 50-year periods without causing significant impacts to water availability or quality for existing users.

In designating brackish groundwater production zones, the TWDB is guided by exclusionary criteria in Texas Water Code § 16.060 that is designed to prevent significant adverse impacts to existing water wells and water quality. These criteria limit production to areas where long-term pumping is unlikely to interfere with fresh groundwater availability or degrade water quality. As a result, the volumes that can be produced from designated brackish groundwater production zones are reduced by orders of magnitude compared to the total in-place storage volumes, underscoring the importance of careful planning and site-specific evaluation for projects within designated zones or in brackish portions of aquifer outside of designated zones.

It is also important to note that in-place storage volume estimates are not the same as the TWDB-calculated total estimated recoverable storage volumes, which are confined to the aquifer boundaries used by TWDB groundwater availability models and provided to groundwater conservation districts for planning purposes. Furthermore, the area, saturated thickness, and storage parameters used in the calculations for this study are different from those used in total estimated recoverable storage reports (Shi and others, 2014; Wade and others, 2014; Wade and Shi, 2014). Finally, the in-place storage volume estimates are not an estimate of recoverable volume.

Not all brackish groundwater can be produced or economically developed. These volumes do not consider the effects of land surface subsidence, degradation of water quality, or any changes to surface water-groundwater interaction that may result from extracting groundwater from the aquifer. These volumes should not be used for joint planning or evaluation of achieving adopted desired future conditions in the same way total estimated recoverable storage and modeled available groundwater are used according to the joint planning process described in Texas Water Code § 36.108.

# 2 Introduction

Brackish groundwater was first mapped in Texas by Winslow and Kister (1956) with the U.S. Geological Survey in a study focused on identifying the occurrence, quantity, and quality of saline aquifers. Nearly two decades later, a Texas Water Development Board (TWDB) study performed a detailed analysis and inventory of the saline aquifers of Texas using a significant quantity of core data (Core Laboratories, 1972). Based on brackish aquifer studies completed by the TWDB so far, including the Woodbine Aquifer, the calculated in-place storage volume of brackish groundwater in the state is estimated at more than 3.3 billion acre-feet.

The TWDB Brackish Resources Aquifer Characterization System (BRACS) Program was established in 2009 to map and characterize the brackish portions of the aquifers in Texas and provide useful data to regional water planning groups and other entities interested in developing and desalinating brackish groundwater as a new water supply.

In 2015, the 84th Texas Legislature passed House Bill 30 (now codified in Texas Water Code § 16.060), which directs the TWDB to 1) identify and designate brackish groundwater production zones in the state, 2) determine the volumes of groundwater that a brackish groundwater production zone can produce over 30- and 50-year periods without causing significant impact to water availability or water quality, 3) make recommendations on reasonable monitoring to observe the effects of brackish groundwater production within that zone, 4) work with groundwater conservation districts and stakeholders, and 5) provide a summary of brackish groundwater production zone designations in a biennial progress report on seawater and brackish groundwater desalination activities, due December 1 of each even-numbered year. Brackish aquifer studies (also called BRACS studies) are necessary before assessing potential brackish groundwater production zones. An evaluation of potential productions zones for the brackish portion of the Woodbine Aquifer will be conducted at a later date.

In 2019, the 86th Texas Legislature passed Senate Bill 1041, extending the deadline to complete zone designations from December 1, 2022 to December 1, 2032, and House Bill 722, establishing a groundwater conservation district permitting framework for developing water supplies from TWDB-designated brackish groundwater production zones. In January 2021, the TWDB adopted rules to implement the permitting requirements codified in Texas Water Code § 36.1015.

The TWDB has completed 17 brackish aquifer studies; eight of these completed studies are contract reports. There are five ongoing aquifer studies, three of which have been contracted, and four remaining aquifers that will need to be characterized by December 1, 2032. At the time of this report's publication, the five brackish aquifer studies currently in progress are 1) the Edwards-Trinity (Plateau) Aquifer, 2) the Yegua-Jackson Aquifer,3) the Ellenburger-San Saba Aquifer, 4) the Hickory Aquifer. and 5) the Dockum Aquifer.

For each brackish aquifer study, TWDB staff make every effort to collect as much geological, geochemical, geophysical, and well data as is available in the public domain at that time to map and characterize both the vertical and horizontal extent of the aquifers. Groundwater is classified into five salinity classes (Table 2-1): 1) fresh, 2) slightly saline, 3) moderately saline, 4) very saline, 5) and brine (Winslow and Kister, 1956). The TWDB defines brackish groundwater as slightly and moderately saline waters (1,000-9,999 milligrams per liter of total dissolved solids concentration) for the purposes of brackish groundwater production zone designation (31 Texas Administrative Code § 356.10). A consistent set of salinity class codes and colors are used in the report discussion and tables, BRACS Database, and geographic information system (GIS) file-naming scheme.

The in-place storage volume of groundwater in each salinity class is then estimated based upon the three-dimensional mapping of the salinity zones. All project information is entered into the BRACS Database, which was developed by the TWDB to store and analyze the information. The BRACS Database is a Microsoft Access database that has been thoroughly documented in the BRACS Database Data Dictionary (TWDB, 2025a). Both the BRACS Database and the database dictionary are available for download from the TWDB BRACS Database webpage.

**Table 2-1 Groundwater salinity classification used in the study (Winslow and Kister, 1956).**

| Groundwater salinity classification | Salinity class codes | Total dissolved solids concentration (units: milligrams per liter) |
|---|---|---|
| Fresh | Fr | 0 to 999 |
| Slightly saline | Ss | 1,000 to 2,999 |
| Moderately saline | Ms | 3,000 to 9,999 |
| Very saline | Vs | 10,000 to 34,999 |
| Brine | Br | Greater than 35,000 |

# 3 Project deliverables

This report discusses previous investigations, data collection and analysis, geology, stratigraphy, lithology, aquifer determination, aquifer properties, measured and calculated water quality, total estimated aquifer storage volumes, and desalination parameters related to the Woodbine Aquifer. Identifying and designating brackish groundwater production zones with volumes of groundwater that may be produced over 30- and 50-year periods without causing significant impact to water availability or water quality will be performed at a later date.

Datasets available with this study include

- subsurface geophysical well data,
- water well reports,
- stratigraphy and lithology interpretations based on these subsurface data,
- measured water quality data,
- calculated water salinity data,
- volumetric calculations, and
- associated GIS datasets.

Only non-proprietary data is incorporated into this brackish aquifer study. Data that is shared with the public by the TWDB does not include any data that are considered by law to be privileged or confidential.

This report, the public BRACS Database, the BRACS Database Data Dictionary (TWDB, 2025a) and all GIS datasets are available for download through the TWDB BRACS study webpage (TWDB, 2024b). Geophysical well logs are available upon request or can be downloaded from the TWDB Groundwater Data Viewer (TWDB, 2024g).

Information produced from these studies is not intended to serve as a substitute for site-specific evaluations of local aquifer characteristics and groundwater conditions for desalination projects. During development of a well field, an entity will need to determine the productivity of the brackish aquifer using test wells, aquifer pumping tests, observation wells, and groundwater modeling. It is important to note that existing TWDB groundwater availability models are designed for regional assessment of future groundwater availability as part of the joint groundwater planning process and are not applicable to well field analysis. These models are not constructed to analyze the effect of salinity on groundwater flow and in general should not be used for estimating saline water withdrawal. Other significant factors an entity should evaluate before developing brackish groundwater are groundwater quantity and quality changes and potential subsidence.

# 4 Study area

The Woodbine Aquifer study area is in northeast Texas and includes all or part of 29 counties (Table 4-1, Figure 4-1). The total surface area of the project is approximately 15,000 square miles. The study area includes the Woodbine outcrop and extends down-dip to the east and south up to approximately 50 miles beyond the TWDB-designated aquifer extent to capture the brackish portion of the aquifer. The BRACS study area boundaries to the south and east are delineated to limit the extent of the study to areas with relevant accumulations of net sand, and to limit the inclusion of areas with known brine down dip of the Mexia-Talco Fault Zone. The study area is bound to the north by the Texas-Oklahoma border along the Red River.

**Table 4-1 Texas counties intersecting the study area.**

| | | |
|---|---|---|
| Bowie | Freestone | McLennan |
| Cass | Grayson | Morris |
| Collin | Henderson | Navarro |
| Cooke | Hill | Rains |
| Dallas | Hopkins | Red River |
| Delta | Hunt | Rockwall |
| Denton | Johnson | Tarrant |
| Ellis | Kaufman | Titus |
| Fannin | Lamar | Van Zandt |
| Franklin | Limestone | |

Seven groundwater conservation districts are partially or completely present within the study area. Groundwater management areas within the study boundary are dominated by Groundwater Management Area 8, with portions of groundwater management areas 12 and 11. The study area lies within parts of three regional water planning areas: Region C, North East Texas (D), and Brazos G. See Figure 4-2 for administrative boundaries.

Figure 4-3 illustrates 126 public water supply systems that have sourced water from the Woodbine Aquifer at some point in time (Figure 4-3) (TWDB, 2024c). For further information on public supply systems in the study area, see Appendix A. TWDB Water Use Survey data from 2022 indicates that an estimated 24,845 acre-feet per year are pumped from the Woodbine Aquifer, with the primary uses being municipal supply (17,220 acre-feet), irrigation (5,864 acre-feet), livestock (1,576 acre-feet), and manufacturing (185 acre-feet) (TWDB, 2025b).

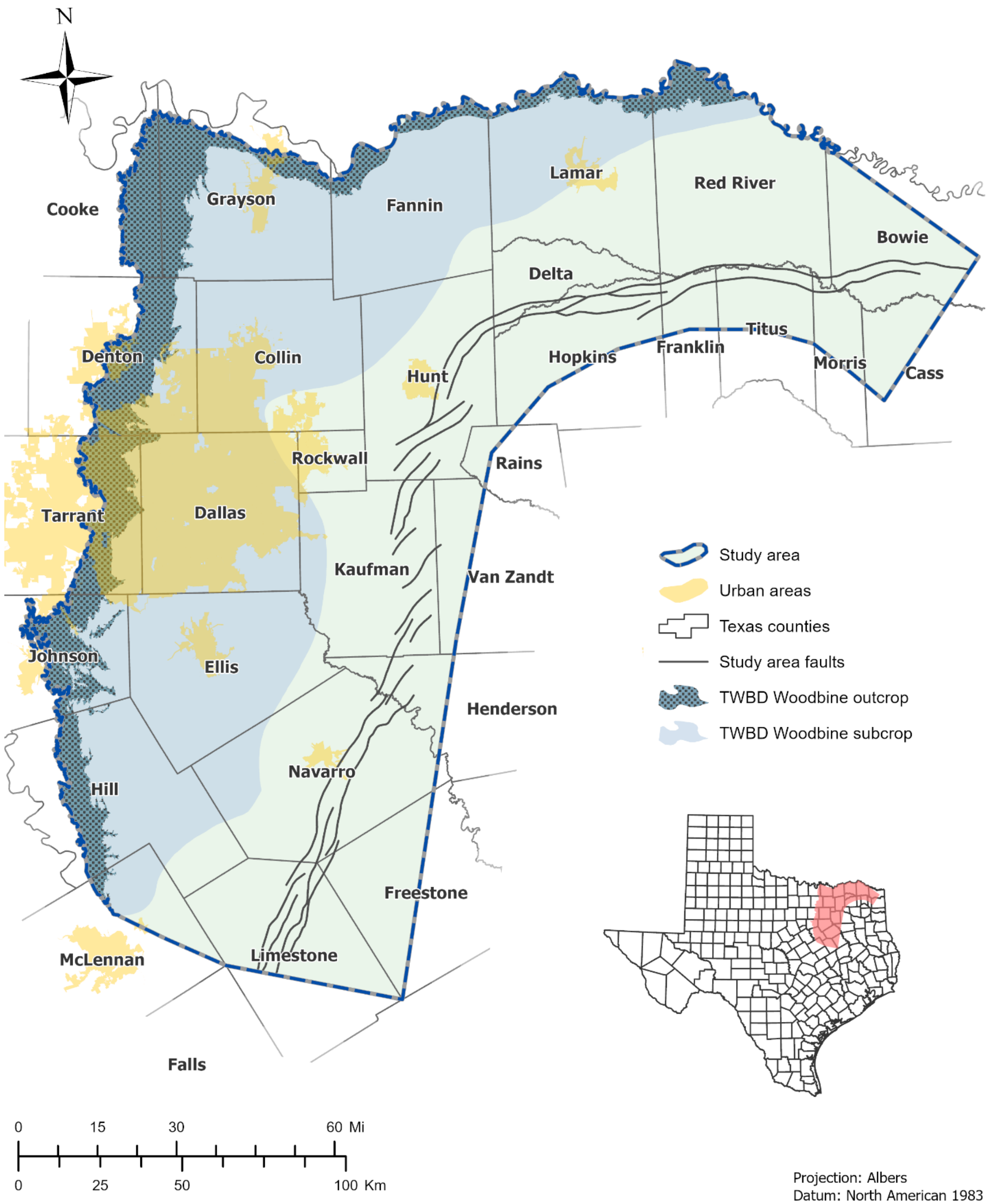


**Figure 4-1** **Study area boundary includes the TWDB aquifer extent and additional down-dip portions including all or part of 29 counties.**

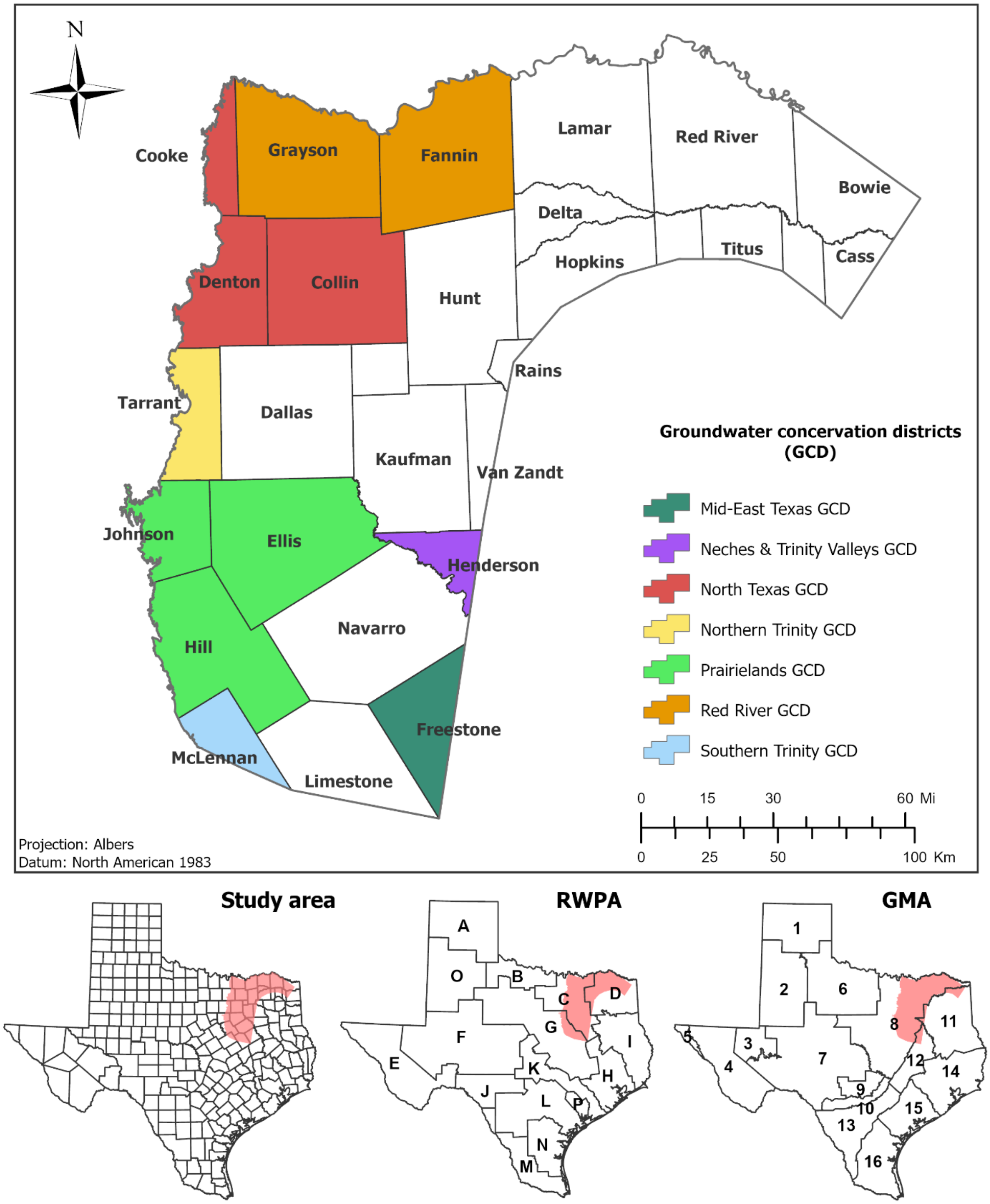


**Figure 4-2** **Administrative boundaries in the Woodbine Aquifer study area. RWPA = regional water planning areas, and GMA = groundwater management areas.**

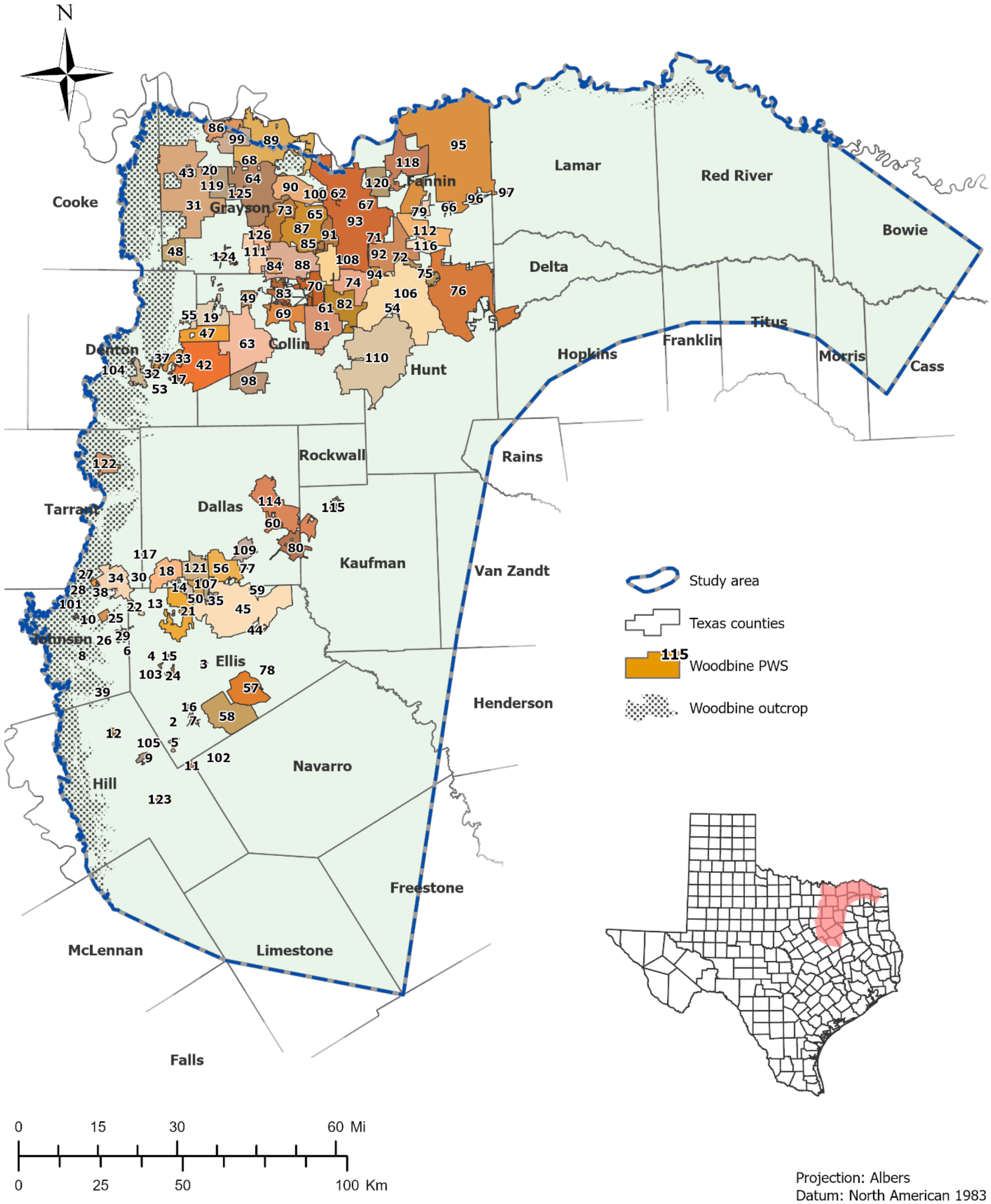


**Figure 4-3** **Public water supply system (PWS) boundaries with Woodbine Aquifer wells within the study area (data from TWDB Texas Water Service Boundary Viewer, 2024f and TWDB, 2024c). A tabulated map reference is available in Appendix A.**

# 5 Geologic setting

The Woodbine Group is an important geologic formation for both groundwater and hydrocarbon production in Northeast Texas. It is a sedimentary sequence from the later part of the Upper Cretaceous geologic period, and the study area is dominated by terrestrial sand and shale beds deposited by rivers and deltas (Oliver, 1971). The stratigraphic chart in Figure 5-1 shows the relationship between the Woodbine Group and the surrounding formations. The Woodbine Group unconformably overlies the carbonate dominated formations of the Washita Group and is unconformably overlain by the organic-rich marine shales of the Eagle Ford Group.

| Age m.y. | Period | Epoch | Group | Formation | Hydrostratigraphic unit |
|---|---|---|---|---|---|
| Undifferentiated post Austin formations and sediments | | | | | |
| 87 | Upper Cretaceous | Coniacian | Austin | Austin Chalk | |
| 90 | | Turonian | Eagle Ford | Eagle Ford Shale | Confining unit |
| 94 | | Cenomanian | | | |
| | | | Erosional unconformity | | |
| | | | Woodbine | Lewisville<br>Dexter<br>Pepper Shale | Woodbine |
| | | | Erosional unconformity | | |
| | | | Washita | Buda Limestone<br>Grayson/Del Rio | Confining unit |
| 100 | Lower Cretaceous | Upper Albian | | Georgetown: Main Street<br>Pawpaw<br>Weno<br>Denton<br>Fort Worth<br>Duck Creek | |
| 110 | | Lower Albian | Fredericksburg | Kiamichi<br>Edwards<br>Comanche Peak<br>Walnut | |

**Figure 5-1 Generalized stratigraphic column of the Woodbine Group and surrounding formations. Geologic epochs and ages are defined by the International Commission on Stratigraphy Chronostratigraphic Chart (modified from Gradstein and others, 2024). Age is in millions of years.**

Woodbine sediments have been identified and mapped since the earliest days of geologic mapping and exploration in Texas (Shumard, 1886; Hill, 1901). These early workers used terms such as “Dakota,” “Tertiary system,” “Arenaceous and Marly Clay,” or “Red River Group.” Because of this, Hill (1901, page 294), felt it was necessary to clear up the confusion and so named these equivalent units as Woodbine “…after a locality in the northeastern part of Cooke County.” Furthermore, Hill divided the Woodbine into an upper Lewisville Member and a lower Dexter Member. Adkins (1932) later formalized the Pepper Shale as the name of the downdip equivalent of the Woodbine when it becomes dominated by marine shale.

A generalized map of the surface geology in the Woodbine Aquifer study area is shown in Figure 5-2, showing that most Woodbine outcrops are along the western edge of the study area. Small discontinuous Woodbine outcrops are found along the northern Texas border. However, much of the outcrop is overlain by Quaternary sediments associated with the Red River.

## 5.1 Stratigraphy, lithology, and depositional environments

The Woodbine Group is the remnant of a regressive sequence of fluvial deltaic sediments deposited upon the Upper Cretaceous Gulf Coast carbonates of the Washita Group. Its source terrains are generally thought to be the Ouachita Highlands to the north in Oklahoma and Arkansas (Adams and Carr, 2010).

Woodbine equivalent sands and shales are thought to have been deposited over much of the Texas Gulf Coast during the Cenomanian high stand. Initially, Woodbine sediments probably formed an extensive unit blanketing the entire western half of the paleo-Gulf of Mexico coastal region. The Woodbine sediments were significantly eroded prior to Eagle Ford deposition except for the East Texas Salt Basin which experienced subsidence and thereby preserved the Woodbine Group. As a result, the present-day distribution of the Woodbine Group and Woodbine equivalent sediments as shown in Figure 5-3 exist predominantly below the surface in East Texas and as outcrops in a relatively narrow band through Oklahoma, Arkansas, and Texas (Oliver, 1971).

Sand units of the Woodbine were among those described by Hill (1901, page 440) as important artesian groundwater systems: “The water beds of the Woodbine formation are embedded beneath all the Black Prairie region north of the Brazos and south of Red River and are available at depths of from 100 to 3,000 feet.” He also recognized the organic-rich shales of the Eagle Ford Group as the regional confining unit for the Woodbine.

Figure 5-4 shows how the Woodbine was deposited in four main depositional systems including: fluvial meander belt, channel-mouth bar, coastal barrier, and prodelta shelf (Oliver, 1971; Adams and Carr, 2010). The thick water-bearing sand units of the Woodbine generally extend southward into McClennan County where sediments transition into the prodelta Pepper Shale facies (Adkins and Lozo, 1951). Section 8.3 of this report includes additional discussion on the quantification and distribution of sand within the Woodbine.

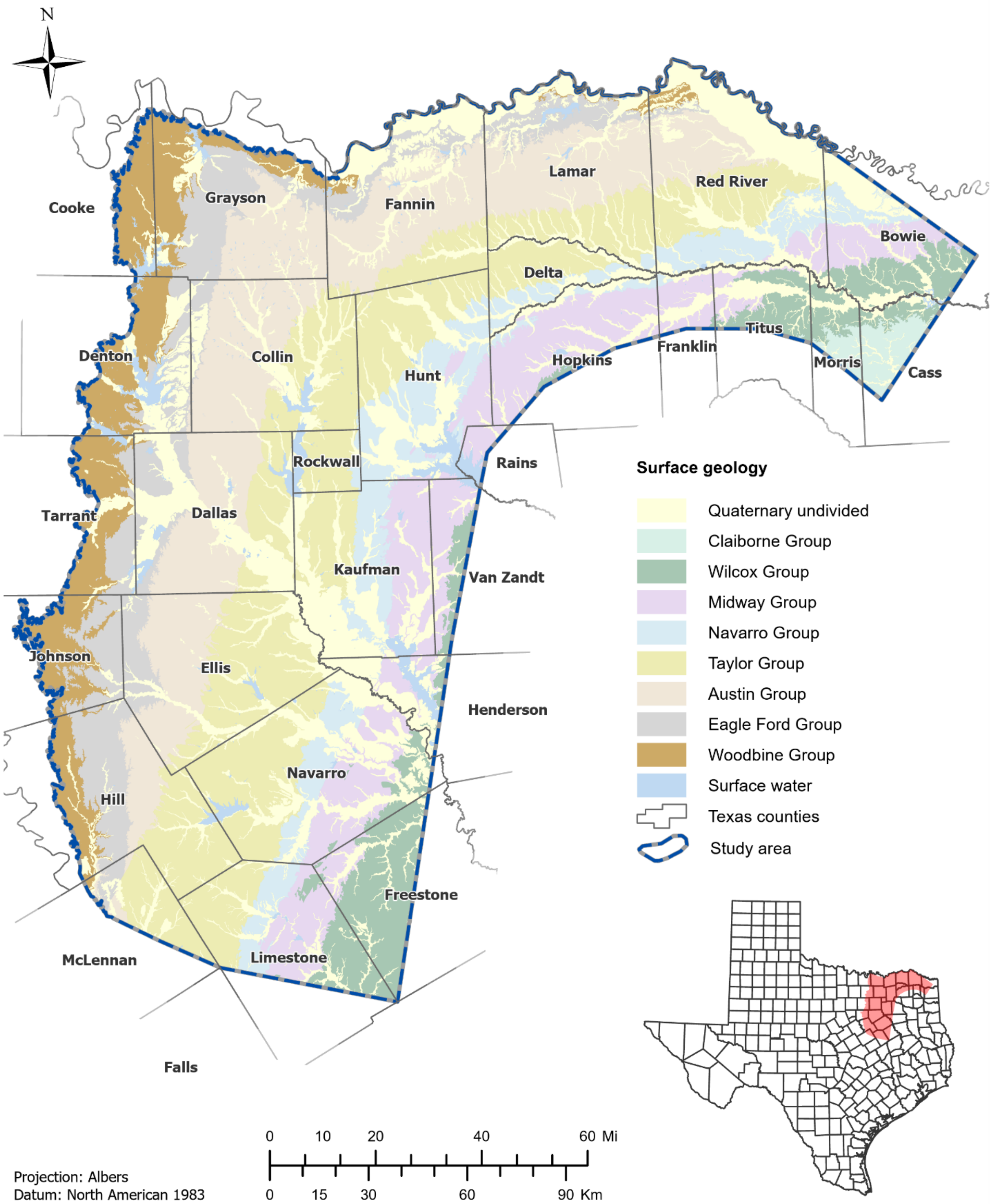


**Figure 5-2 Surface geology in the Woodbine Aquifer study area (modified from TWDB, 2007).**

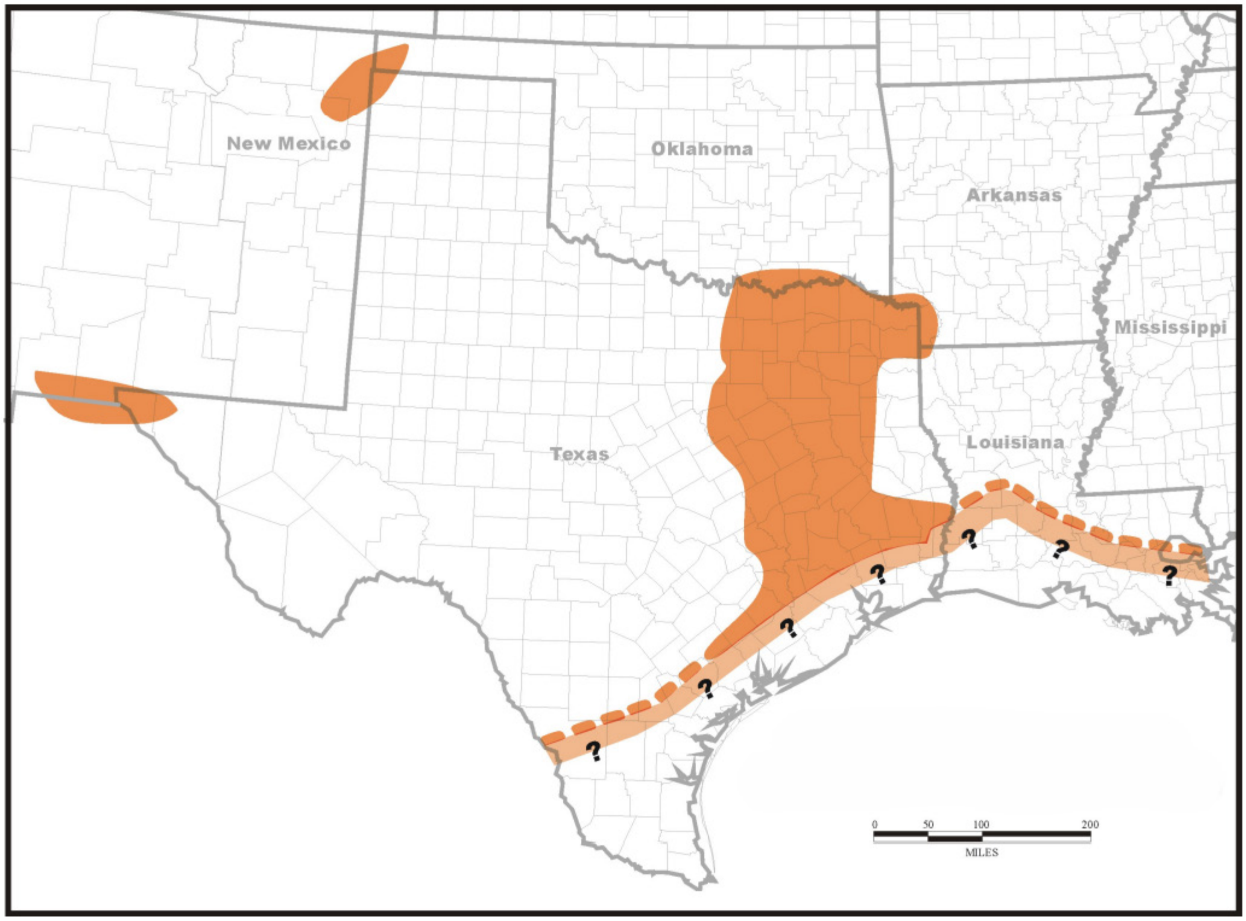


**Figure 5-3 Map of approximate distribution of Woodbine-aged sediments on the U.S. Gulf Coast (modified from Adams and Carr, 2010 and Adkins, 1932).**

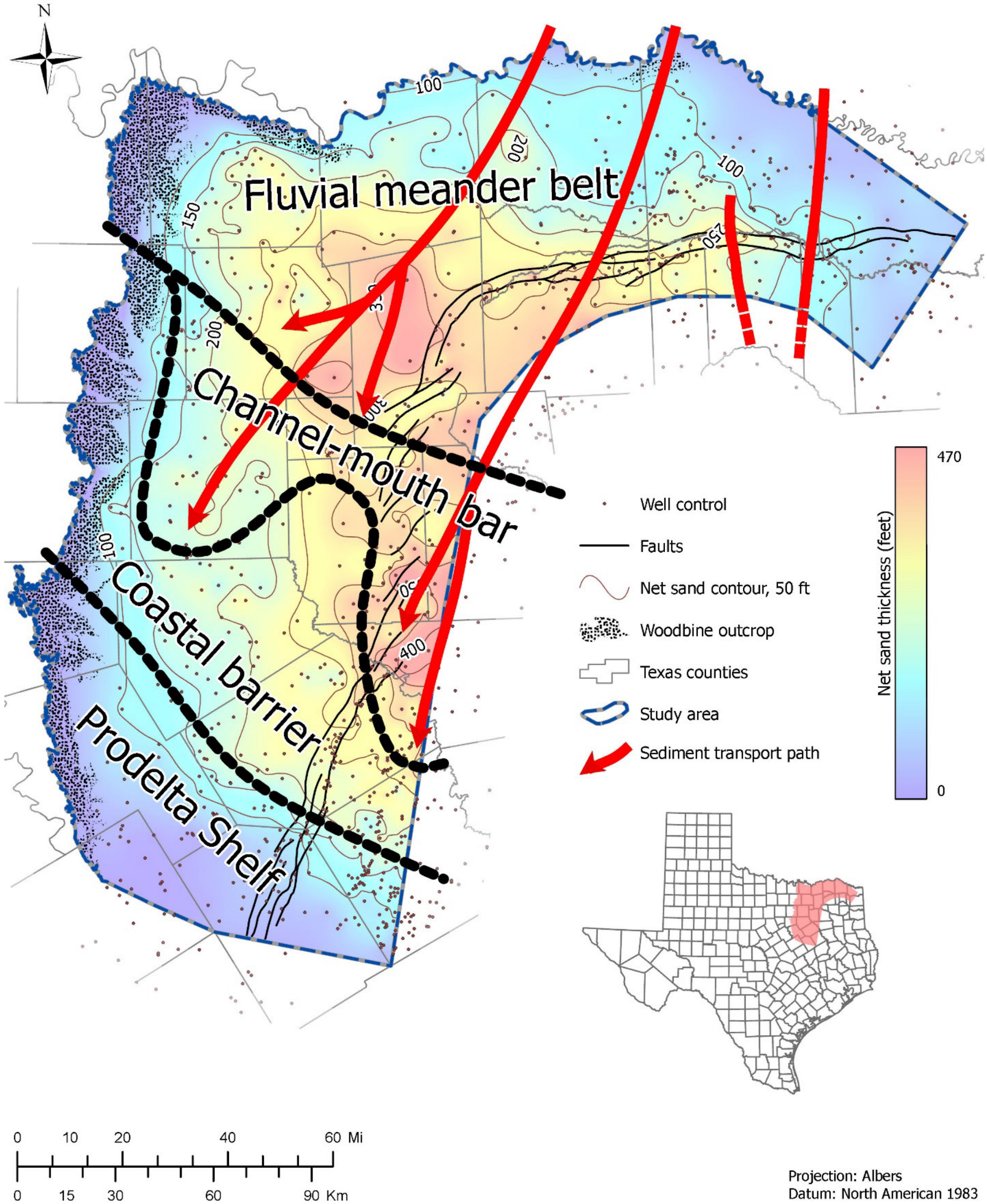


**Figure 5-4 Generalized facies map (modified from Oliver, 1971 and Adams and Carr, 2010) overlain on study net sand map. See Section 8.3 for additional information on the net sand analysis.**

## 5.2 Structural features

Tectonic forces have played an important role in the deposition, erosion, and occurrence of the Woodbine formations. At the end of the Washita Group deposition, the Gulf of Mexico shoreline receded leaving a broad shallow shelf. The northern and western portions of this shelf were exposed and underwent variable amounts of erosion and weathering. At the onset of the Upper Cretaceous Period, sand and clays eroded from the Ouachita Highlands in southern Oklahoma and Arkansas were the first Woodbine sediments deposited in the study area (Adams and Carr, 2010). Figure 5-5 illustrates the major structural features that have impacted the deposition and occurrence of Woodbine sediments.

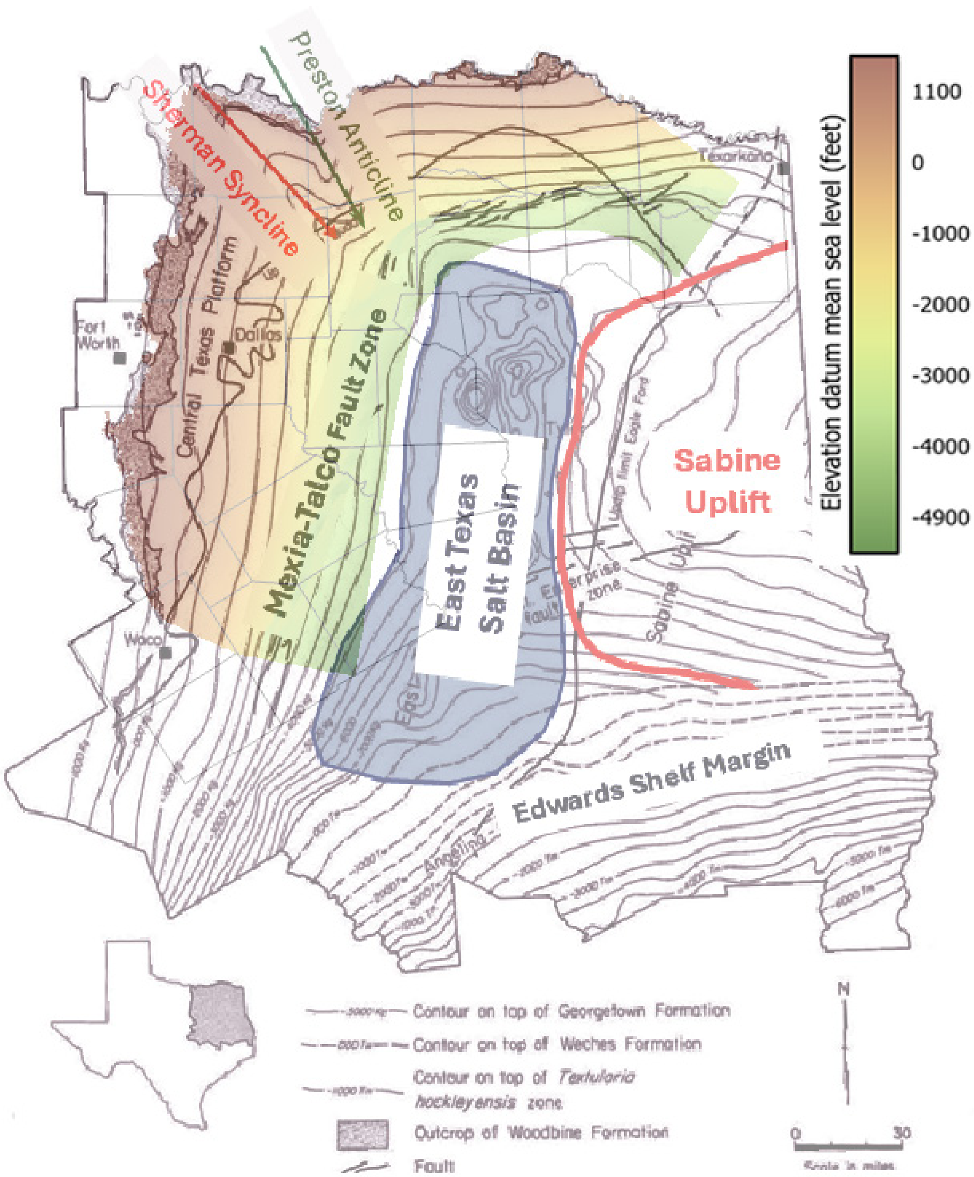


**Figure 5-5 Regional structural framework (modified from Oliver,1971). Color contours represent the top of the Woodbine. (See Section 8 of this report for additional information on study raster surface interpolation.)**

The Woodbine was deposited upon the eroded Washita shelf in a fluvial deltaic environment as rivers flowed to the south and southwest across the shelf and into the ancestral Gulf of Mexico. The rise of the Sabine Uplift and the formation of the east Texas Salt Basin occurred late in the Cenomanian and may have impacted deposition of the Lewisville Member of the Woodbine (Oliver, 1971, Adams and Carr, 2010).

Flanking the southern and southeastern boundaries of the study area is the Mexia-Talco Fault Zone. This fault zone forms large grabens with throws ranging from 800 to 1,000 feet, which we observed as missing sections in well logs during stratigraphic interpretation and mapping. A well in Delta County (BRACS ID#86474) was interpreted to have almost 850 feet of the Washita Group faulted out. This displacement potentially places the porous sands of the Woodbine Aquifer adjacent to less porous rocks thereby impeding the southeastern flow of groundwater. This likely contributes to the elevated salinity of the aquifer in and around the fault zone.

Oliver (1971) mentions growth-faulting of the Woodbine along the Mexia-Talco Fault Zone. The density of well data available did not provide direct evidence of sandstone units thickening on the downthrown side of faults which would have indicated active growth faulting during Woodbine deposition. We also did not have seismic data that might have provided us with some insights. The Woodbine thickness map we developed from our stratigraphic interpretations (Figure 8-13) does depict the Woodbine interval as thicker in several locations on the downthrown side of faults in Kaufman, Henderson, and Navarro counties.

Prominent structural features in Grayson County in the northwestern part of the study area are the Preston Anticline and the Sherman Syncline. The Preston Anticline was mapped by Stephenson (1919) and explained the stratigraphic offsets that Hill (1901) had originally attributed to faulting. The Sherman Syncline was named and mapped by Hopkins and others (1922). Both structural features were formed after Woodbine deposition.

Figure 5-6 depicts structural cross sections of the Woodbine Group along both strike and dip. These cross sections provide a generalized presentation of how the Woodbine interval has been impacted by post-depositional structural deformations. Section A-A’ is a dip section across the northern portion of the study area, and section B-B’ runs along the depositional strike of the Woodbine Group outcrops.

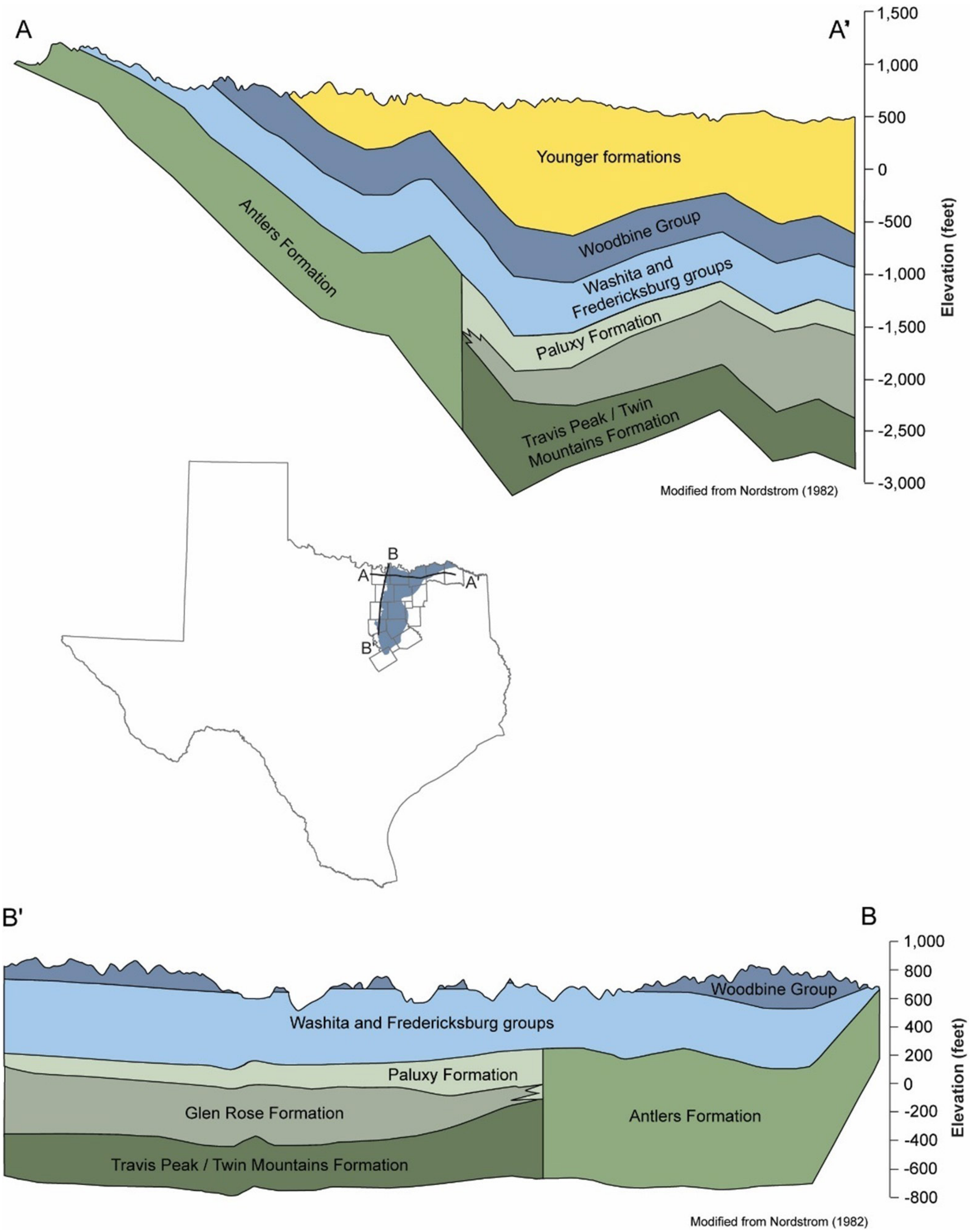


**Figure 5-6** **Generalized strike and dip structural cross sections depicting the Woodbine Group and adjacent formations (after George and others, 2011; Nordstrom, 1982).**

# 6 Previous groundwater investigations

Groundwater investigations of the Woodbine Aquifer date back to at least the beginning of the 20th century. Some of these studies are accounted for herein. However, this is not meant to serve as a comprehensive list of all available work covering the Woodbine Aquifer. In one of the earliest known reports, Hill (1901) characterizes both the geology and groundwater of Cretaceous-age rocks in the study area. An assessment of the chemical composition and temperature of groundwater in Woodbine oil fields was completed by Plummer and Sargent in 1931. With a focus on the structural drivers of Woodbine geochemistry, the authors found that areas with significant structural features, such as the Preston Anticline, exhibit higher total dissolved solids concentrations.

The Texas Board of Water Engineers (the precursor to the TWDB), in conjunction with the U.S. Geological Survey and other agencies, began to publish county reports and other locality-based studies in the mid-1900's. Four examples of these studies relevant to this work are Leggat (1957), Baker (1960), Thompson (1967), and Thompson (1972), which outline the groundwater resources of Tarrant, Grayson, Ellis, and Navarro counties, respectively. Other relevant studies in this series include George and Rose (1942) and Livingston (1945), which evaluated the water resources of the cities of Fort Worth and Sherman. The TWDB and its predecessors have also published a series of reconnaissance investigations of groundwater resources in area river basins, including the Sabine River basin (Baker and others, 1963a); the Red River, Sulphur River, and Cypress Creek basins (Baker and others, 1963b); the Trinity River basin (Peckham and others, 1963); and the Brazos River basin (Cronin and others, 1973). The Woodbine Aquifer is discussed to varying degrees in these river basin reports.

While not a groundwater study, Alexander (1951) provided an overview of the history of the discovery and development of Woodbine oil fields in East Texas. Because hydrocarbons can influence geophysical logging tools, understanding potential locations where hydrocarbons might be present is important to accurately calculating salinity from geophysical well logs.

To identify possible sources of groundwater for desalination in areas with insufficient water sources, Winslow and Kister (1956) detail the saline water resources of Texas including the Woodbine Aquifer. This report also forms the basis for the salinity classification used herein. TWDB Report 157 (Core Laboratories, 1972) investigated the major saline aquifers of Texas. This investigation included mapping the Woodbine structure, net sand, and salinity.

Nordstrom (1982) provides a characterization of the groundwater in the Cretaceous aquifers of north central Texas. This report notes that the Woodbine can be divided into three distinct water-bearing sections: upper, middle, and lower, that do not all produce the same quality and quantity of groundwater. Water in the upper portion of the Woodbine can contain high concentrations of iron along the outcrop and be of extremely poor quality further downdip. Both the middle and lower portions can contain water of good quality. However, the lower section is the most productive.

TWDB Report 318 (Baker and others, 1990), a study of the groundwater resources in north central Texas, was conducted to characterize the groundwater conditions in the

Trinity Group and other aquifers (including the Woodbine). This study found significant, localized water-level declines in the Woodbine Aquifer of up to 150 feet particularly in Grayson, Collin, and Fannin counties. Water-quality issues were also identified that could potentially be attributed to various occurrences including 1) surface contamination, 2) poor well completion, or 3) poor well operation. Pockets of naturally occurring, elevated levels of sulfate associated with lignite beds are noted, along with elevated levels of boron. TWDB Report 349 (Langley, 1999) serves as a follow up to Report 318. Langley observed that water levels in the Woodbine Aquifer remained mostly stable since the 1990 report.

Mace and others (1994) investigated water level declines in the Woodbine and other aquifers from 1900 to 1990. They found that by 1990 water levels in the Woodbine had declined 200 to 400 feet, with the greatest decline observed near the Dallas area. Additionally, it was found that groundwater flow gradients have increased, and in some cases reversed groundwater flow direction was observed.

In the TWDB Hydrogeologic Atlas Number 4, Hopkins (1996) summarizes the findings of 78 wells completed in the Woodbine Aquifer and sampled between 1993 and 1995. Where possible, samples included in the analyses were taken from municipal, industrial, and irrigation wells across the TWDB Woodbine Aquifer extent. The report shows that certain key chemical constituents exceed the Texas Commission on Environmental Quality (TCEQ) maximum contaminant levels (TCEQ, 2019) in certain parts of the aquifer, including but not limited to iron and manganese.

A groundwater availability model for the Northern Trinity and Woodbine aquifers (Kelley and others, 2014) is available. As part of the modelling process, a vast amount of data was collected and analyzed to develop the conceptual model, including stratigraphy, lithology, and aquifer characteristics including pumping data, water quality, and properties. This model serves as an update to the model developed by Bené and others (2004). At the time of this report’s publication, a draft groundwater availability model update for the Northern Trinity and Woodbine aquifers has been submitted through Groundwater Management Area 8 and the public comment period has ended. The model update will be available in 2026.

# 7 Data collection and analysis

Data collection is a significant component of all BRACS studies. Data used to characterize an aquifer during a BRACS study is added to the BRACS Database (TWDB, 2024c). New data were added during each project task, such as stratigraphy, lithology, and salinity mapping. Digital and physical geophysical well logs, water well reports, water geochemical datasets, and groundwater reports were all important sources of information for this study. A description of some of the main tables in the BRACS Database is included in Appendix B.

A typical BRACS study starts with gathering and reviewing previously published studies that are relevant and applicable to the study area. Subsurface data collection and analysis is an ongoing process during the study but is the primary focus after collecting published materials.

Primary public databases utilized for well data in this report were the

- BRACS Database maintained by the TWDB;
- Groundwater Database (GWDB) maintained by the TWDB;
- Submitted Drillers Reports (SDR) Database, which is maintained cooperatively by the Texas Department of Licensing and Regulation (TDLR) and the TWDB;
- Oil and gas well database maintained by the Texas Railroad Commission (RRC); and
- Public Water Supply (PWS) and Water Well Report (WWR) databases maintained by the Texas Commission on Environmental Quality (TCEQ).

The information collected for this study includes raw data such as water well reports, geophysical well logs in numerous digital formats, processed data such as lithology, simplified lithologic descriptions, stratigraphic picks, water chemistry, and interpreted results in the form of GIS datasets.

Due to the large volume of available well data, we did not verify the location of every well in the BRACS Database at the time of data analysis for this report. Locations were assumed to be entered accurately at the time of input into the database unless our data review proved otherwise such as a discrepancy in geology. We also did not verify the location of every well that was obtained from other agency datasets unless there appeared to be a problem. When locations had to be verified or digital locations were not available, the digital files of the Original Texas Land Survey and linen maps from the Groundwater Advisory Unit of the RRC were used as base maps. The location's legal description noted on the geophysical log header or noted in the well record was used to plot the location of the well using a GIS to determine the latitude and longitude coordinates. We recommend that users of our study data make their own effort to verify the location of wells. All the source databases used in this study are updated on a regular basis by their respective agencies so new well data will become available in the study area in the future.

A total of 7,148 well records were identified for the study area. These wells were appended to the study aquifer determination table described in Section 9. These include 4,671 water wells, 2,361 oil and/or gas wells, and 116 other types of wells such as geothermal or waste disposal (Figure 7-1). It should be noted that while these wells are present in the study area, they were not all used for the analyses described herein. Additionally, this is likely to represent only a portion of the wells drilled within the study area. Information for wells may be either unavailable, incomplete, limited in scope, of poor quality, confidential, or did not meet the requirements of the study. Well control for the Woodbine Group can also be found outside of the study area boundary, particularly down dip. Finally, due to the substantial nature of the database, only wells from the SDR Database with data that were utilized for this study are appended to the aquifer determination table.

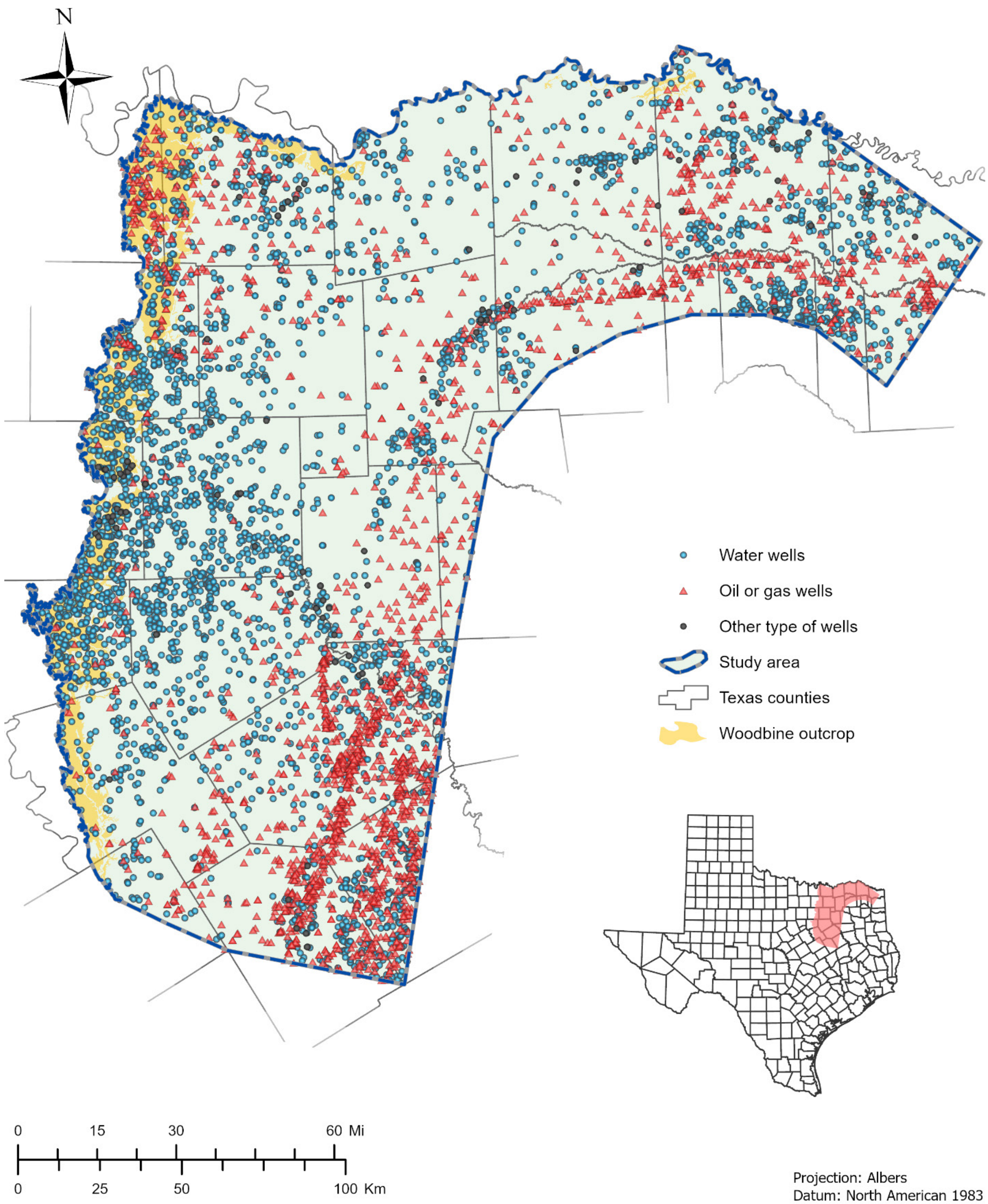


**Figure 7-1 Well control within the study area identified through the aquifer determination process. Additional well control exists outside of the study area, particularly down dip of the study area boundary.**

# 8 Study stratigraphic and lithologic interpretation

Geophysical well logs, water well reports, and published reports were the most important sources used to define stratigraphy and lithology in the study area. Regional geologic maps and cross sections were also used as a reference. We used the S&P Global Kingdom™ (Kingdom) geological software to interpret stratigraphic units and formation sand picks. This software uses depth-calibrated images of geophysical well logs and provides efficient tools for their visualization and interpretation.

## 8.1 Stratigraphic correlation logs and cross sections

Geophysical well log responses are a result of the lithologic and depositional characteristics of the rocks being measured and the fluids that they contain. These logs can be used to map geologic contacts between formations when there are significant changes in the character of the rocks because of composition, compaction, and fluid content. For the Woodbine Group, we were able to map regionally correlative geologic surfaces from deep in the subsurface to their outcrops.

We developed a series of four correlation cross sections to document the geophysical log character used to correlate the Woodbine Group. Locations of the type log cross sections are shown on Figure 8-1. Each cross section contains four geophysical well logs from wells located in selected study area counties (Figures 8-2 to 8-5). Each set of wells is depicted for the interval between the top of the Eagle Ford Shale to the top of the Washita Group. The type logs are arranged approximately northwest to southeast and are stratigraphically flattened on the top of the Woodbine Group.

The top of the Eagle Ford Shale generally represents a maximum flooding surface which indicates the maximum marine transgression. This surface can be identified in most wells throughout the study area by the abrupt well log changes between the Austin Chalk and the Eagle Ford Shale. A solid blue line has been used to denote the top of the Woodbine Group. It can also be observed that all four wells in each figure have been positioned so that the top of the Woodbine is flat, this is known as a “stratigraphic” section and is helpful in depicting how geologic units change laterally. The wells are also positioned a constant distance apart that does not represent their true spatial separation.

Most of the wells used to create the type log correlation sections were drilled prior to 1970 and were logged with older electric logging tools. Therefore, the logs displayed are composed of a spontaneous potential (SP) curve in the left-hand track and resistivity curves (RES) in the right-hand track. Appendix C of this report introduces the properties of various geophysical well logging tools.

We also digitized gamma ray and resistivity curves from raster logs to construct three additional correlation cross sections: one oriented northeast to southwest (strike-oriented) and two oriented northwest to southeast (dip-oriented). The digitization process was performed using Kingdom geologic software. The resulting cross sections illustrate subsurface stratigraphy and variations in aquifer thickness across the study area (Figures 8-6 to 8-8).

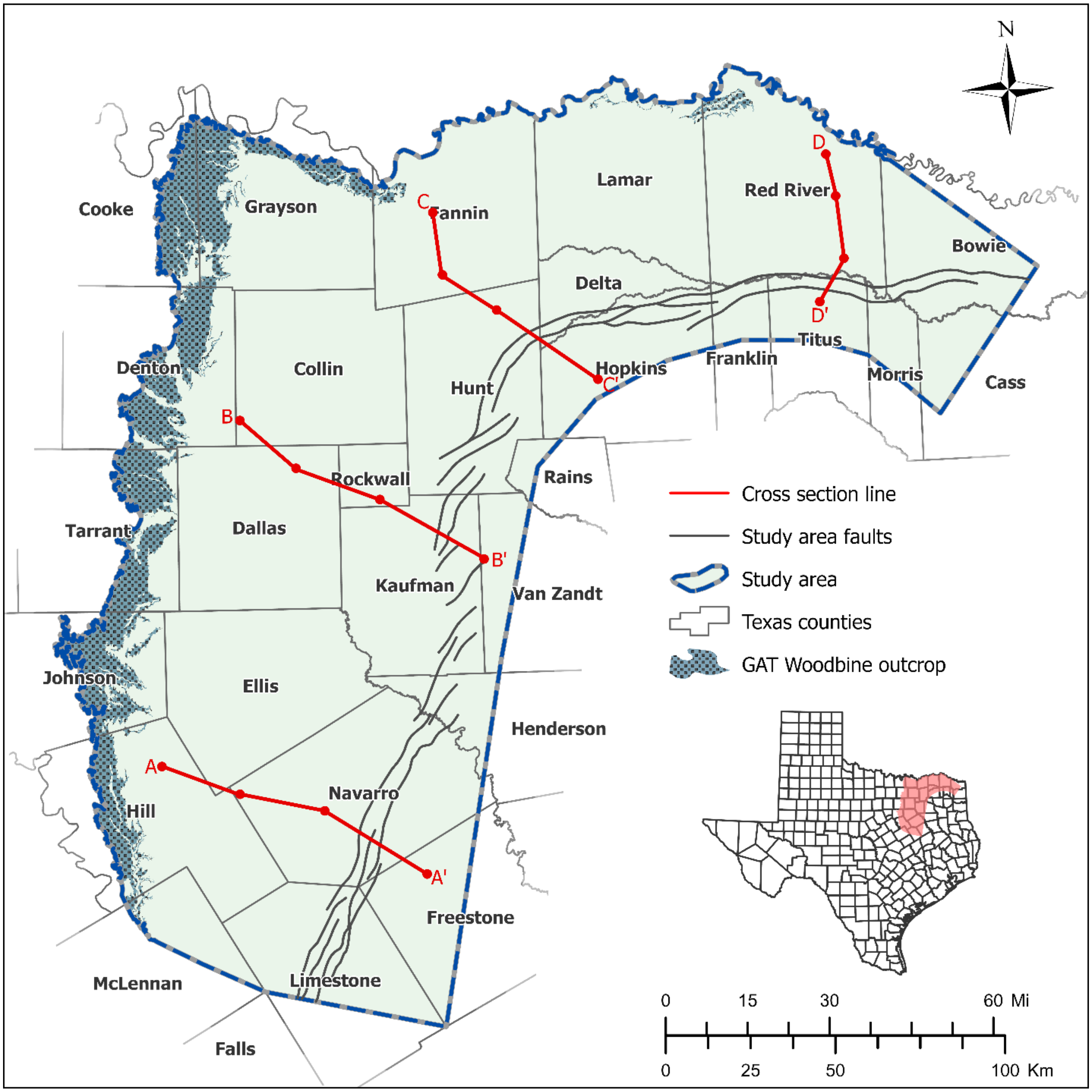


**Figure 8-1** **Location of type log correlation cross section lines in the Woodbine Aquifer study area.**

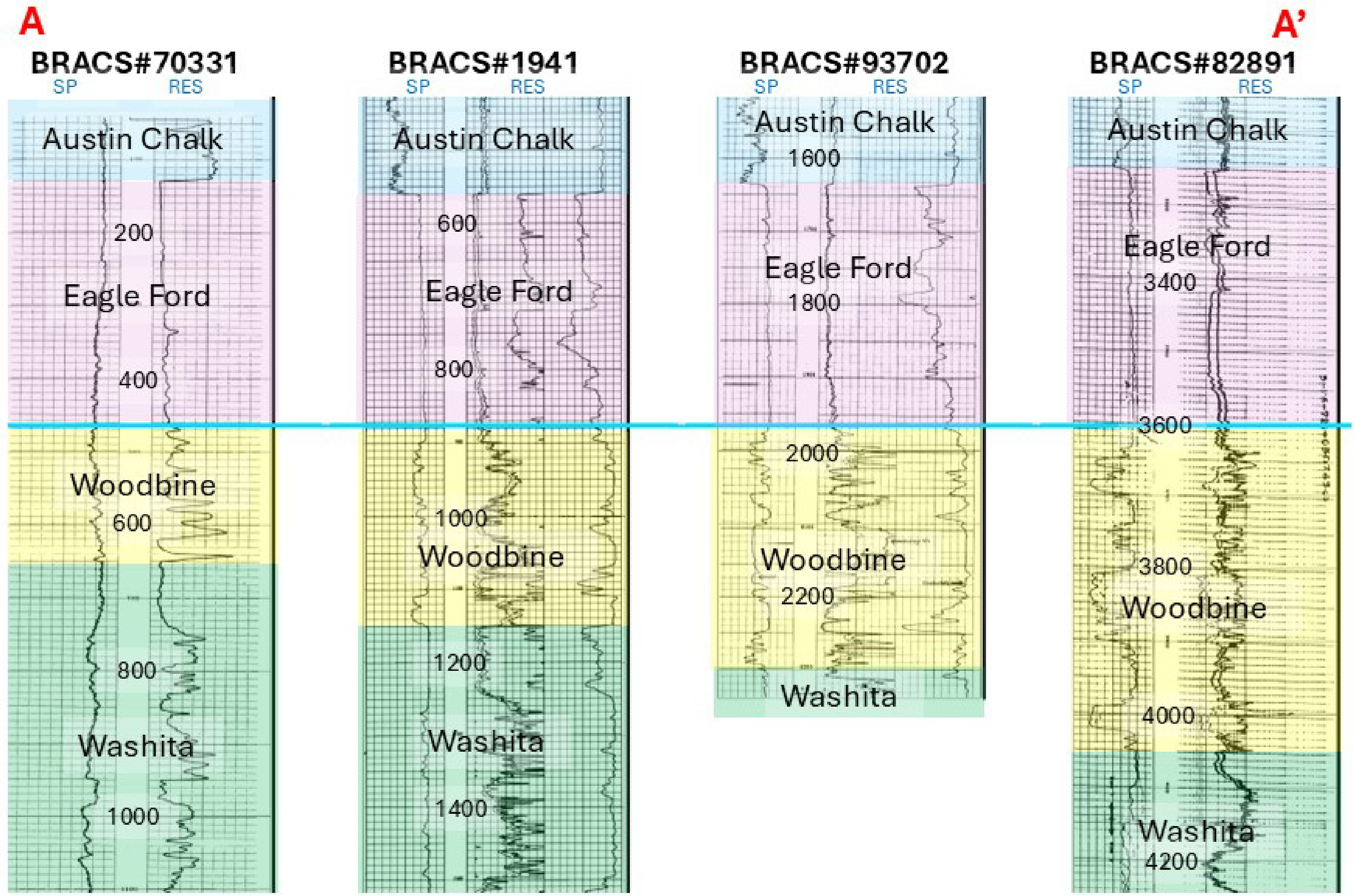


**Figure 8-2** **Correlation cross section A-A’ in Hill, Navarro, and Freestone counties illustrating correlations for the top of the Eagle Ford Shale, Woodbine Group, and Washita Group on BRACS Database wells (numbers 70331, 1941, 93702, and 82891). The spontaneous potential (SP) is shown in the left track, depth (in feet below reference elevation) is shown in the middle track, and the resistivity tools (RES) are shown in the right track.**

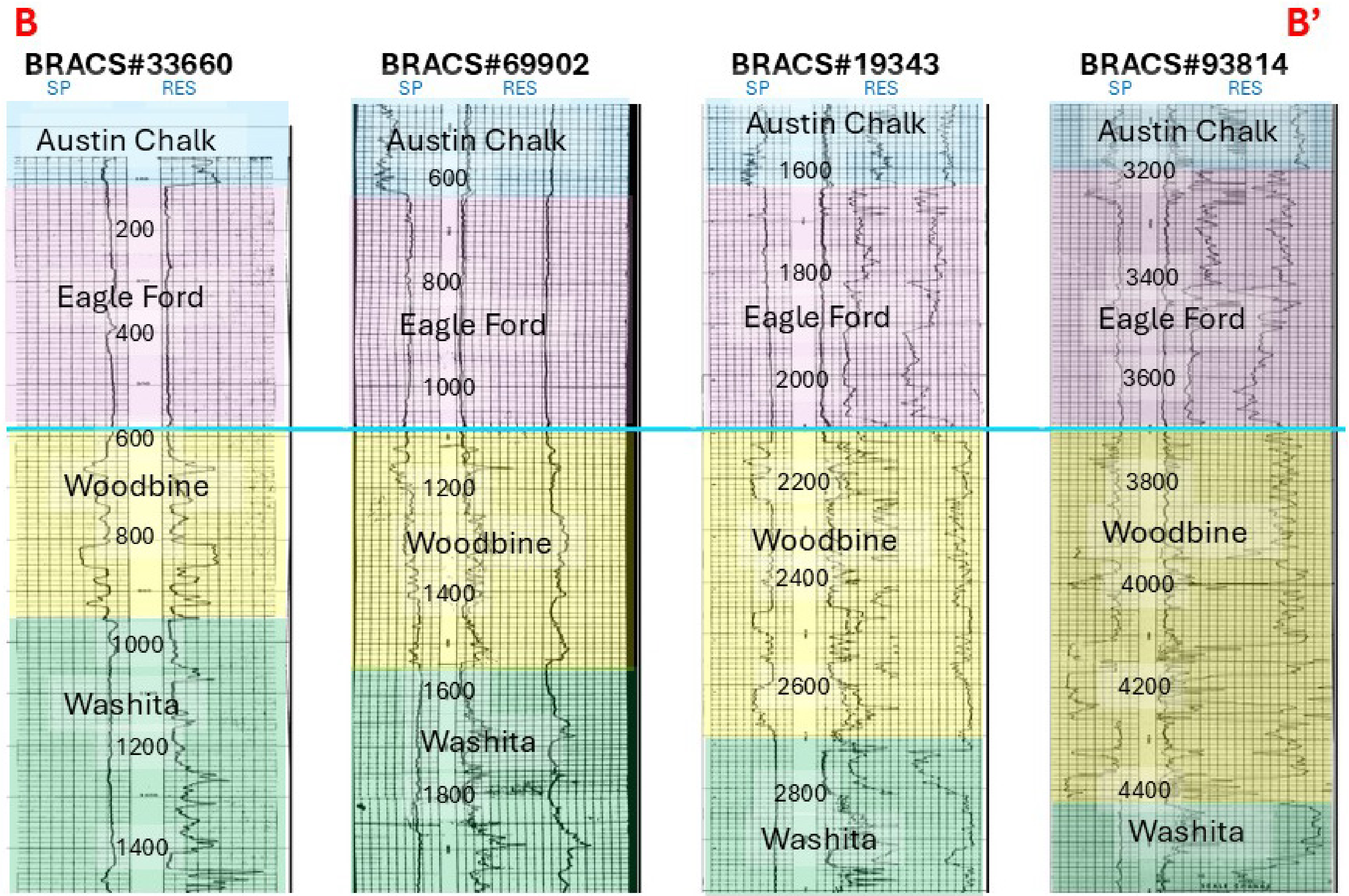


**Figure 8-3** **Correlation cross section B-B' in Collin, Dallas, Rockwall, and Van Zandt counties illustrating correlations for the top of the Eagle Ford Shale, Woodbine Group, and Washita Group. on BRACS Database wells (numbers 33660, 69902, 19343, and 93814). The spontaneous potential (SP) is shown in the left track, depth (in feet below reference elevation) is shown in the middle track, and the resistivity tools (RES) are shown in the right track.**

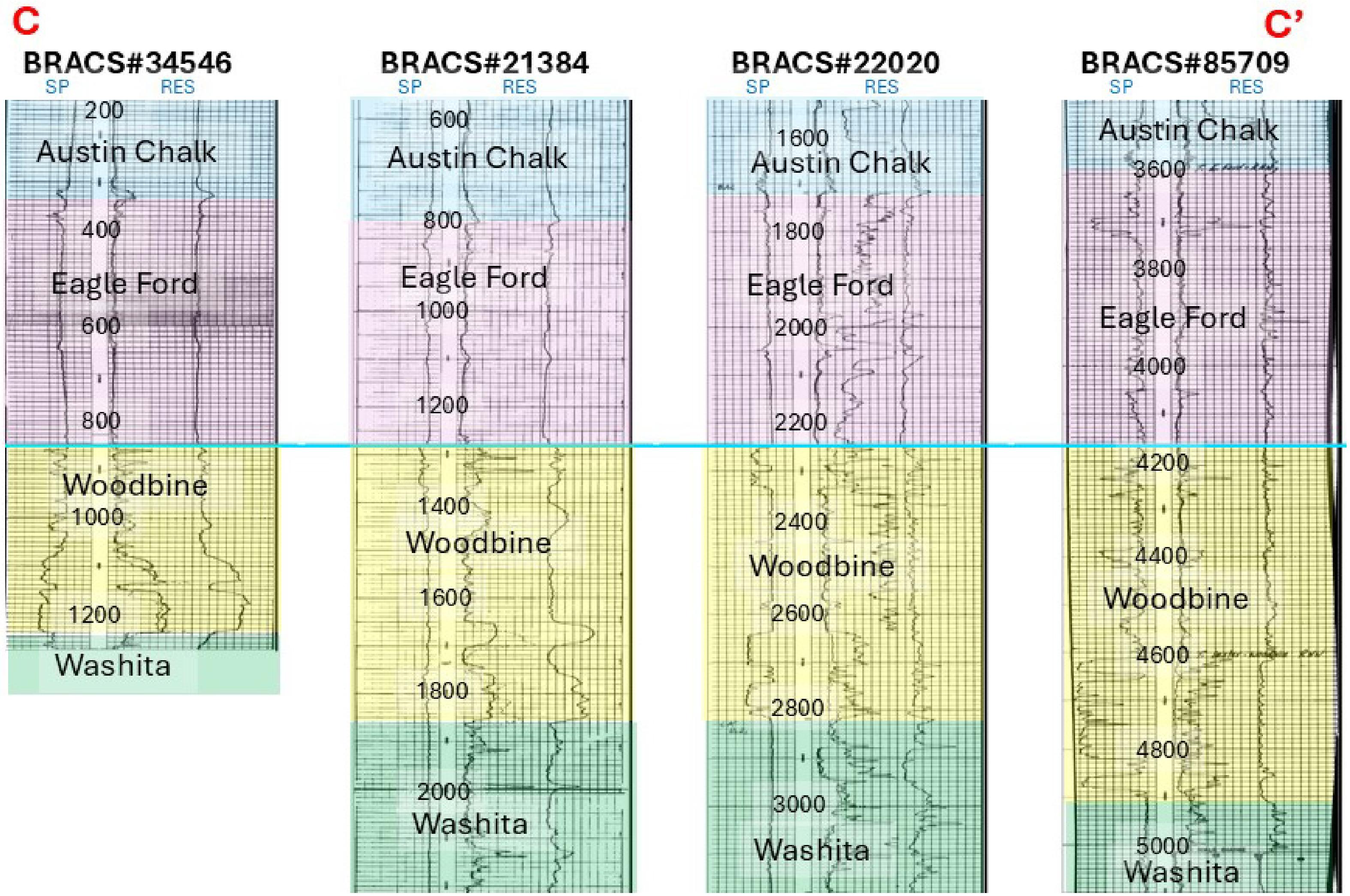


**Figure 8-4** **Correlation cross section C-C' in Fannin, Hunt, and Hopkins counties illustrating correlations for the top of the Eagle Ford Shale, Woodbine Group, and Washita Group. on BRACS Database wells (IDs 34546, 21384, 22020, and 85709). The spontaneous potential (SP) is shown in the left track, depth (in feet below reference elevation) is shown in the middle track, and the resistivity tools (RES) are shown in the right track.**

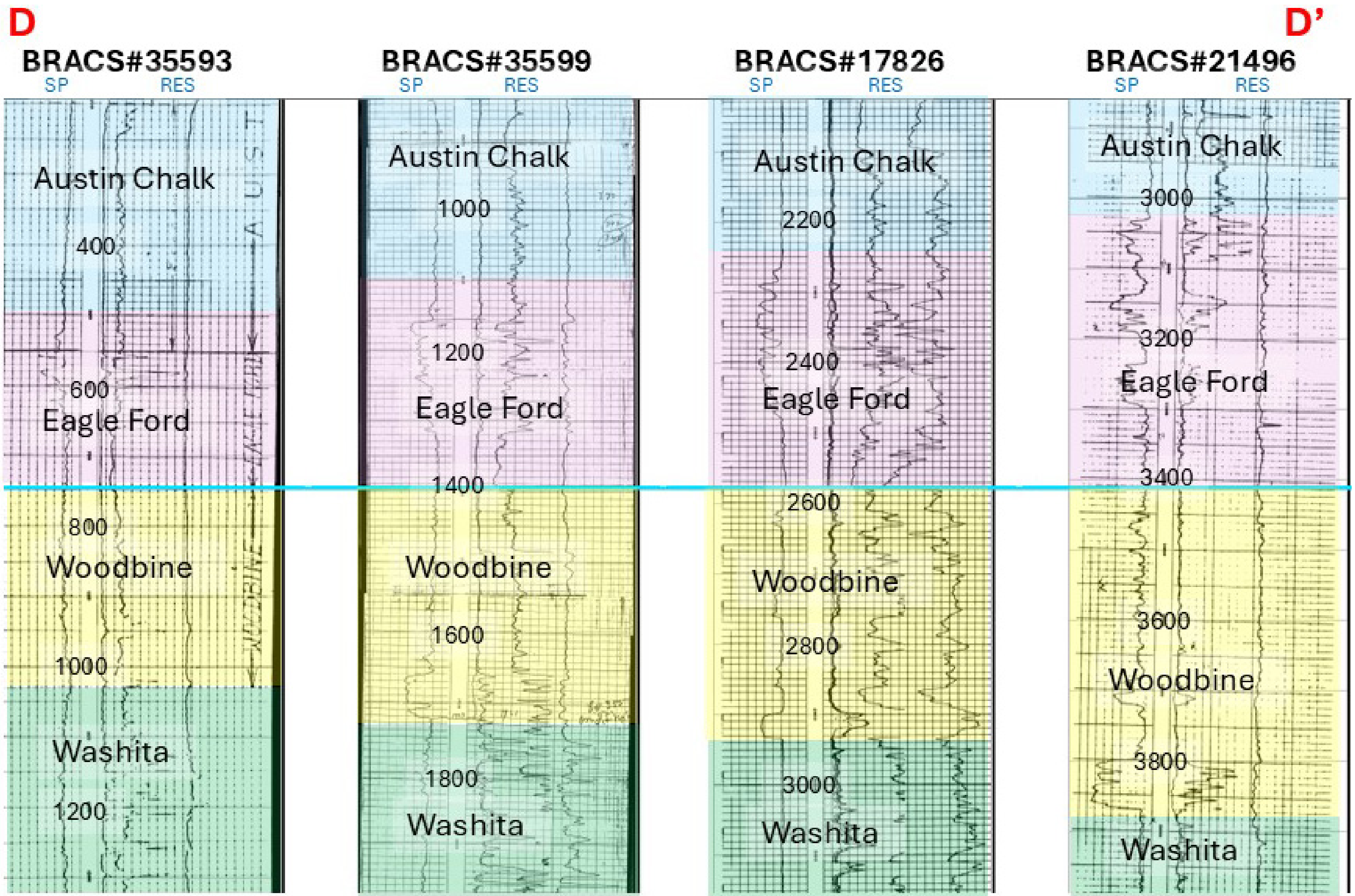


**Figure 8-5** **Correlation cross section D-D' in Red River and Titus counties illustrating correlations for the top of the Eagle Ford Shale, Woodbine Group, and Washita Group in BRACS Database wells (IDs 35593, 35599, 17826, and 21496). The spontaneous potential (SP) is shown in the left track, depth (in feet below reference elevation) is shown in the middle track, and the resistivity tools (RES) are shown in the right track.**

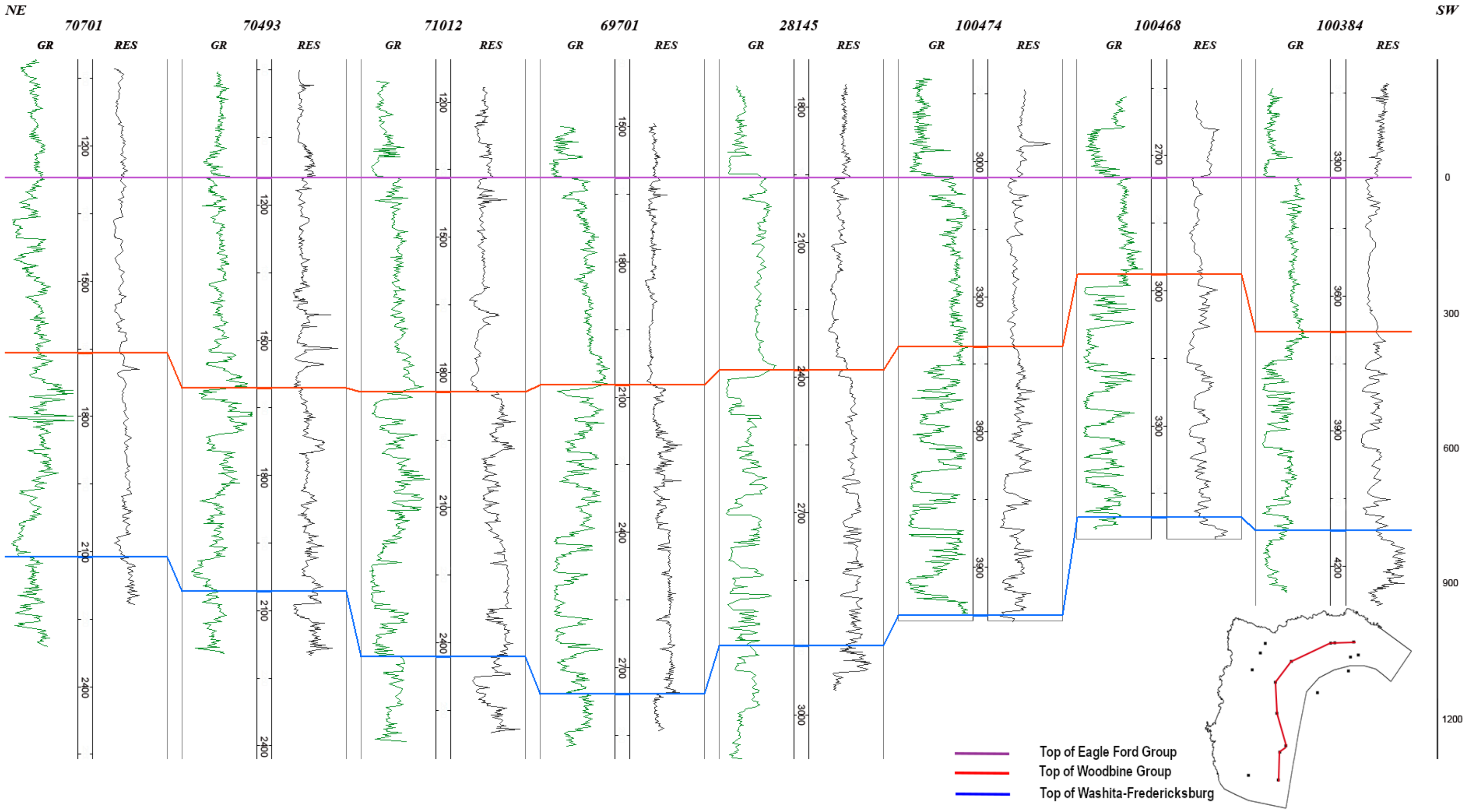


**Figure 8-6** **Strike-oriented correlation cross section through study area digitized well logs (GR = gamma ray, RES = deep resistivity). The numbers at the top of the logs represent the corresponding BRACS ID. The cross section is flattened on the Eagle Ford top.**

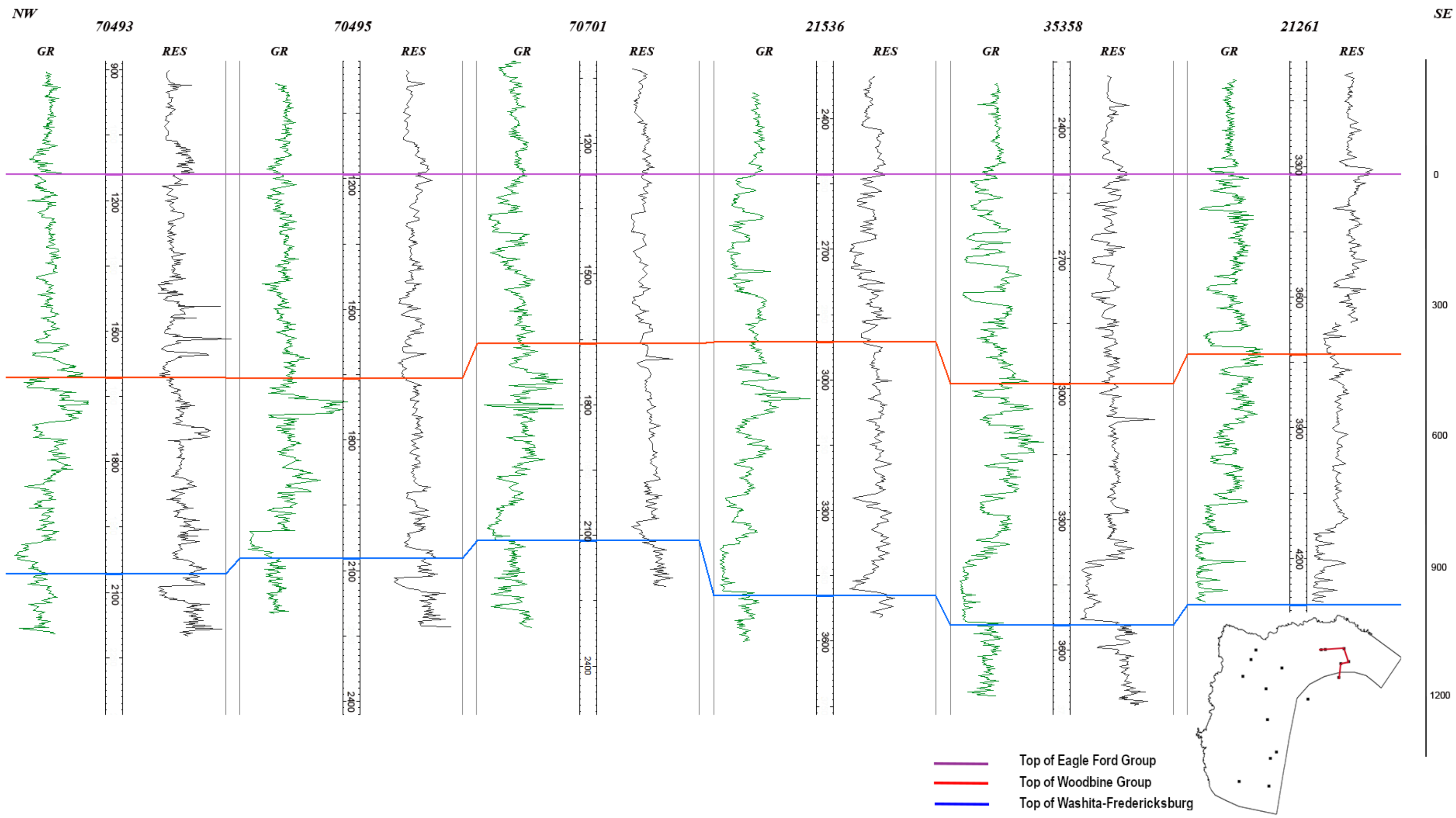


**Figure 8-7** **Dip-oriented correlation cross section through study area digitized well logs (GR = gamma ray, RES = deep resistivity) located in the northern portion of the study area. The numbers at the top of the logs represent the corresponding BRACS ID. The cross section is flattened on the Eagle Ford top.**

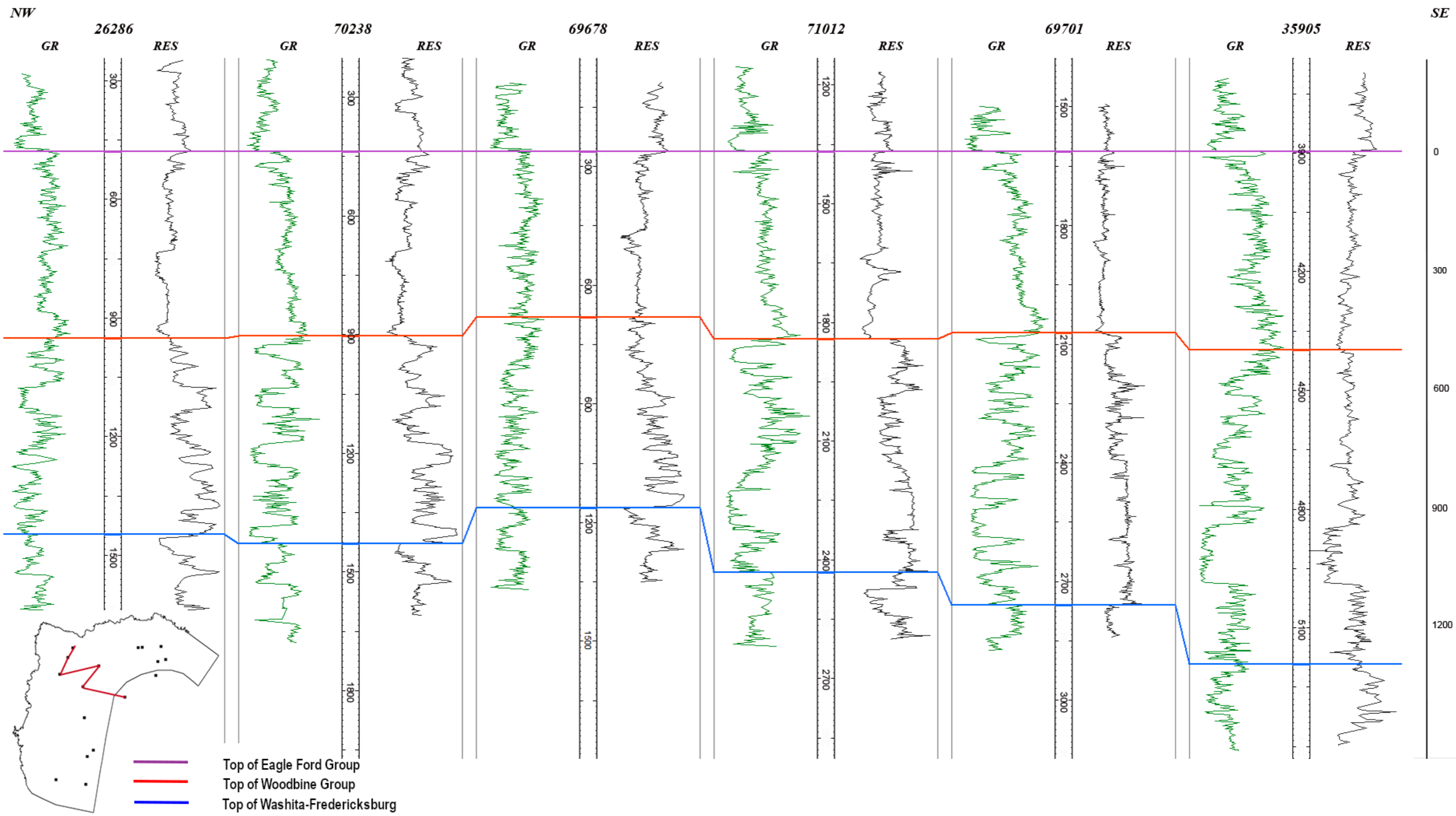


**Figure 8-8** **Dip-oriented correlation cross section through study area digitized well logs (GR = gamma ray, RES = deep resistivity) located in the central portion of the study area. The numbers at the top of the logs represent the corresponding BRACS ID. The cross section is flattened on the Eagle Ford top.**

## 8.2 Stratigraphic interpretation

Surfaces utilized in BRACS studies must meet several criteria related to data transparency, reproducibility, and technical defensibility. Data transparency requires that all the data used in the study, including the generation of the surfaces, must be public and available for inclusion in the BRACS Database. Reproducibility addresses the need for the surface generation methodology to use commonly available tools and well-defined processes so that the surfaces can be generated by other agencies or individuals if necessary. Finally, it is important that all aspects of the surface generation process be technically defensible. Stratigraphic interpretations from well logs must generally agree with previously published studies and surfaces must intersect wells with interpretations at the appropriate depths.

### 8.2.1 Stratigraphic raster generation

Kingdom geologic software was used to interpret geophysical well logs within the study boundary and surrounding areas where data was available and the Woodbine Group was present. This software provides efficient tools for the visualization and interpretation of depth-calibrated images of geophysical well logs. We mapped the stratigraphic units in the subsurface primarily based upon geophysical well log characteristics. The stratigraphic formation picks were exported from Kingdom to a tabulated spreadsheet for input into Esri ArcMap® geospatial software, which was used to interpolate the geologic surfaces. The stratigraphic elevation values are corrected with the well's kelly bushing height, where available, and the site elevation based on a statewide seamless 30-meter digital elevation model. Stratigraphic picks were appended to the geology table in the BRACS Database (tblWell_Geology) and can be found in the GIS source data table (gBRACS_ST_WB).

The Woodbine outcrop extent was extracted from the Geological Atlas of Texas (TWDB, 2007) to define the formation at the ground surface. Elevation points from the digital elevation model were extracted at each outcrop point for use in the stratigraphic raster interpolation process. The outcrop outline point sample rate was set to 250 feet to reflect the accuracy of the interpolated surfaces more closely. Surface contact elevation points were interpolated with the point data from well log correlations to further define the surfaces.

Faults are an important geologic feature of the Woodbine Aquifer study area. The Mexia-Talco Fault Zone consists of numerous individual faults with offsets ranging from tens of feet to more than 1,000 feet (Ewing, 1991). For this study, we identified 22 normal faults with significant offsets and proximal well control that have been modified and digitized from Ewing (1991) and utilized in the raster interpolation process to further constrain the surfaces. While we have not comprehensively mapped or characterized all faults or structural features within the study area, they do provide some insight into the geologic structure in the southern and eastern extents.

We used Esri ArcMap® release 10.8.2 to generate the top and bottom elevation surfaces of the Woodbine utilizing stratigraphic picks from 1,507 and 1,349 wells, respectively. Stratigraphic picks from wells both within the study area and outside of it were incorporated into the raster interpolation process. The benefit of including wells from outside of the study boundary is the reduction of raster edge effects when the final raster surfaces are constrained to only the study area. Well data used in the initial raster interpolation and provided in the GIS files associated with this study may extend down dip more than 50 miles from the study area due to the abundance of geophysical logs in the East Texas Basin. However, relevant formation picks from wells farther than 15 miles outside of the study boundary have not received the same level of quality review during this study since their influence on the final raster maps is negligible. Of the total wells used for the initial top and bottom elevation raster interpolation, 1,075 and 1,020 wells, respectively, are located within the study area boundary.

The resulting surfaces are raster grids consisting of 250-foot square cells coincident with the study snap grid. We employed the Spatial Analyst® Topo to Raster with Cliffs interpolation toolbox to create the surfaces since this tool can incorporate the offsets associated with large displacement faults. The large number of smaller faults associated with the Mexia-Talco Fault Zone and the structural complexities associated with the fold system in the northwest could not be modeled at the scale used for this project, and their effects can be considered as averaged within the modeled surfaces.

In certain cases, the interpolation process resulted in anomalies that created formation surfaces that were too thin, too thick, or even inverted. In these cases, we examined the well attributes such as location and formation picks for accuracy. If the well attributes appeared reliable, we searched for additional well control within the affected area. Where additional well control was unavailable, we created estimated formation elevation points utilizing best professional judgement to guide the interpolations to a more geologically defensible surface. Guide points were used in both the top and bottom formation elevations where needed, mainly in four general areas: 1) where Quaternary deposits covered the Woodbine outcrop, 2) where the well log did not capture the formation bottom elevation, 3) sparse well control near the outcrop, and 4) sparse well control near large faults. Guide point elevations were determined utilizing the geologist's best professional judgement based on local formation thickness identified from nearby well locations. Additionally, any remaining surface inversion was corrected by setting the inverted cells to an elevation value less than the overlying surface.

When the Woodbine top and bottom elevation surfaces were completed, they were then used to create formation top and bottom depth maps and an isochore thickness map. The Woodbine top and bottom depth maps were created by subtracting the respective elevation surface from the study digital elevation model. The isochore thickness map was created by subtracting the formation bottom elevation raster from the top elevation raster. The thickness map was created by subtracting the raster surfaces rather than interpolating thickness values at each well to prevent areas of interpolated thickness that may have exceeded the difference between the interpolated surfaces. These raster calculations were performed using the Raster Calculator tool within EsriArcMap®. A list of the GIS files utilized and generated during this process are tabulated in Appendix D. Additional details of the raster interpolation process can be found in Appendix E.

### 8.2.2 Stratigraphic surface discussion

Figure 8-9 and Figure 8-10 show the final structure maps for the top and bottom elevations of the Woodbine Group. These maps indicate a generally smooth dip to the south and east away from the outcrop and into the East Texas Basin with dips increasing with depth. Additionally, structural variances associated with the Preston Anticline and Sherman Syncline are present in the northwestern portion of the study area where steeper formation dips are encountered as indicated by the contour inflections and thinning of the outcrop expression.

Woodbine Group tops identified in well data within the study area range from 638 feet above mean sea level in Grayson County to 4,315 feet below mean sea level in Freestone County. The interpolated elevation surface for the top of the Woodbine Group ranges from 1,041 feet above mean seal level to 4,421 feet below mean sea level. The highest elevations are observed in the northeast portion of the study area.

The base of the Woodbine Group, represented as the top of the Washita-Fredericksburg Group, ranges from 817 feet above mean sea level in Johnson County to 4,701 feet below mean sea level in Freestone County. The interpolated bottom elevation surface for the Woodbine ranges from 976 feet above mean sea level to 4,848 feet below mean sea level.

As described in Section 8.2.1, the Woodbine top and bottom depth surfaces were generated by subtracting the elevation surfaces from the study 30-meter digital elevation model. The calculated top depth ranges from 0 feet in the outcrop to 4,941 feet below ground surface (Figure 8-11). The bottom depth ranges from 0 feet in the outcrop to 5,344 feet below ground surface (Figure 8-12).

Figure 8-13 illustrates the Woodbine Group isochore thickness within the study area. The calculated formation thickness map ranges from 0 feet at the lower outcrop contact to 825 feet in Kaufman County. The thickest sections of the Woodbine are generally present within the fault grabens and south of the Mexia-Talco Fault Zone. Additionally, thicker accumulation of sediments is observed within the region of eastern Collin and Hunt counties generally along deposition axes interpreted by Oliver (1971). Thinner sections are present in the southern and northeastern portions of the study area. Thinning also occurs in the outcrop due to the top erosional surface.

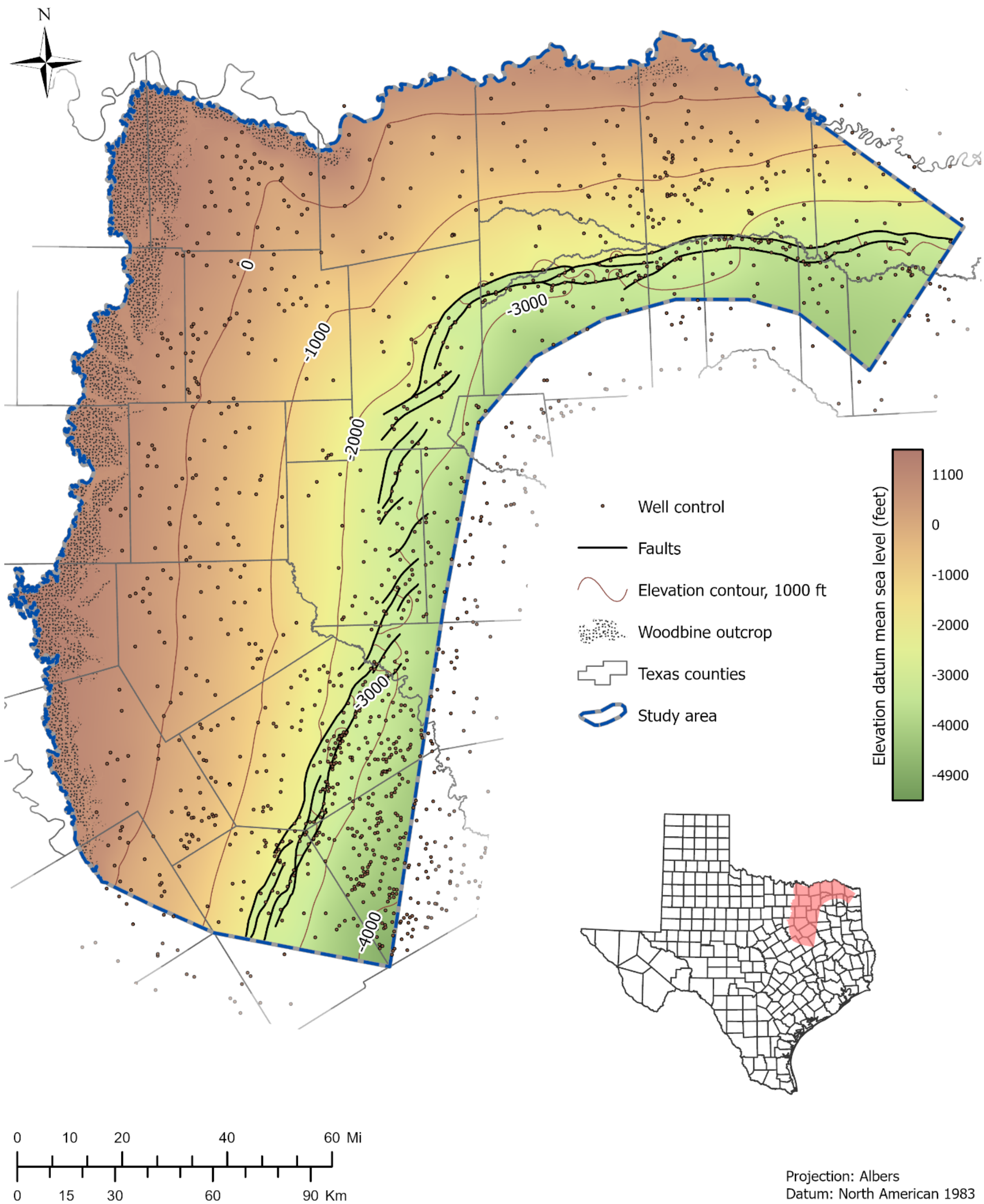


**Figure 8-9 Top of Woodbine Group structure map (elevation datum is mean sea level, feet).**

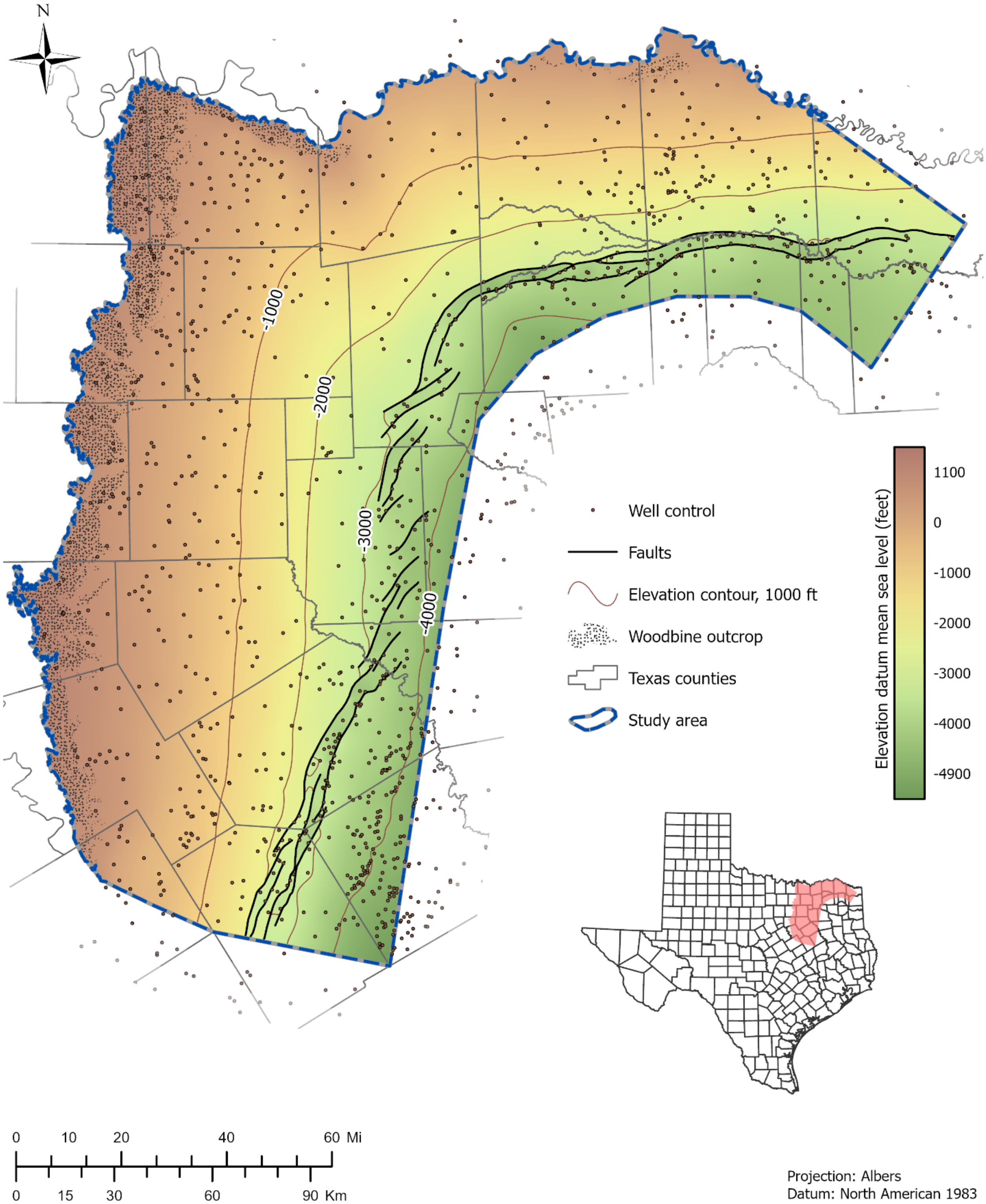


**Figure 8-10 Bottom of Woodbine Group structure map (elevation datum is mean sea level, feet).**

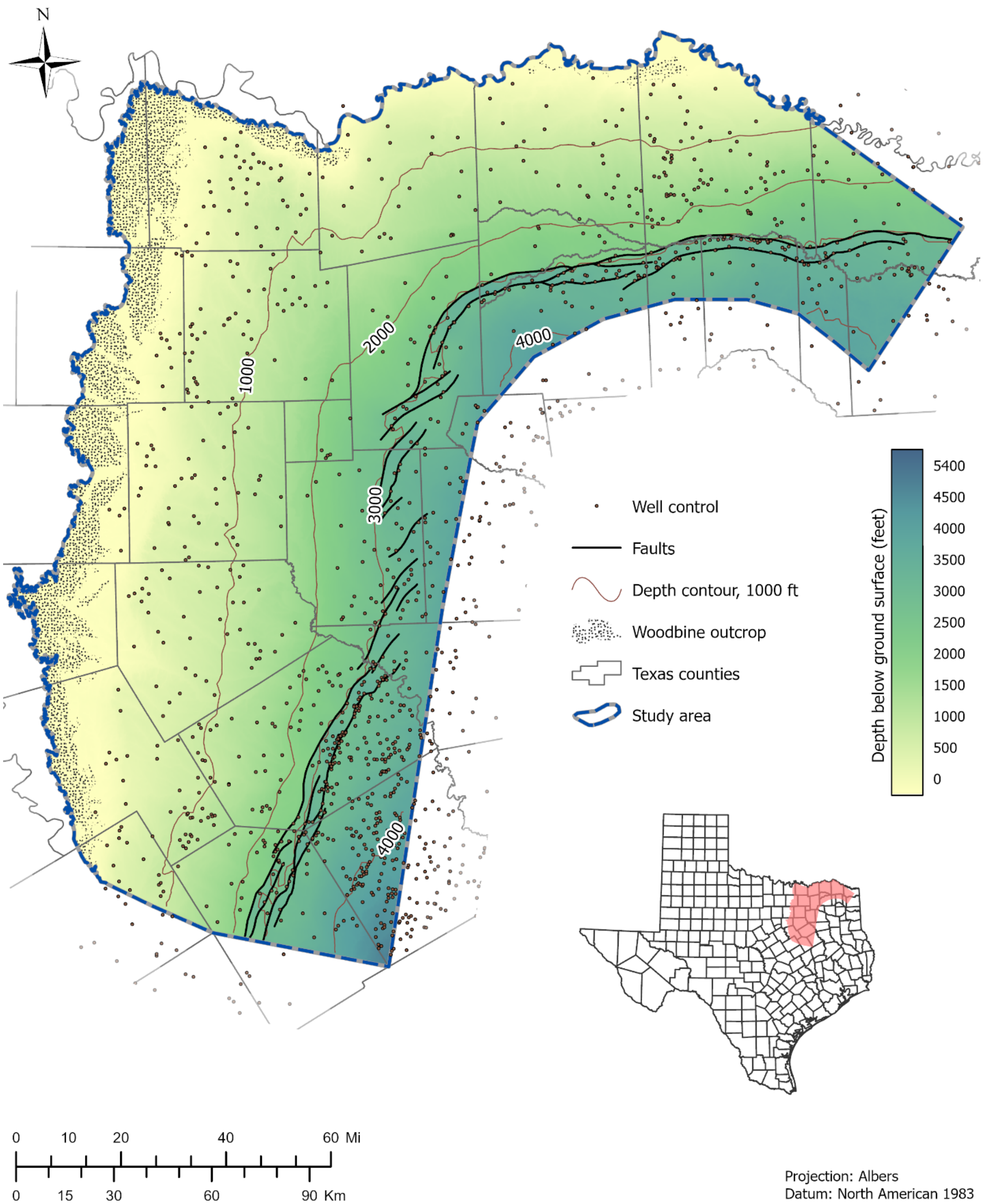


**Figure 8-11 Top of Woodbine Group depth surface map (depth below ground surface, feet).**

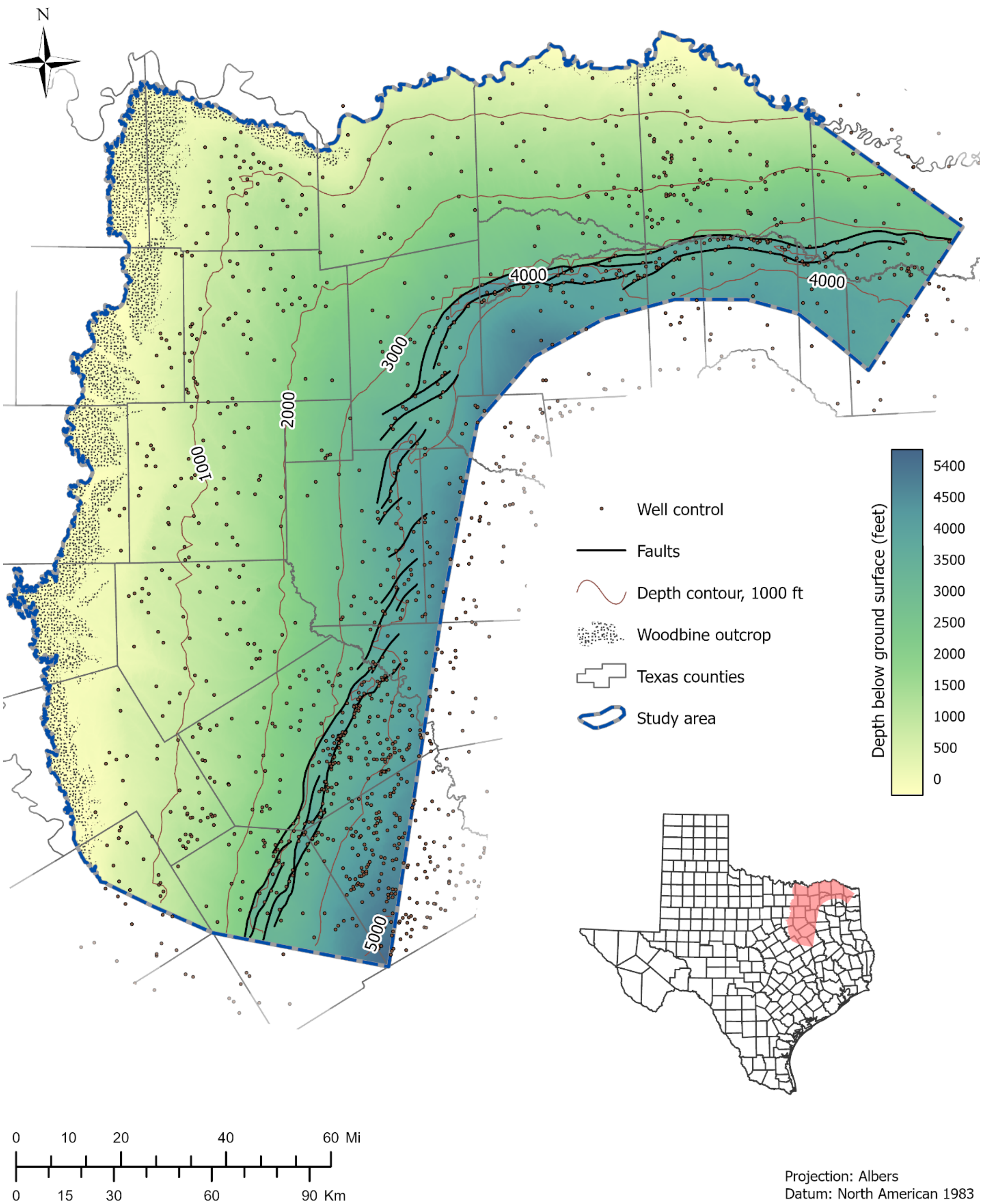


**Figure 8-12 Bottom of Woodbine Group depth surface map (depth below ground surface, feet).**

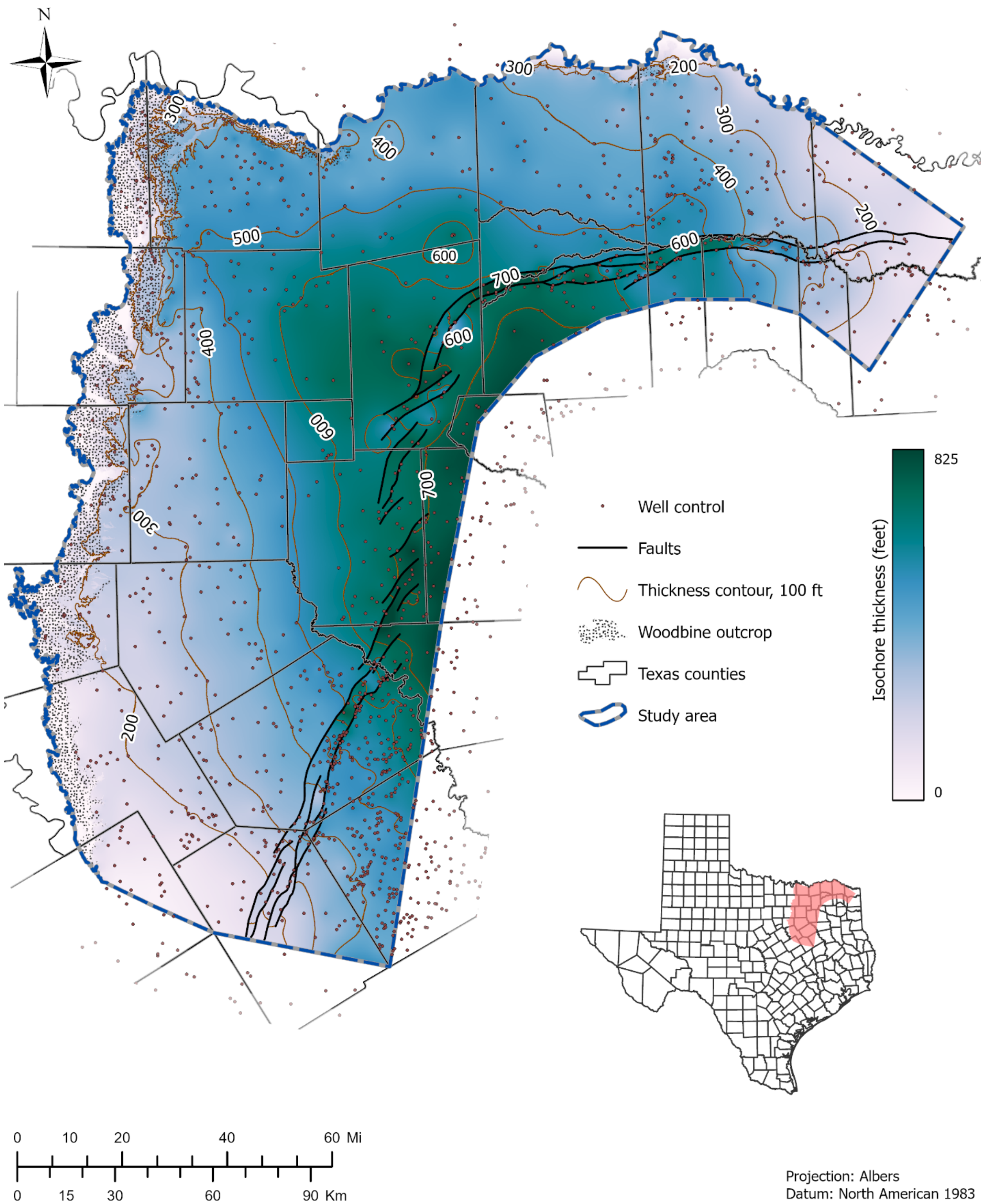


**Figure 8-13 Woodbine Group isochore thickness map (thickness in feet).**

## 8.3 Net sand analysis

The Woodbine Group primarily consists of sand and sandstone with interbedded layers of shale and clay. Although both sandstone and shale can contain groundwater, and water saturated clay layers may leak into adjacent sands, the hydrologic properties of sandstone enable groundwater to be more economically produced. For this study, we utilized a simplified two-tier method to characterize lithology as either sandstone or shale.

A combination of resistivity tools, a spontaneous potential tool, and a gamma ray tool, where available, were used to interpret lithology from geophysical well logs. We identified the sand intervals using the "Picked Intervals" function within Kingdom. Then we used the "Zone Attribute Calculator" to sum the individual sand intervals for each well to calculate the cumulative thickness of sand. We exported the cumulative sand thickness for each well location to interpolate net sand utilizing the Spatial Analyst® Topo to Raster function in Esri ArcMap®. This simplified two-tier method allowed for quick interpretation of net sands in a large volume of data by assuming each "picked" sand body is 100 percent sand and that anything not picked is something other than sand (generally shale). However, because this method assumes 100 percent sand within each picked interval, there is some degree of overestimation. However, because unpicked intervals with sandy-shale may not be included we considered the sand count to be representative.

We evaluated anomalies on a case-by-case basis, and added well control where needed or removed well control if the information did not support the regional net sand trend. Wells with only partial penetration of the Woodbine, such as those within the outcrop or those that may have significant sections faulted out, were excluded from the interpolation. The total number of well control points used for the initial net sand interpolation was 1,086, of which 813 are within the study area boundary. Control points with a forced net sand value of zero were added to the interpolation process at the up-dip extent of the outcrop during raster interpolation. Generally, net sand present within the outcrop will exhibit diminishing quantities due to erosional thinning and cover by Quaternary deposits. In general, lithology from driller's logs was not utilized for this study due to challenges with determining clear formation boundaries from descriptions.

As a quality control measure, the cumulative thickness of sand (net sand) was compared to the isochore formation thickness. In areas where net sand was interpolated at values greater than the overall formation thickness, the net sand raster was set to be equal to that of the formation thickness. These corrections were generally limited to 1) eroded drainage valleys within the outcrop area where the formation is relatively thin and covered by surface water features or Quaternary deposits, 2) where the bottom elevation raster was previously corrected for inversion, 3) at well locations where there is missing section within the Woodbine stratigraphic interval due to faulting causing localized formation thinning, and 4) areas of sparse well control.

Within the study area, net sand ranges from zero feet at the up-dip outcrop extent to 470 feet near the eastern edge of the study area in Henderson County (Figure 8-14). Thick accumulations of sand are present along the eastern edge of the study area within and south of the fault zone spanning from Henderson County through Hopkins County. Oliver (1971) indicates that these sand accumulations are associated with the Freestone Delta depositional system.

Additional thick sequences of sand are found in the vicinity of Hunt, eastern Collin, and northern Rockwall counties in the central part of the study area. Oliver (1971) notes that massive channel sands associated with the meander belt facies are present at thicknesses ranging from 180 feet up to 380 feet. These sand bodies contribute significantly to the overall net sand accumulation in this area. Generally, areas of greater net sand align with areas of thicker overall Woodbine accumulation and depositional axes.

In the study area, sand content diminishes to the south of Ellis and Navarro counties as sediment accumulation transitions into the shale-dominated pro-delta shelf facies (see Figure 5-4 in this report). Sand accumulation is also limited in the northeastern portion of the study area in parts of Lamar, Red River, Bowie, and Cass counties closer to the up-dip extent and sediment source (Oliver, 1971, Adams and Carr, 2010).

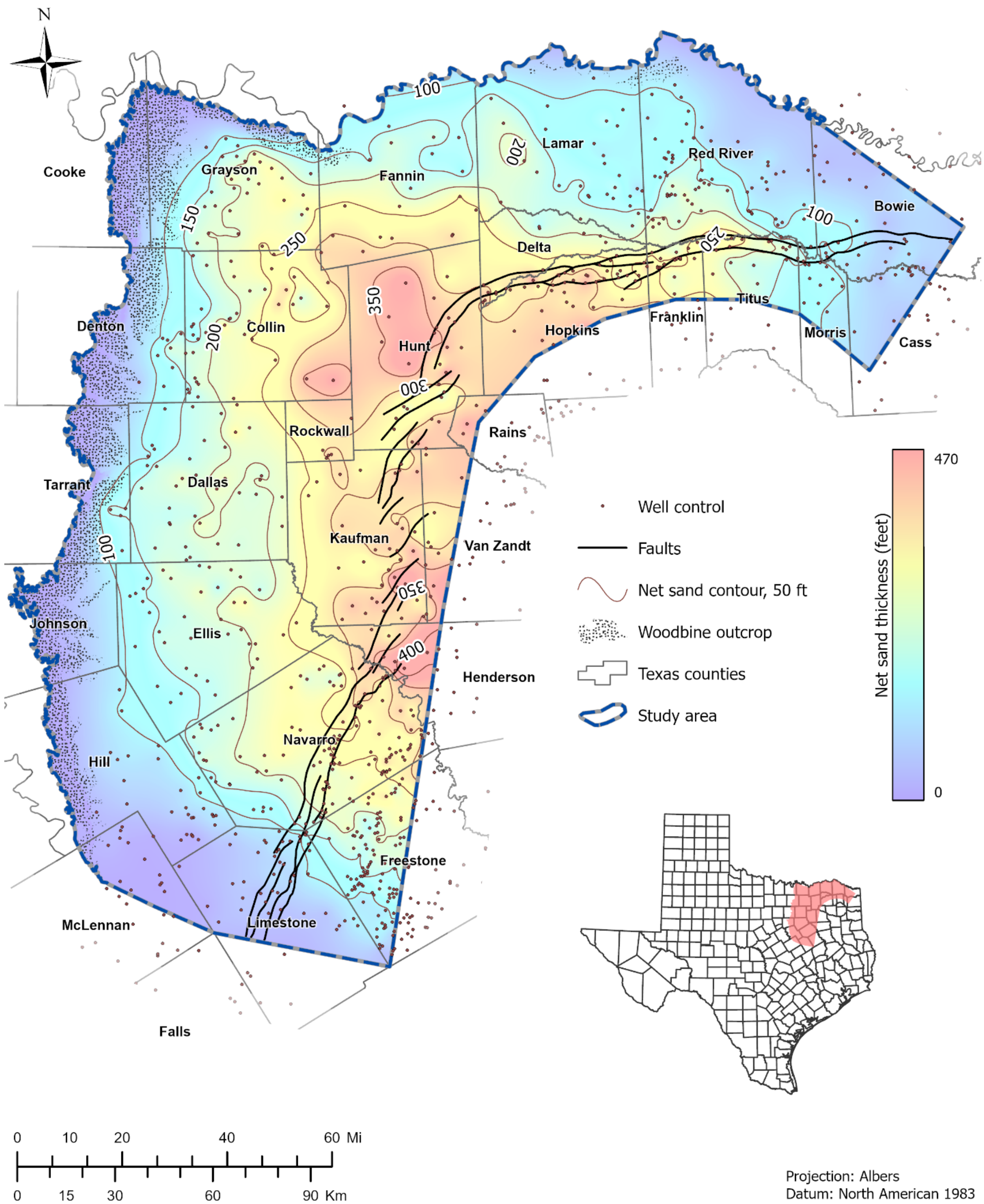


**Figure 8-14 Woodbine Group net sand thickness map (thickness in feet).**

# 9 Aquifer determination

An important part of a BRACS study is the accurate assignment of water quality samples, hydraulic properties, and geophysical well log analyses to the correct aquifer. We used the formation top and bottom raster surfaces to calculate their intersection with all study area wells available in the TWDB BRACS and Groundwater databases. This data is compiled into the BRACS Database study aquifer determination table (tblAquifer_Determination_WB), which allows us to evaluate which wells penetrate the Woodbine Aquifer. This process includes a review of wells in the TWDB Groundwater Database that have an existing aquifer code for the Woodbine Aquifer (212WDBN) and provides an opportunity to revise any wells with aquifer codes that may have been erroneously assigned.

The stratigraphic top and bottom depths were extracted from the formation raster surfaces for each well location and compared with the well's depth and completion information within the aquifer determination table. For quality control purposes, we evaluated all wells assigned a Woodbine Aquifer code or where the depth comparison indicated the well likely targeted the Woodbine Aquifer. In total, 1,398 wells were individually reviewed, of which 1,292 were determined to likely be completed within the Woodbine Aquifer. This decision is indicated in the aquifer determination table with a designation of "Yes" under the WB_AQUIFER field in the table. Wells with aquifer codes that indicate dual completions in the Woodbine and any other formation were not considered to be representative of the Woodbine Aquifer and were excluded from this study. Other exclusions include wells that have the Woodbine Aquifer code but lack sufficient well data to determine if there is potentially commingling with adjacent aquifers such as overlying alluvium in the outcrop area.

In some cases, the interpolated formation surfaces deviated slightly from the formation depths indicated by well data. These wells were reviewed on a case-by-case basis for aquifer assignment. These discrepancies generally occurred where

- the geologic formation is known to be structurally faulted within the well bore,
- well control is sparse,
- Quaternary deposits overlie the Woodbine in the outcrop area,
- wells are within structural zones where the raster surface could not replicate the complex geology, and
- where the location was verified but the stratigraphic interpretation using geophysical well log did not match the surficial mapped geology.

# 10 Aquifer hydraulic properties

An aquifer's hydraulic properties refer to the physical characteristics that control groundwater flow within the aquifer. These hydraulic properties can include transmissivity, hydraulic conductivity, specific yield, specific capacity, drawdown, pumping rate (well yield), storage coefficient, and porosity. Factors that affect the changes in hydraulic properties include depositional environments, faults or fractures, and aquifer structure, among others. Aquifer properties are commonly determined from aquifer test data, which involves an analysis of drawdown measurements over time in either one or multiple monitoring wells. The primary hydraulic properties we considered in this study are:

**Specific yield** ($S_y$) – The estimated percent pore volume in the aquifer that can be drained in an unconfined aquifer. Some water will remain trapped in pores when there is insufficient permeability, such as when clays are present. Our study determined this unitless number based upon a literature review.

**Specific storage** (*Ss*) – This term describes the volume of water a unit thickness of a confined aquifer will release when the water level in the aquifer is lowered. Specific storage has dimensions of inverse length.

**Storativity** *(S)* – The product of effective aquifer thickness and specific storage (*Ss*). This term is used to refer to the volume of water that a unit thickness of confined aquifer will release when the water level in the aquifer is lowered.

$$S = Ss \times b \qquad \textbf{(Equation 10-1)}$$

where:

$S$ = storativity (unitless)

$Ss$ = specific storage (1/feet)

$b$ = aquifer thickness (feet)

**Specific capacity** (*SC)* – This term describes the volume of water released per unit decline in water level (unit drawdown). It is calculated by dividing the total pumping rate by the drawdown and is generally reported in gallons per minute per foot.

**Hydraulic conductivity** *(K)* – The measure of ease with which groundwater can flow through an aquifer. Greater conductivity indicates greater ease of flow. Dimensions are typically expressed in units of feet per day or gallons per day per square foot.

**Transmissivity** *(T)* – This term is related to hydraulic conductivity and describes the ability of groundwater to flow through the thickness of an aquifer, *b*. The greater the thickness of an aquifer, the greater the transmissivity at a given hydraulic conductivity. The dimensions are expressed in units of square feet per day or gallons per day per foot and the relationship of transmissivity to hydraulic conductivity and aquifer thickness is as follows:

$$T = K \times b$$ **(Equation 10-2)**

where:

$T$ = transmissivity (feet$^2$/day)

$K$ = hydraulic conductivity (feet/day)

$b$ = aquifer thickness (feet)

These hydraulic parameters can be used for calculating groundwater volume, designing a well field in a potential production area, assessing and assigning production permits, and modeling the impacts of pumping wells on other nearby wells and surface water.

## 10.1 Pumping test data

We compiled and reviewed the hydraulic properties of well yield, specific capacity, hydraulic conductivity, and transmissivity for 449 wells within the study area. The data collected for these wells has been saved in the BRACS Database in a study specific aquifer test table (tblBRACS_AT_WB). Detailed maps of the locations of compiled aquifer test data can be found in Appendix F. Table 10-1 summarizes pumping test data.

The main sources of aquifer test data for this study include the TWDB Groundwater Database (TWDB, 2024e) and SDR Database (TDLR, 2024). There were also multiple historical TWDB reports that contain compiled aquifer test results from Texas water wells (Myers, 1969; Christian and Wuerch, 2012).

Many of the well yields are from tests conducted decades ago and may not be indicative of what a properly designed, large capacity well could produce. Additionally, these tests are generally from portions of the aquifer that are relatively shallow and closer to the outcrop and may not be representative of conditions at increased depths where brackish water is generally found. The accuracy of results depends upon factors such as test duration and spacing and location of monitoring wells. Users of the hydraulic property data presented in our study should evaluate the data in the proper context and local studies should be conducted.

Generally, owner-estimated, or owner-reported well yields without additional data or documentation were not included in this compilation. Additionally, data of questionable quality with water level, drawdown, or well yield that appeared to be estimated in units of tens or hundreds of feet were examined for additional documentation and evaluated on a case-by-case basis. Well performance tests of less than one hour were not included. Due to the large volume of data available from the SDR Database, capturing records of pumping tests with durations greater than twelve hours was prioritized. Additional test data beyond what is presented in this report may be available in the TWDB Groundwater and SDR databases.

**Table 10-1 Summary of aquifer test data.**

| | Specific capacity (gpm/ft)[a] | Well yield (gpm)[b] | Transmissivity (gpd/ft)[c] | Hydraulic conductivity (gpd/ft$^2$)[d] |
|---|---|---|---|---|
| **Count** | 305 | 440 | 32 | 26 |
| **Minimum** | <1 | 2 | 337 | 3 |
| **Maximum** | 74 | 1,170 | 26,400 | 183 |
| **Average** | 3 | 143 | 5,679 | 64 |
| **Median** | 1.45 | 75 | 3,372.5 | 42.5 |

[a]gpm/ft = gallons per minute per foot of drawdown

[b]gpm = gallons per minute of discharge

[c]gpd/ft = gallons per day per foot

[d]gpd/ft$^2$ = gallons per day per foot squared

# 11 Measured water quality

To map salinity across the study area, we used both total dissolved solids derived from measured water quality from groundwater samples and estimated total dissolved solids calculated from geophysical well logs. These two datasets are combined to allow characterization of the brackish portion of the aquifer where a limited number of groundwater wells exist.

Measured groundwater sampling data utilized for this study is primarily from the TWDB Groundwater Database (TWDB, 2024e) with additional samples from the U.S. Geological Survey Produced Waters Database (USGS, 2023b).

Utilizing the results of the aquifer determination process, we were able to classify if water samples were sourced from the Woodbine Aquifer in the study master water quality table (tblBRACS_WB_MasterWaterQuality). The master water quality table contains a total of 5,992 samples from 2,488 wells across the study area, of which 1,803 samples are determined to be exclusively from the Woodbine Aquifer. Of the samples from the Woodbine Aquifer, 1,482 were determined to be balanced.

## 11.1 Measured sample quality assurance

Two methods for determining milligrams per liter of total dissolved solids for a water sample include: 1) dry the sample at temperatures above 103° Celsius to as high as 180° Celsius and weigh the residue, or 2) sum the individually determined chemical constituents (Hem, 1985). Because laboratory methods for determining the weight of residue may differ and reported total dissolved solid values do not always specify whether the value is from a weighed residue or calculated, we used only total dissolved solid values calculated from the sum of the major constituents for this study to assure that our values are directly comparable.

Estimating total dissolved solids from geophysical well logs requires establishing the relationship between total dissolved solids and specific conductance, discussed later in Section 11.2.2. The benefit of using the full value of bicarbonate for the plot of total dissolved solids versus specific conductance is that it yields a more accurate relationship.

We summed the following major constituents to calculate total dissolved solids: $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Na^{+}$, $Sr^{2+}$, $SiO_2$, $HCO_3^{-}$, $CO_3^{2-}$, $Cl^{-}$, $SO_4^{2-}$, F, and $NO_3^{-}$.[1] We verified the accuracy of the reported major constituent values by verifying the charge balance between the major anions and cations and by comparing the total anion milliequivalents per liter to the total cation milliequivalents per liter. Equations associated with this process are listed in Appendix G. For accurately analyzed water quality samples, the total anion and cation milliequivalents per liter should only differ by one to two percent (Hem, 1985). Measured water quality samples from the TWDB Groundwater Database include a flag to indicate whether they are balanced or unbalanced. However, there are some inconsistencies between the ion concentrations and reported balance in the TWDB Groundwater Database. For example, samples that appear to be balanced are flagged as unbalanced. Because of this uncertainty, we recalculated the balance for all TWDB Groundwater Database samples that we designated as Woodbine and reflagged them as balanced or unbalanced. We marked samples with less than or equal to five percent difference (negative or positive) as balanced.

We identified one groundwater sample from the USGS Produced Water Database, which we considered to have an accurate location and balanced sample data, with total dissolved solids concentration of 20,027 milligrams per liter.

## 11.2 Total dissolved solids

The total dissolved solids value is defined as the total concentration of ions and molecules dissolved in the water and is reported in units of milligrams per liter. In this report, the total dissolved solids concentration of water is also referred to as the salinity of the water. Five salinity classes defined by total dissolved solids concentration are used throughout this report following usage in the U.S. Geological Survey paper by Winslow and Kister (1956):

1. fresh water (0 to 999 milligrams per liter total dissolved solids)
2. slightly saline water (1,000 to 2,999 milligrams per liter total dissolved solids)
3. moderately saline water (3,000 to 9,999 milligrams per liter total dissolved solids)
4. very saline water (10,000 to 34,999 milligrams per liter total dissolved solids)
5. brine (greater than 35,000 milligrams per liter total dissolved solids)

Although brackish water can refer to total dissolved solid concentrations ranging from 1,000 to 34,999 milligrams per liter (slightly saline to very saline water), we focus on

---

[1] Calcium ($Ca^{2+}$), Magnesium ($Mg^{2+}$), Potassium ($K^{+}$), Sodium ($Na^{+}$), Strontium ($Sr^{2+}$), Silica ($SiO_2$), Bicarbonate ($HCO_3^{-}$), Carbonate ($CO_3^{2-}$), Chloride ($Cl^{-}$), Sulfate ($SO_4^{2-}$), Fluoride (F), and Nitrate ($NO_3^{-}$).

slightly saline and moderately saline water in our mapping and volume estimates. However, for this study we calculated the volume of brackish groundwater up to 34,999 milligrams per liter of total dissolved solids to include very saline groundwater. This volume has been presented separately from the total volume of slightly and moderately saline groundwater. It is important to note that desalination often requires reducing total dissolved solids concentrations below 1,000 milligrams per liter, thus the total dissolved solids concentration of brackish water is a primary concern for desalination. Slightly saline and moderately saline brackish water is preferable to very saline brackish water as it requires less effort and expense to desalinate to fresh drinking water standards. The TWDB defines brackish groundwater as slightly and moderately saline waters (1,000-9,999 milligrams per liter of total dissolved solids concentration) for the purposes of brackish groundwater production zone designation (31 Texas Administrative Code § 356.10).

### 11.2.1 Major chemical constituents

To analyze the major chemical constituents of groundwater in the Woodbine Aquifer, we reviewed 622 balanced samples representing the most recent sampling event for each well deeper than 30 feet. These samples date from 1938 to 2019 with approximately 62 percent of them collected from 1970 through 1989. Table 11-1 summarizes the balanced water quality sample data. The dominant hydrochemical facies within the Woodbine Aquifer is sodium bicarbonate (Hopkins, 1996). Sodium chloride and mixed-type facies are also present, particularly at higher salinities. Fresh water is also characterized by mixed-type and magnesium bicarbonate waters, with some sodium chloride type samples proximal to the outcrop (Figure 11-1). The major anions and cations are discussed below. Ion percentages are calculated using milliequivalents per liter.

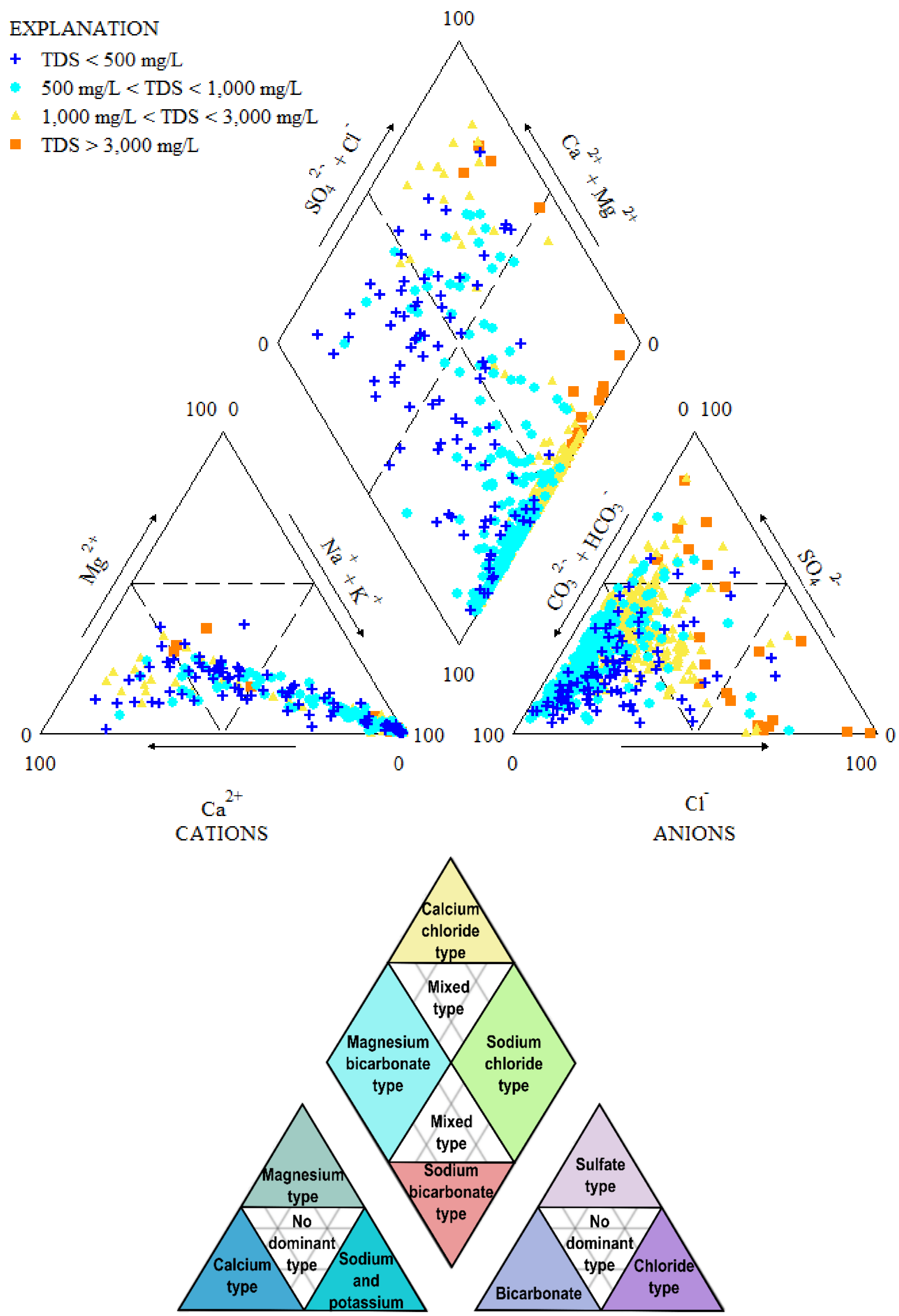


**Figure 11-1** **Piper diagram of balanced groundwater samples in the study area with dominant geochemical signatures index map. The blue crosses and circles are fresh water, the yellow triangles are slightly saline, and the orange squares are moderately saline.**

The overall concentration of total dissolved solids appears to increase with depth and distance from the outcrop. However, there are isolated areas of elevated total dissolved solids concentrations near and within the outcrop. Locally, dissolved solids may be elevated by human activity such as surface contamination or injection of wastewater into aquifers at depth. Surface contamination is assumed to not affect the deeper, brackish portions of the aquifer which are the primary concern of this study. We did not investigate injection of wastewater in detail for this study. However, this will be further investigated during the evaluation for potential brackish groundwater production zones following this study. As discussed in other sections of this report, elevated total dissolved solids associated with increased sulfates due to the presence of lignite can be found in portions of the study area. The upper sand beds of the Woodbine may contain poorer quality water and are less developed for production than the lower sand units (Peckham and others, 1963, Nordstrom, 1982) in certain areas. Elevated concentrations of iron also occur in some areas.

**Table 11-1 Water quality summary for most recent samples per well. All units are in milligrams per liter unless otherwise noted.**

| Constituent | Minimum | Maximum | Average | Sample count |
|---|---|---|---|---|
| Silica | 3 | 59 | 13.7 | 483 |
| Calcium | < 0.2 | 950 | 22.4 | 630 |
| Magnesium | 0.01 | 260 | 6.4 | 662 |
| Potassium | < 0.1 | 20 | 2.7 | 190 |
| Sodium | 5 | 3,420 | 334.6 | 631 |
| Carbonate + bicarbonate ($CO_3$ + $HCO_3$) | 16 | 1,200 | 468.7 | 631 |
| Sulfate | 1.9 | 2,210 | 230.8 | 631 |
| Chloride | 4 | 5,820 | 126.7 | 631 |
| Fluoride | 0.06 | 6.08 | 1.6 | 617 |
| Total dissolved solids (all bicarbonate) | 84 | 9,747 | 1,205 | 631 |
| Specific conductance (micromhos/centimeter) | 56 | 17,167 | 1,629 | 631 |

## Anions

For all samples, bicarbonate (plus carbonate) averages 57 percent of total anions across all total dissolved solids concentrations. For samples with total dissolved solids concentrations less than 1,000 milligrams per liter, the bicarbonate group averages 65 percent of the anions. Bicarbonate (plus carbonate) is the dominant anion group in 512 samples. The highest concentration of bicarbonate in this data set is 1,200 milligrams per liter. Percentages are based on milliequivalents per liter (mEq/L).

Elevated concentrations of chloride can be found dispersed throughout the study area, including within the outcrop. Chloride is naturally derived from subsurface material but can also be introduced anthropogenically from sources such as sewage or oil-field and industrial brines (Hopkins, 1996). Chloride is the dominant anion in 27 samples averaging 59 percent of the total anions. In samples with total dissolved solids less than 1,000 milligrams per liter, chloride averages 13 percent of anions. The highest concentration of chloride was 5,820 milligrams per liter.

Localized pockets of elevated sulfate concentrations, generally resulting in higher total dissolved solids, can be found in and near the outcrop particularly in Johnson and Tarrant counties, but also in Denton, Grayson, Ellis, and Fannin counties. The elevated sulfate concentrations are associated with the presence of lignite beds (Baker and others, 1990; Nordstrom, 1982; TWDB, 1999). In samples with total dissolved solids less than 1,000 milligrams per liter, sulfate averages 23 percent of the total anion concentration. When considering all samples, sulfate averages 28 percent. In 83 samples, sulfate is the dominant anion. Most of these samples are in Tarrant, Johnson, Dallas, and Ellis counties, with the remainder dispersed throughout in counties proximal to the outcrop. The highest concentration of sulfate was 2,210 milligrams per liter.

Figures 11-2 and 11-3 illustrate the percentage milliequivalents per liter of the anion groups as a function of total dissolved solids concentration and well depth.

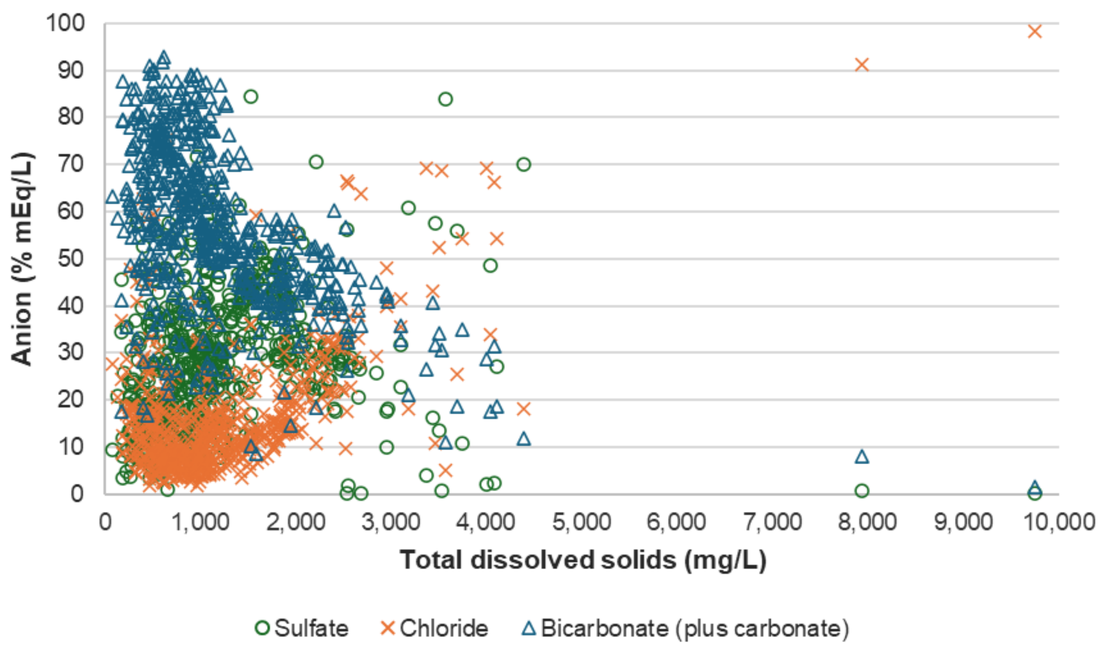


**Figure 11-2 Major anion concentrations versus total dissolved solids in milligrams per liter. Anion concentrations are in percent milliequivalents per liter of total anions. The number of samples is 622.**

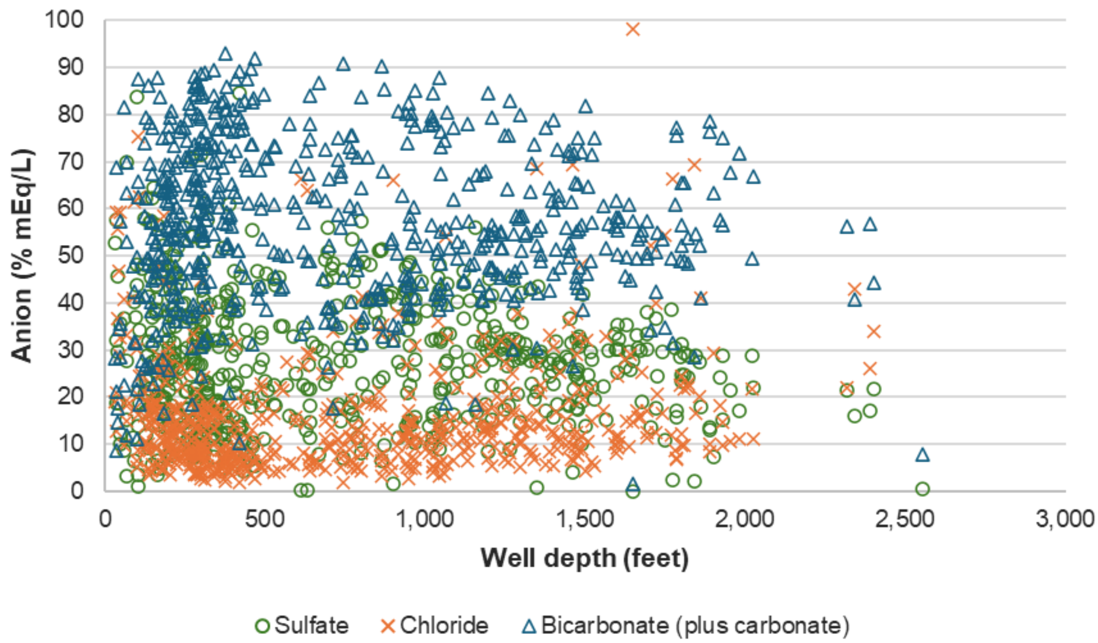


**Figure 11-3 Major anion concentrations versus well depth in feet. Anion concentrations are in percent milliequivalents per liter of total anions. The number of samples is 622.**

## Cations

Sodium (plus potassium) is the dominant cation group across all concentrations of total dissolved solids. For samples with less than 1,000 milligrams per liter total dissolved solids, sodium (plus potassium) averages 80 percent of the total cations. For all samples, this average increases to 87 percent of cations. The highest concentration of sodium was 3,420 milligrams per liter.

Over all samples, calcium averages nine percent of the total cations. In samples with total dissolved solids concentrations of less than 1,000 milligrams per liter, calcium averages 14 percent. The highest concentration of calcium was 940 milligrams per liter in a shallow well drilled to less than 30 feet. The next highest concentration was 640 milligrams per liter in a well drilled to a depth of 70 feet.

Magnesium averages only four percent of the total cations across all samples. It is only slightly higher at six percent in samples with total dissolved solids less than 1,000 milligrams per liter. The highest concentration of magnesium was 260 milligrams per liter in a shallow well. The next highest concentration was 235 milligrams per liter. These are the same wells with the highest concentrations of calcium.

The following graphs illustrate that, while sodium is the dominant cation overall, there is considerably more variability in samples from groundwater with less than 1,000 milligrams per liter total dissolved solids (Figure 11-4). Largely, these samples are located within or proximal to the outcrop with most of them occurring in wells shallower than 500 feet (Figure 11-5).

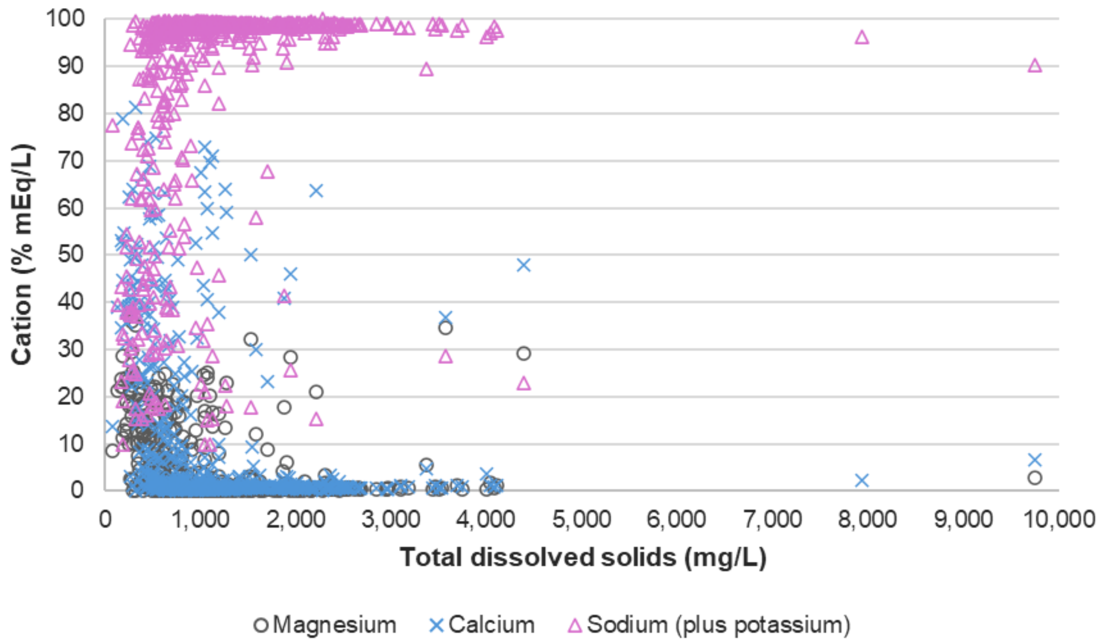


**Figure 11-4** **Major cation concentrations versus total dissolved solids in milligrams per liter. Cation concentrations are in percent milliequivalents per liter of total cations. The number of samples is 622.**

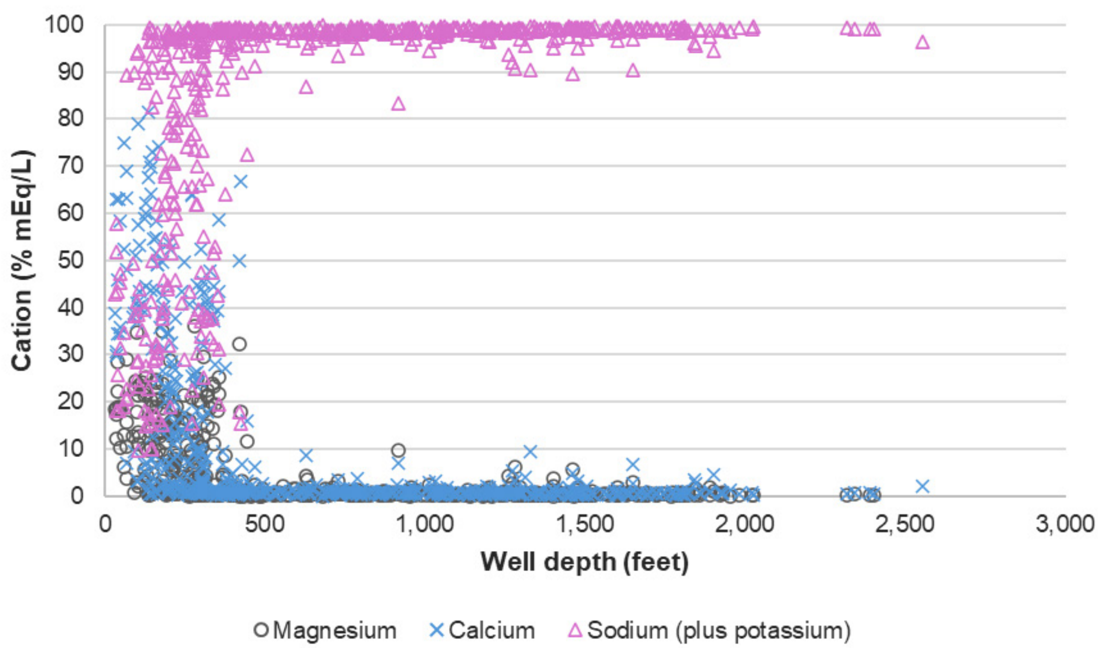


**Figure 11-5** **Major cation concentrations versus well depth in feet. Cation concentrations are in percent milliequivalents per liter of total cations. The number of samples is 622.**

### 11.2.2 Total dissolved solids and specific conductance relationship

Understanding the relationship between total dissolved solids and specific conductance across the study area is necessary for calculating total dissolved solids from geophysical well logs. Because the resistivity of the formation water is a function of the dissolved solids concentration, we can calculate the dissolved solids concentration using the resistivity measurements from geophysical well logs. Measured water quality often includes a measurement of specific conductance in units of micromhos per centimeter, which is the inverse of resistivity in ohm-meters multiplied by 10,000.

Specific conductance can be related to the concentration of total dissolved solids by applying a multiplier (conductivity conversion factor) ranging from 0.4 to as high as 0.96 for high sulfate waters (Hem, 1985).

$$SC = \frac{TDS}{ct}$$ **(Equation 11-1)**

where:

$SC$ = specific conductance (mS/cm)

$TDS$ = total dissolved solids concentration (mg/L)

$ct$ = multiplier

The multiplier (*ct*) that relates specific conductance to total dissolved solids concentration is typically averaged across an aquifer or portion of an aquifer to determine a representative *ct* for the area of interest.

To establish this relationship, the total dissolved solids concentrations calculated from all ions for balanced samples were compared to the specific conductance calculated with the U.S. Geological Survey software PHREEQC version 3. Calculating the specific conductance from ions is necessary as Collier (1993) notes that measurements by the Texas Department of Health analyses between 1960 and 1988 are “diluted conductance” measurements, which are not equivalent to specific conductance and cannot be used to determine relationships of total dissolved solids versus specific conductance. Due to the large number of samples analyzed by the Texas Department of Health, specific conductance was calculated for all samples used in these analyses.

Eight samples from four unique well locations were removed from these analyses as data outliers. These are generally wells with isolated geochemistry that differs from the surrounding wells. Additionally, wells with depths less than 30 feet were excluded due to the high possibility of anthropogenic contamination. One groundwater sample from the U.S. Geological Survey Produced Water Database was included in establishing the relationship between total dissolved solids and specific conductance. The sample selected from the U.S. Geological Survey Produced Water Database had pH available, which is required to calculate the specific conductance.

This data set was divided into three subsets based on similar trends (Figure 11-6). The first subset includes samples with less than 3,500 micromhos per centimeter specific conductance. The second subset ranged from 3,500 to 10,000 micromhos per centimeter specific conductance, and the third subset contains samples with greater than 10,000 micromhos per centimeter specific conductance. Best fit trendlines were generated for each data set.

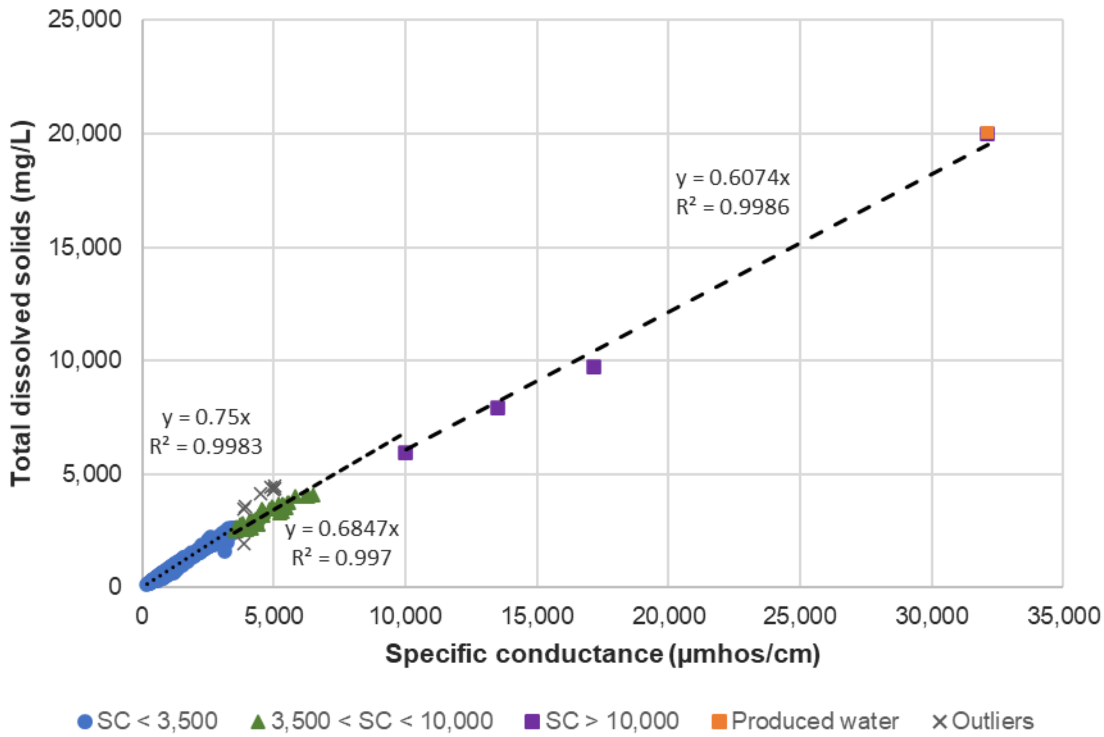


**Figure 11-6 The relationship between total dissolved solids and specific conductance (SC) for the BRACS Woodbine Aquifer study. Total dissolved solids is in milligrams per liter and specific conductance is in micromhos per centimeter.**

The *ct* value is derived from the linear regression, simplified by setting the intercept to zero for each dataset. A summary of this data is presented in Table 11-2 below. The three conductivity conversion factors allow us to characterize salinity through a broad range of values across the study area.

**Table 11-2 Total dissolved solids versus specific conductance regression summary.**

| Range of specific conductance (SC)[a] | Linear regression | *ct* |
|---|---|---|
| < 3,500 | y = 0.75x | 0.75 |
| 3,500-10,000 | y = 0.6847x | 0.68 |
| > 10,000 | y = 0.6074x | 0.61 |

[a] specific conductance is in in micromhos per centimeter

## 11.3 Other parameters of concern for desalination

Although the concentration of total dissolved solids is the primary concern for desalination, there are also physical parameters and chemical constituents of concern (Table 11-3). The presence of several minor chemical constituents is also of concern because they may violate drinking water standards or lead to fouling during the desalination process even when present in relatively small amounts. Select chemical parameters are discussed further herein. Consideration of chemicals of concern for desalination projects should be evaluated locally on a case-by-case basis.

**Table 11-3 Possible parameters of concern for desalination. The integers with a positive or negative sign indicate ion valence**

| Physical parameters | Cations | | Anions | Other |
|---|---|---|---|---|
| Conductivity | $Al^{+3}$ | $K^{+1}$ | $Cl^{-1}$ | Alkalinity |
| pH | $As^{+3}$ | $Mg^{+2}$ | $CO_3^{-2}$ | Boron |
| Silt density index | $As^{+5}$ | $Mn^{+2}$ | $F^{-1}$ | Dissolved oxygen |
| Temperature | $Ba^{+2}$ | $Na^{+1}$ | $HCO_3^{-1}$ | $H_2S$ |
| Turbidity | $Ca^{+2}$ | $NH_4^{+1}$ | $NO_2^{-1}$ | Hardness |
| | $Cu^{+2}$ | $Ni^{+2}$ | $NO_3^{-1}$ | Pesticides |
| | $Fe^{+2}$ | $Sr^{+2}$ | $OH^{-1}$ | Radionuclides |
| | $Fe^{+3}$ | $Zn^{+2}$ | $SO_4^{-2}$ | Silica |
| | | | | Total dissolved solids |
| | | | | PFAS substances |

### 11.3.1 Iron

Iron in groundwater can become oxidized and will precipitate when it reaches the ground surface. To avoid fouling reverse osmosis membranes, water with elevated levels of iron must be pre-treated. Of the available groundwater samples in this study, there are 954 with reported iron above the laboratory detection limit for that sample. Of those samples, 332 from 234 unique wells are equal to or exceed the TCEQ secondary maximum contaminant level of 0.3 milligrams per liter for iron (TCEQ, 2019). The maximum concentration of 99 milligrams per liter was detected in a sample from State Well Number 1964914 in December 1975. These exceedances are dispersed throughout the study area.

### 11.3.2 Manganese

Manganese, like iron, has the potential to foul reverse osmosis systems and may require treatment based on local conditions. Additionally, TCEQ (2019) has set a secondary maximum contaminant level of 0.05 milligrams per liter. There were 789 samples of manganese from 346 unique wells with reported values. Of these, 407 samples were below the laboratory detection limits, 304 of which had a detection limit equal to the maximum contaminant level of 0.05 milligrams per liter. There were 112 samples from 83 unique wells that exceeded the secondary maximum contaminant level. The top 12 wells with the highest concentration of manganese (ranging from greater than one to greater than 70 milligrams per liter) are shallow observation wells (generally less than 30 feet) and may not be representative of the deeper aquifer. The next highest concentration was 0.0514 milligrams per liter found in 1994 from State Well Number 1821901.

### 11.3.3 Nitrate

Nitrate is a human health concern for drinking water. For this study, we identified 1,524 samples that were likely analyzed for nitrate. Of these, 755 samples were below the laboratory detection limits, all of which are below the TCEQ maximum contaminant level of 10 milligrams per liter. There are 769 samples from 624 unique wells with nitrate detections. Of these, 29 samples from 24 unique wells are equal to or greater than the maximum contaminant level. The highest concentration of 294 milligrams per liter was identified in a sample from State Well Number 1964603 in 1970.

### 11.3.4 Fluoride

Fluoride is a human health concern for drinking water. For this study, we identified 1,629 analyses for fluoride from 663 unique wells. Of these, 16 samples were found to be below the laboratory detection limit. There are 167 samples from 65 unique wells that exceeded the TCEQ maximum contaminant level of 4.0 milligrams per liter (TCEQ, 2019). The highest concentration of 18 milligrams per liter was identified in a sample collected in 1961 from State Well Number 1847501. TCEQ (2019) has set a secondary maximum contaminant level for fluoride of 2.0 milligrams per liter.

### 11.3.5 Arsenic

Arsenic is a human health concern for drinking water. We found 316 water quality analyses for dissolved arsenic from 164 unique wells for the Woodbine Aquifer. Of those samples, 23 appear to have laboratory detection limits equal to the TCEQ maximum contaminant level for arsenic of 0.010 milligrams per liter (TCEQ, 2019). There are an additional 5 samples that either have reported values that exceed the maximum contaminant level or have laboratory detection limits that are higher than the maximum contaminant level. The highest concentration detected was 0.051 milligrams per liter from a sample collected in 1998 from State Well Number 1836805. However, a sample collected from this well in 2001 indicated arsenic was non-detect with a reporting limit less than or equal to the maximum contaminant level.

### 11.3.6 Radionuclides

The radionuclides uranium, radium-228 and radium-226 are human health concerns and regulated by the TCEQ. Radionuclides are unstable atoms which release gamma radiation or alpha and beta particles (also types of radiation) as the atoms undergo radioactive decay. The presence of radionuclides in groundwater is important when selecting screen zone(s) for a well, as elevated naturally occurring radiation should be avoided. Test wells should always be logged with a gamma ray tool to identify elevated radionuclides (specifically gamma radiation) in formation materials.

Three Woodbine Aquifer wells in the TWDB Groundwater Database were sampled for radium-228. The three results were below the maximum contaminant level of five picocuries per liter (TCEQ, 2019). Seventy-two wells were tested for dissolved uranium. One well (State Well Number 3224111), located in Tarrant County, exceeded the maximum contamination level of 30 micrograms per liter (TCEQ, 2019) with a result of 35 micrograms per liter. This is a shallow observation well located in the Woodbine outcrop and may not be representative.

# 12 Porosity

Formation porosity, a measurement of the ratio of pore space (void) volume to total volume, is a required parameter for calculating groundwater volume and total dissolved solids concentration when using the $R_{wa}$ minimum method described in Section 13.1. We calculated an estimated total porosity of the water-bearing portion of clean Woodbine sands using density, neutron, and sonic geophysical well log tools. Porosity information was appended to the BRACS Database table (tblGeophysicalLog_Porosity).

Porosity values estimated from geophysical logs are likely a high estimation for sands within the study area since clean, thick (greater than five feet) sands were preferentially selected for interpretation. For porosity estimations, we selected clay-free and hydrocarbon-free sand units with good caliper curves (no washouts). However, sometimes a thinner sand was chosen where such ideal sands were not present.

See Appendix H for additional details on the porosity calculations completed for this study.

## 12.1 Porosity data analysis

Interpreted porosity data are sparse, with some counties lacking available data (Hill, Dallas, Rockwall, Collin, Grayson, Fannin, Delta, Bowie, and Morris counties). In areas where porosity logs were present, we used neutron-density and sonic porosity equations from Asquith (1982) to estimate total porosity, depending on the type of log available.

Calculated porosity data for this study consists of 39 measurements from 34 wells. The neutron-density well logs, calibrated for limestone matrix, were converted to a sandstone matrix using Porosity Equivalence Curves chart for recorded NPHI and back calculating the recorded DPHI. Porosity values estimated using neutron-density well logs are more reliable than the individual density tool or sonic tool estimates. The sonic tool is less reliable in unconsolidated sediment and requires a compaction correction factor based on an adjacent shale unit. Furthermore, sonic-derived porosity readings most likely do not account for secondary porosity due to fractures and voids. Nevertheless, the estimated sonic porosity compared favorably with neutron-density porosity values in the nearby wells.

We used porosity values estimated from geophysical logs, along with porosity data obtained from the Bureau of Economic Geology Atlas of Major Texas Oil Reservoirs database (Holtz and others, 1991) and TWDB Report 157 (Core Laboratories, 1972), to approximate the total porosity for our study area. These porosity values from three different sources are depicted in a kernel density estimate (KDE) plot, which visualizes the probability density function of a continuous random variable (Figure 12-1). This kernel density estimate plot illustrates the density distribution of porosity data across the entire study area. Following an analysis of the estimated porosity depicted in the KDE plot, we have opted for a porosity value of 0.28 (28 percent) for further analysis. Generally, the distribution and density of available porosity data was poor, and wells from the reports did not often contain detailed sample locations. Spatially varying the porosity value used in calculations based on depth and location was determined to be unfeasible for this study.

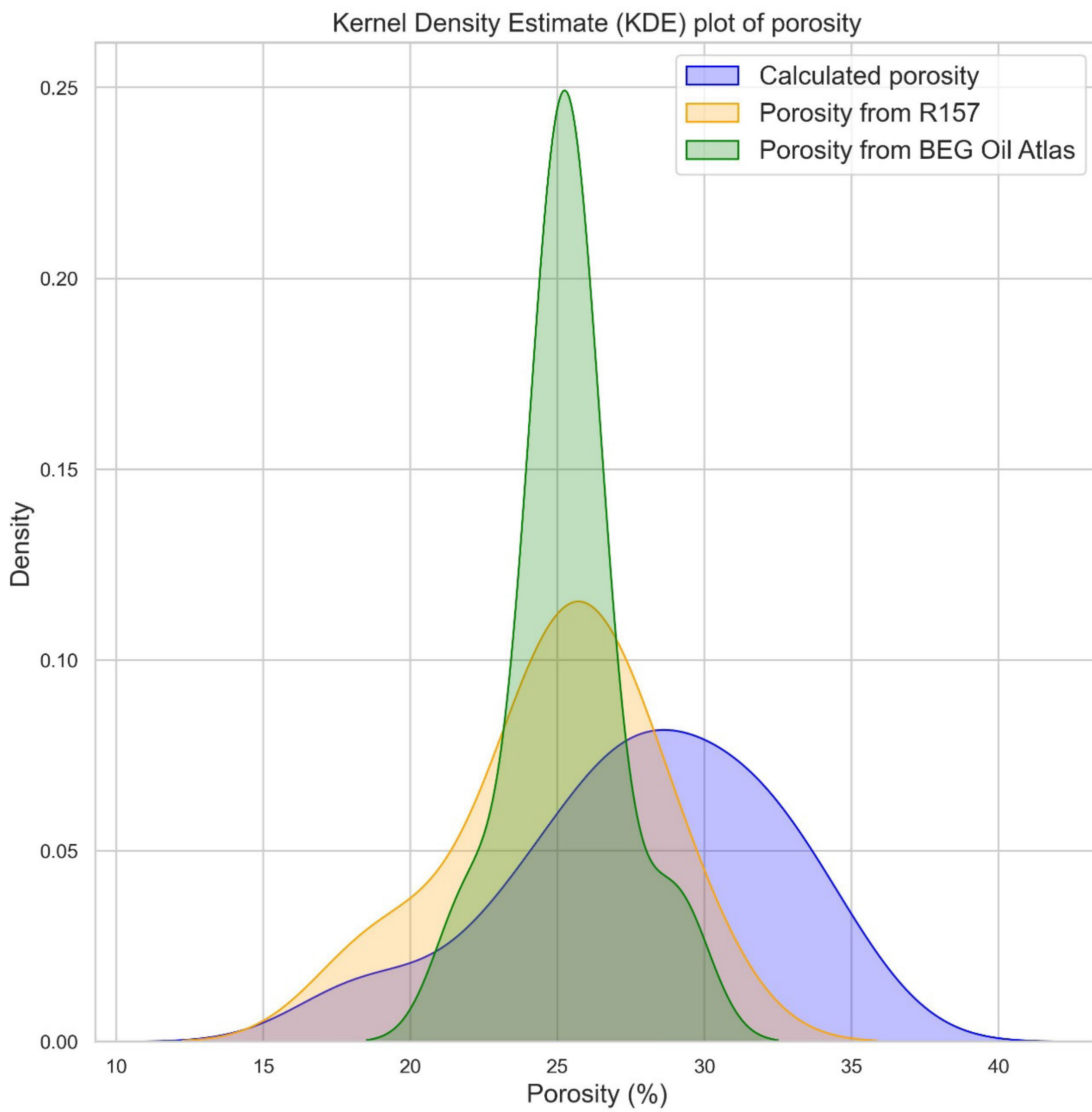


**Figure 12-1** **Kernel density estimate (KDE) plot of porosity from sources considered for this study. This includes porosity calculated from geophysical well logs, TWDB Report 157 (Core Laboratories, 1972), and the BEG Oil Atlas (Holtz and others, 1991).**

# 13 Salinity calculations from geophysical well logs

Following completion of the raster surfaces and net sand map, salinities were calculated as total dissolved solids concentration (in milligrams per liter) from applicable geophysical logs and then mapped collectively with the measured water quality data. There are several methods described by Estepp (1998, 2010) for interpreting total dissolved solids concentration in a formation using geophysical well logs. Calculating total dissolved solids concentration is complicated for many reasons such as the heterogeneity of geology, differing tools used for measurement, and other factors influencing how each calculation method was derived. Most existing geophysical logs for this study were developed for petroleum exploration and production where groundwater composition is predominantly sodium and chloride ions. Given the available data and assumptions for this study, we used the $R_{wa}$ (apparent water resistivity) minimum method for calculating salinity.

## 13.1 $R_{wa}$ minimum method

The $R_{wa}$ minimum method (Estepp, 1998) is based on Archie's equation (Archie, 1942). Archie's equation is:

$$R_o = R_w \cdot \frac{a}{\phi^m} \cdot \frac{1}{S_w{}^n} \quad \textbf{(Equation 13-1a)}$$

where:

$R_o$ = resistivity of the formation (ohm-meter)

$R_w$= resistivity of water (ohm-meter)

$a$ = Winsauer tortuosity factor (dimensionless)

$\phi$ = porosity (percent)

$m$ = cementation exponent (dimensionless)

$S_w$ = water saturation (percent)

$n$ = saturation exponent (dimensionless)

In a 100-percent water-saturated aquifer ($S_w$ = 1), as would be assumed in a fresh or brackish aquifer, $S_w$ can be eliminated from the equation. Based on recommendations from Estepp (1998) and Torres-Verdin (2017), the Winsauer tortuosity factor is assigned as 1. Therefore, the equation could be further simplified to:

$$R_w = R_o \cdot \phi^m \quad \textbf{(Equation 13-1b)}$$

The deep-investigation geophysical logging resistivity tool measures a combination of the formation rock matrix and groundwater resistivity. The measured resistivity of a formation is due to several parameters: resistivity of formation minerals, sediment grain size, and surface conductance on mineral grains (Alger, 1966). Explanations of the input parameters to calculate total dissolved solids concentration from resistivity logs are described in Section 13.3.

A total of 338 salinity calculations were performed with the $R_{wa}$ minimum method, of which 330 were used for salinity zone delineation. Some calculations were disregarded due to reasons such as questionable log quality or results that were out of trend. Equations were coded in Visual Basic for Applications® and completed as a class object within the BRACS Database for automated calculation. Using Microsoft Access allowed us to quickly evaluate parameters for calibration using groundwater chemistry samples as discussed previously. Furthermore, this process ensured consistency and retained all inputs for future use. The software runs the calculations in the following order

1) Calculate a corrected bottom hole temperature ($T_{BH\_cor}$) using the Southern Methodist University (SMU) -Harrison equation (Blackwell and others, 2010) with the log reported *Tbh*, total depth of the well ($D_t$) and a surface temperature from Larkin and Bomar's (1983) 30-year average surface temperature data.

   Depending on the total depth of the well:

   a. $D_t$ < 3,000

$$T_{BH\_cor} = T_{BH} \quad \textbf{(Equation 13-2)}$$

   b. 3,000 ≤ $D_t$ ≤ 12,900

$$T_{BHC\_cf} = -16.51213476 + 0.01826842109 \cdot D_{tm} - 0.000002344936959(D_{tm})^2 \quad \textbf{(Equation 13-3a)}$$

$$T_{BH\_cor} = 1.8\left(T_{BHC} + T_{BHC\_cf}\right) + 32 \quad \textbf{(Equation 13-3b)}$$

2) Determine the temperature at the selected depth of the formation being investigated ($T_f$).

$$G_g = \frac{T_{BH\_cor} - T_s}{D_t} \quad \textbf{(Equation 13-4)}$$

$$T_f = \left(G_g \cdot D_f\right) + T_s \quad \textbf{(Equation 13-5)}$$

where:

$D_t$ = total depth of the well, (feet)

$D_{tm}$ = total depth of the well, (meters)

$G_g$ = geothermal gradient, (unitless)

$T_{BH}$ = the temperature of the bottom hole, (degrees Fahrenheit)

$T_{BH\_cf}$ = the correction factor to the bottom hole temperature, (degrees Fahrenheit)

$T_{BH\_cor}$ = the corrected bottom hole temperature, (degrees Fahrenheit)

$T_{BHC}$ = the bottom hole temperature, (degrees Celsius)

$T_{BHC\_cf}$ = the correction factor to the bottom hole temperature, (degrees Celsius)

$T_f$ = the temperature of the formation, (degrees Fahrenheit)

$T_s$ = the surface temperature, (degrees Fahrenheit)

3) Determine the water-equivalent resistivity ($R_w$) with the $R_{wa}$ minimum method using a deep resistivity value ($R_o$). **Error! Reference source not found.** illustrate how formation resistivity ($R_o$) is read from a geophysical log.

$$R_w = R_o \cdot \Phi^m \quad \textbf{(Equation 13-6)}$$

4) Convert the corrected water-equivalent resistivity ($R_{wc}$) to the resistivity of the water at 77°F ($R_{w77}$) using Arp's equation (Torres-Verdin, 2017).

$$R_{w77} = R_{wc} \cdot \frac{T_f + 6.77}{77 + 6.77} \quad \textbf{(Equation 13-7)}$$

5) Convert the resistivity of water at 77°Farenheit ($R_{w77}$) to conductivity of water at 77°F ($C_w$).

$$C_w = \frac{10{,}000}{R_{w77}} \quad \textbf{(Equation 13-8)}$$

6) Calculate the interpreted milligrams per liter total dissolved solids concentration using a value for *ct* for the respective resulting total dissolved solids concentration (TDS) range.

$$TDS = ct \cdot C_w \quad \textbf{(Equation 13-9)}$$

There are disadvantages to using the $R_{wa}$ minimum method, including its dependance on empirical input parameters, the assumption that only water exists in the aquifer (no hydrocarbons), and it is a shale free sandstone. Where possible, sandstone bodies that may contain hydrocarbons were avoided for calculations. However, in cases where this was unclear, salinity calculations were evaluated on a case-by-case basis for inclusion in the salinity mapping. Figures 13-1 and 13-2 illustrate sand intervals chosen for analysis and how formation resistivity ($R_o$) is read from a geophysical log.

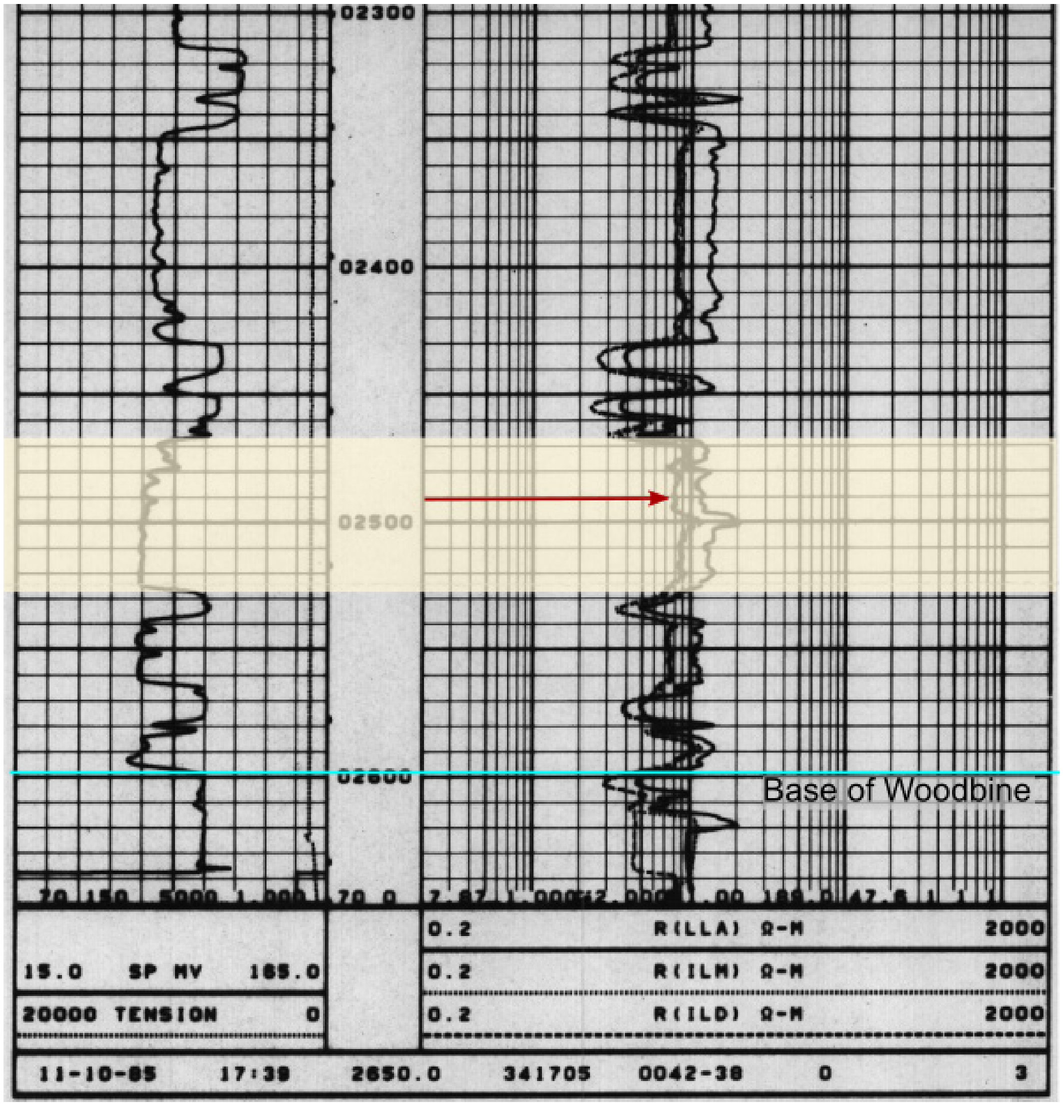


**Figure 13-1 Example of the depth selected on a geophysical log to assign a salinity calculation for BRACS ID 1897 in Kaufman County. The sand body selected is highlighted in yellow and the depth is denoted with a red arrow. The left-hand side of the log displays the spontaneous potential tool, and the right-hand side of the log displays the deep induction log (bold dashed line), medium induction (thin dashed line) and shallow laterolog (solid line).**

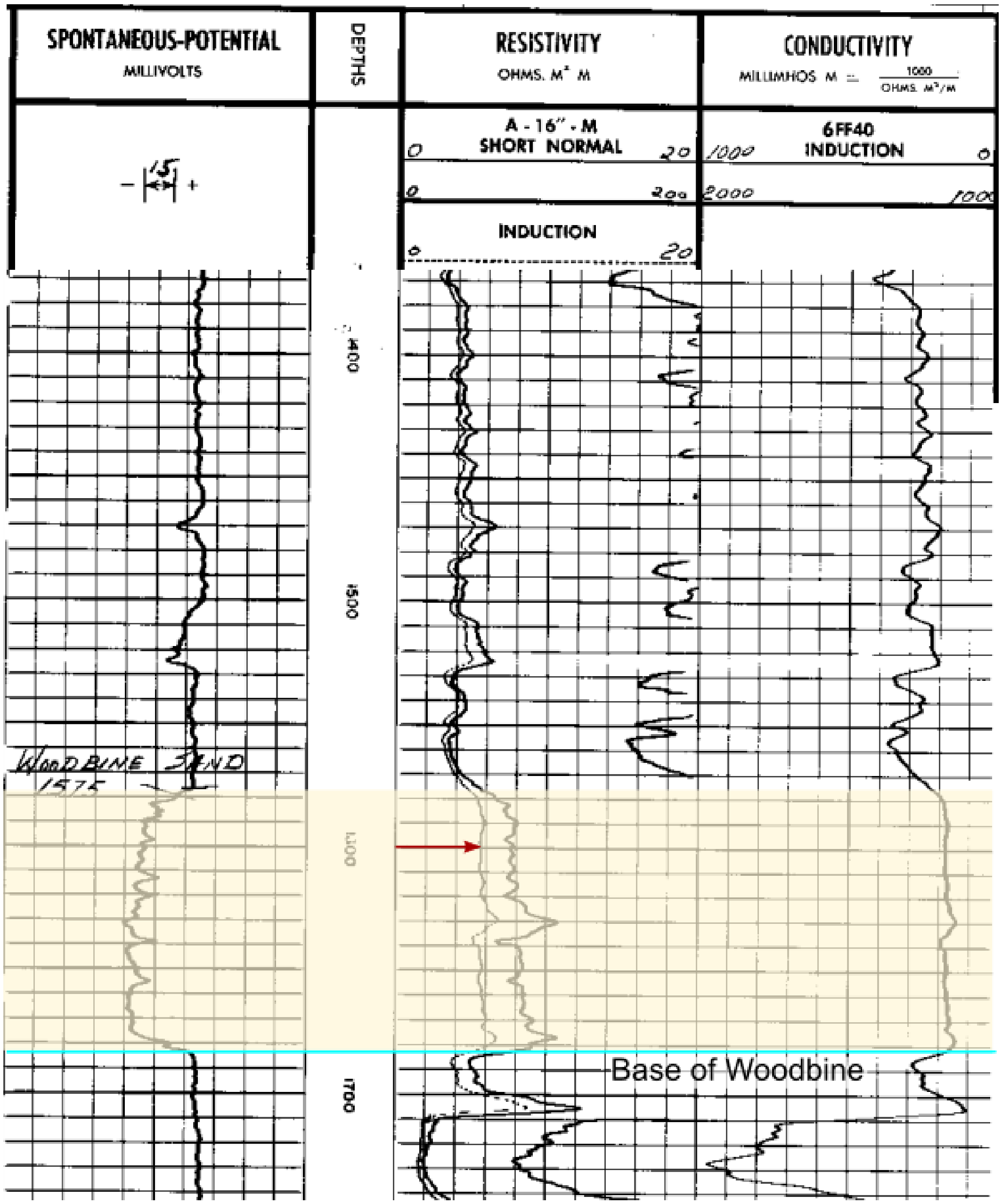


**Figure 13-2** **Example of the depth selected on a geophysical log to assign a salinity calculation for BRACS ID 34977 in Lamar County. The sand body selected is highlighted in yellow and the depth is denoted with a red arrow. The left-hand side of the log displays the spontaneous potential log, and the right-hand side displays the deep induction log (dashed line) and short normal (solid line).**

### 13.1.1 Input parameters

**Depth total (*$D_t$*)** – The total depth of the well is required to calculate the formation temperature at the depth of investigation. If a well was logged with multiple depth runs, the total depth of the logging run applicable to the depth of investigation must be used.

**Depth formation (*$D_f$*)** – Depth of the Woodbine Formation within the log being investigated is required to calculate the formation temperature. Specifically, this number denotes the depth of the middle of a thick, shale-free, water-saturated sand where the resistivity reading is obtained. This depth, the thickness of the evaluated sand unit, and geologic formation are recorded in the BRACS Database (tblGeophysicalLog_WQ).

**Temperature surface (*$T_s$*)** – The temperature at the well-site surface is required to calculate the formation temperature at the depth of investigation. Contour maps of temperature records from 1951 to 1980 compiled by Larkin and Bomar (1983) were used to determine the average annual temperature at any given well location. A temperature between 62- and 66-degrees Fahrenheit was assigned for each well location.

**Temperature bottom hole (*$T_{bh}$*)** – The bottom hole temperature of the logging run applicable to the depth of investigation is needed. If multiple logging runs were completed, care was taken to ensure the correct temperature was read for the correct depth of investigation.

Corrections to the bottom hole temperature can be performed using a variety of techniques. The correction technique chosen for this study was a modification of the Harrison correction by Southern Methodist University (SMU-Harrison correction) reported in Blackwell and others (2010) and is based on a depth correction. Their study evaluated geothermal gradients east of the Interstate 35 corridor in Texas. Temperature correction is not made for wells with a total depth of less than 3,000 feet. The equation used for depths between 3,000 and 12,900 feet in depth is found in Section 13.1.

The correction factor is added to the bottom hole temperature from the geophysical log header (converted to units of degrees Centigrade) and then the final temperature is converted to degrees Fahrenheit for use in log analysis. Wells drilled deeper than 12,900 feet have an additional correction factor of 0.05 degrees Fahrenheit per 500 feet of depth added to the maximum correction value of 34.3 degrees Fahrenheit at 12,900.

If the bottom hole temperature is missing from the log header, a bottom hole temperature can be calculated using the well's surface temperature and well depth (or depth of logging run) with a geothermal gradient calculated from the log of a nearby well. Calculated bottom hole temperatures are noted in the BRACS Database table (tblGeophysicalLog_Header_LogRuns) with supporting information.

**Formation Deep Resistivity (*$R_o$*)** – The resistivity of the formation is determined with a deep-investigation resistivity logging tool and is a combination of formation rock matrix resistivity and groundwater resistivity. The deep-investigation tool is used because a shallow tool reading is usually affected by mud cake on the wellbore and invaded drilling fluid in the formation. To avoid "shouldering" effects attributed to lowered vertical resolution of well logs due to speed of logging or sampling interval, the formation resistivity was determined by reading resistivity at the peak in a ten foot or greater layer of shale-free sand that is not affected by hydrocarbons (Torres-Verdin, 2017).

**Formation porosity ($\phi$)** – The three types of porosity include primary porosity, secondary porosity, and micropores. For this study, total porosity is measured indirectly from porosity logs and used as the estimated total porosity (Torres-Verdin, 2017). Porosity logs include density, neutron, and acoustic (sonic) logs. Neutron and density logs were preferred due to their reliability for total porosity estimates, in comparison to acoustic (sonic) logs, which are more accurate in unconsolidated, low porosity mediums, and do not account for secondary porosity due to vugs or fractures (Doveton, 1999). A porosity of 0.28 was used for this study. Porosity is described in more detail in Section 12.

**Conductivity conversion factor (*ct*)** – Information on the designation of the ct factor is described in detail in Section 11.2.2. The *ct* values derived to characterize the salinity in the Woodbine Aquifer within the study area are as follows:

- where specific conductance is less than 3,500 milligrams per liter, *ct* = 0.75,
- where specific conductance is between 3,500 and 10,000 milligrams per liter, *ct* = 0.68, and
- where specific conductance exceeds 10,000 milligrams per liter, *ct* = 0.61.

**Cementation exponent (*m*)** – The cementation exponent is a dimensionless parameter determined empirically from detailed core analysis or theoretically based on other known related parameters. It accounts for the effective porosity or connectedness of pore and fracture network. Based on the results of the well pair analysis discussed in Section 13-2, we used a cementation exponent of 1.5 for this study, which is within the range of suggestions for well-cemented sandstones (Kwader, 1986).

## 13.2 Log-groundwater sample pairs

To test plausible input parameters for salinity calculations, we used wells with groundwater sampling data that are proximal to wells with geophysical logs for comparison. The total dissolved solids concentration calculated from the geophysical log is “calibrated” to the sample result by adjusting the parameters used in the calculation. The parameters that are derived from the well pair calibration were then used as study-wide input values.

Potential log-sample pairs were identified using a spatial join of the sample locations and geophysical log locations. The maximum distance between a pair of wells was set at 1.5 miles. Fourteen well pairs were identified for this analysis (see Appendix I).

Primarily, well pairs were used to test candidate values for the cementation exponent (*m*) since we did not have laboratory data available to establish this value. The porosity value of 0.28 as discussed in Section 12.1 and the conductivity conversion factors (*ct*) discussed in Section 11.2.2 were tested with a range of cementation exponents (1.5, 1.6, and 1.75). Through the well pair testing, it was determined that a cementation exponent of 1.5 yielded the least average difference between the water samples and calculated salinity for the test well pairs given the other designated parameters.

# 14 Salinity zone delineation

To delineate the salinity zones based on the five salinity classes previously outlined herein, we combined the total dissolved solids concentration from 628 balanced measured water quality samples with the estimated total dissolved solids from 329 geophysical well log salinity calculations. The measured water quality samples utilized for this part of the study represent the most recent sampling event available at the time for each location. However, many of these samples are several decades old and water quality may have changed over time.

During the salinity calculation process, we took care to select log signatures in zones that appeared to be unaffected by hydrocarbons. However, the possible presence of hydrocarbons could not always be ruled out in cases of older well logs or those with limited log curve suites. Wells where the calculated salinity did not align with the overall trend and the presence of hydrocarbons could not be ruled out were excluded from the salinity zone delineation. Additionally, well locations with local aquifer characteristics that differ greatly from the established calculation input parameters may yield calculations that are not representative.

Certain measured water quality samples were excluded from the salinity zone delineation process. Several samples in Tarrant County were from wells completed at depths less than 30 feet in developed areas. Due to the potential for additional anthropogenic contamination sources, these samples were not included in the overall salinity class analysis. Additionally, we excluded several anomalous samples from older wells (usually aged greater than 100 years) that are generally completed at depths shallower than the surrounding modern wells.

The combined total dissolved solids point data was first interpolated using the Esri ArcGIS Pro Topo to Raster tool. This interpolated surface was used as a guide for the process of hand contouring the 1,000; 3,000; 10,000; and 35,000 milligrams per liter total dissolved solids lines (Figure 14-1). Once these contour lines were finalized, they were used to delineate the salinity class polygons. This study assumes that salinity is constant vertically within the aquifer. However, particularly in thicker sections of the Woodbine, there may be water quality variations within the section.

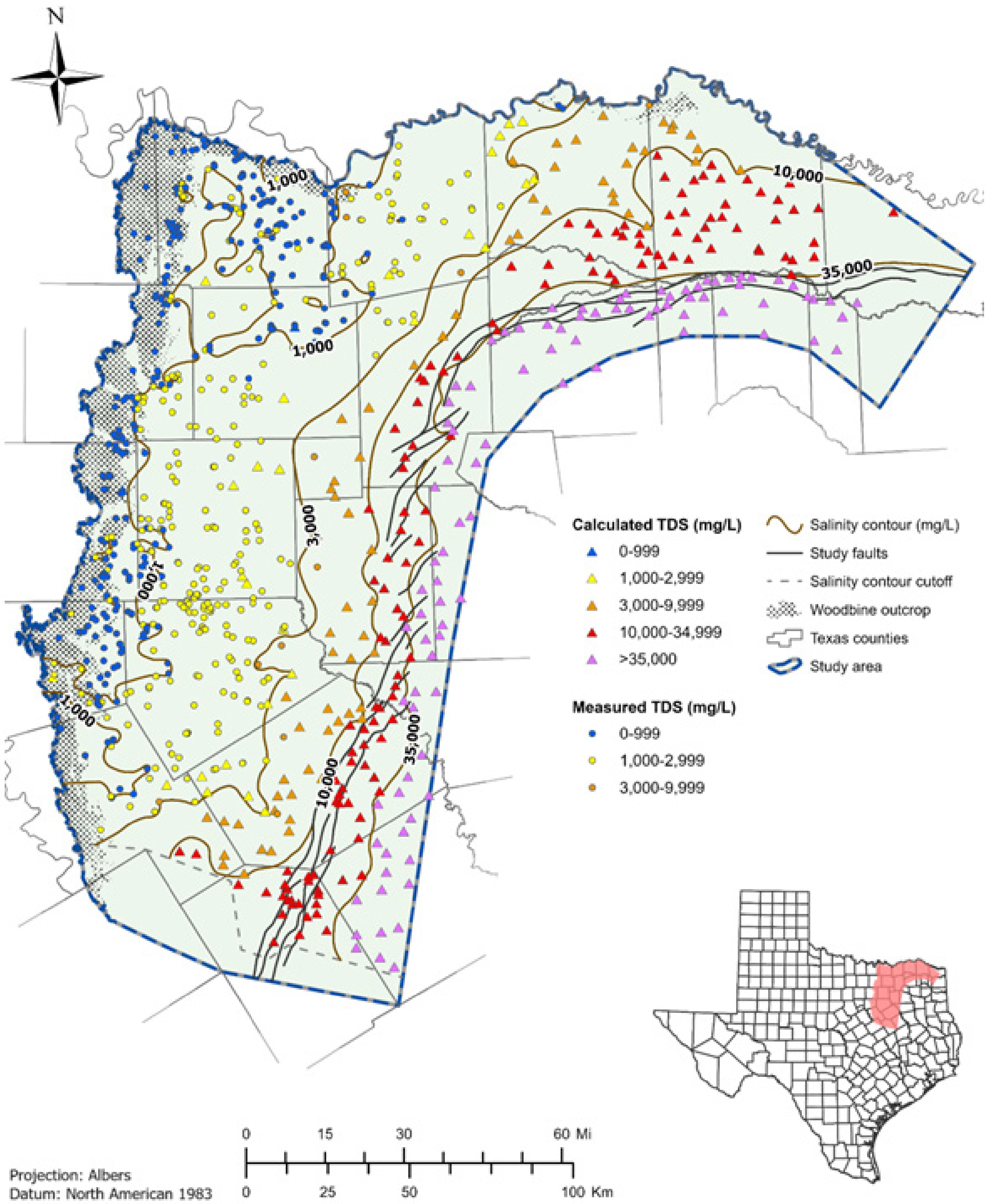


**Figure 14-1 Measured water quality and calculated water quality points used for salinity class delineation.**

## 14.1 Salinity map discussion

In general, salinity increases downdip to the east away from the outcrop, and to the south in the northeastern portion of the study area (Figure 14-2). Fresh water is found within and proximal to the outcrop where recharge from precipitation and infiltration from lakes and streams occurs. However, fresh water extends significantly downdip in the northwestern portion of the study area, predominantly in Grayson and Collin counties where it is intermingled with slightly saline groundwater. Pockets of fresh groundwater also occur in the northern portion of Fannin and Lamar counties.

Slightly saline groundwater (1,000-2,999 mg/L TDS) is mapped across portions of 14 counties within the study area and covers the greatest lateral extent of the five salinity classes. It is generally present downdip from the outcrop except for localized areas where the salinity in the outcrop may be elevated due to high sulfates from the presence of lignite beds, predominantly in Tarrant and Johnson counties (Baker and others, 1990). According to the TWDB Groundwater Database and illustrated in Figure 14-1, it is apparent that the slightly saline zone of the Woodbine Aquifer has seen significant prior development. This has been primarily for public supply (168 wells) and domestic water use (139 wells). However, of the 643 wells identified in the slightly saline zone, almost one-third of them (202 wells) are indicated as unused or plugged/destroyed. It is possible that some of the wells indicated otherwise may be additionally unused or plugged but the well status information has not been provided to the TWDB or the Texas Department of Licensing and Regulation.

The transition from slightly saline groundwater to moderately saline groundwater (3,000-9,999 mg/L TDS) occurs between depths of 1,000 and 2,000 feet below ground surface across most of the study area with exceptions in both the north and the south. Moderately saline groundwater can be found across parts of 15 study area counties and generally occupies a relatively narrow band within the Mexia-Talco Fault Zone. However, in the northeastern portion of the study area, moderately saline groundwater occupies shallower depths where it trends north of the faulting.

There is a relatively quick transition from brackish groundwater to very saline groundwater approaching the Mexia-Talco Fault Zone. Groundwater that is classified as very saline and brine with total dissolved solids concentrations greater than 10,000 milligrams per liter is present across the eastern and southern portions of the study area. The distribution of this highly saline groundwater closely mirrors the structural strike. This fault zone may act as a groundwater flow barrier preventing the migration of fresher water from the outcrop recharge zone into the deeper portions of the aquifer. There is a relatively abrupt transition from moderately saline groundwater through very saline groundwater to brine across this zone.

The salinity distribution in the Woodbine Aquifer appears to be controlled mainly by recharge and geologic structures. However, the presence of elevated levels of sulfates associated with lignite deposits exhibits some local control.

Due to the limited sand content, part of the southern portion of the study area has been excluded from the aquifer salinity class delineation and volume analysis. This exclusion area includes parts of McLennan, Hill, Limestone, and Freestone counties where the

Woodbine has transitioned to the shale-dominated pro-delta shelf facies. It is denoted as "salinity class cutoff" in the salinity figures.

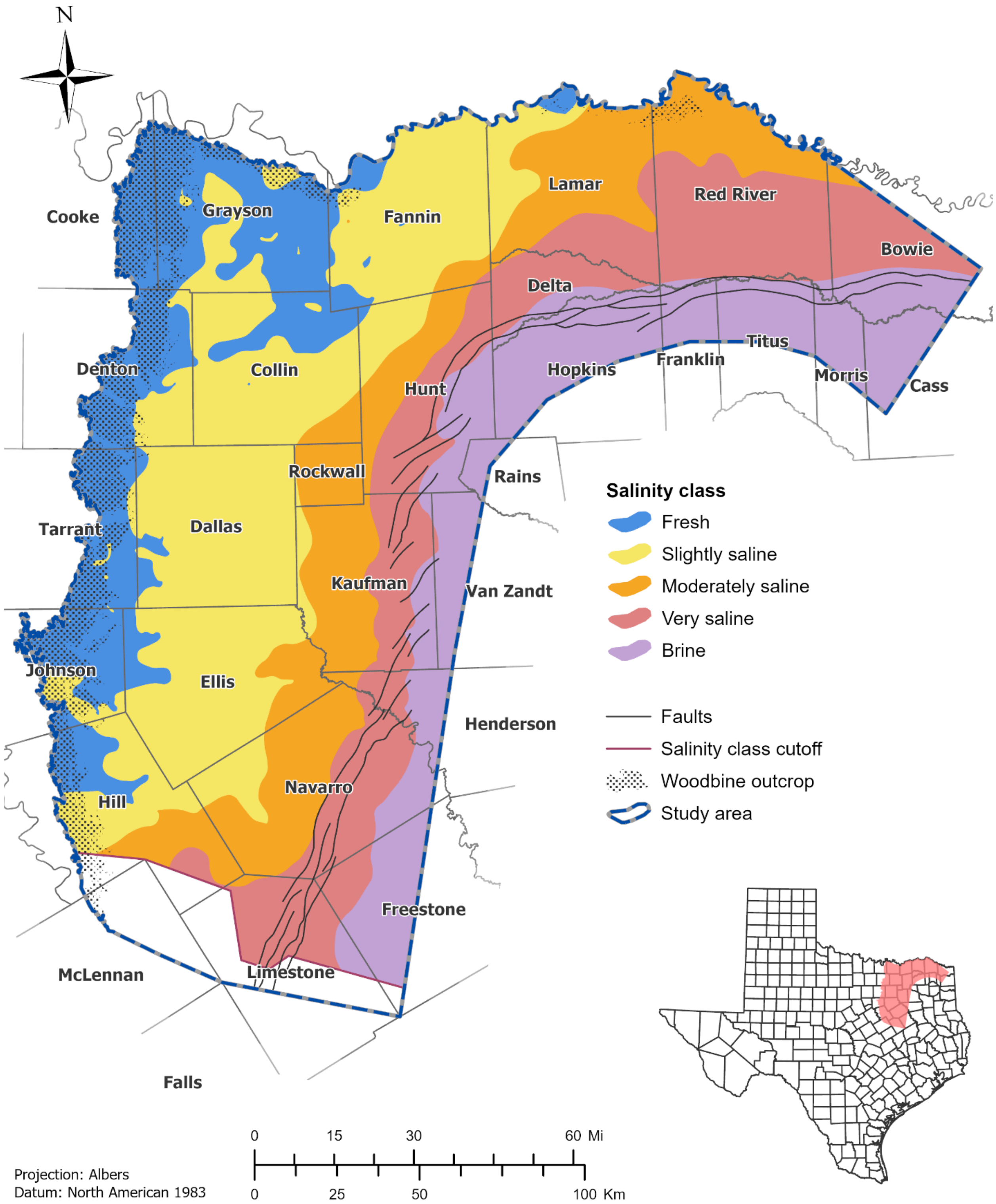


**Figure 14-2 Interpreted salinity classes within the Woodbine Aquifer study area.**

# 15 Estimated brackish groundwater volumes

Total aquifer storage volumes were calculated for the slightly saline, moderately saline, and very saline salinity classes developed for this study and outlined in Section 14. We did not calculate volumes for fresh groundwater or brine. Our primary purpose for calculating these volumes is to provide some form of quantitative volumetric measurement of the brackish groundwater resources of the Woodbine Aquifer study area. The work presented here is foundational to the TWDB in assessing potential brackish groundwater production zones, required by Texas Water Code § 16.060 and to entities seeking to develop brackish groundwater resources.

Figure 15-1 shows a simplified schematic of groundwater conditions in an unconfined aquifer (left) and a confined aquifer (right). Groundwater storage volume in an unconfined aquifer is the volume of storage attributed to drainage ($V_{drained}$) (Equation 15-1a) from declining water level conditions ($V_{drained}$). Groundwater volume calculations in a confined aquifer typically include both 1) the portion of the aquifer storage volume derived from drainage under a declining potentiometric surface condition ($V_{drained}$) and 2) the portion of aquifer storage that is from compressibility of aquifer materials and water ($V_{confined}$) (Equation 15-1b).

We calculated the volume of in-place brackish and saline groundwater in the Woodbine Aquifer based on salinity class, percent sand, and specific yield. For this study, we used a specific yield of 0.15 (15 percent). We did not calculate the portion of confined storage volume ($V_{confined}$) above the top elevation of the Woodbine Formation because we did not have sufficient static water level data in the downdip portion of the aquifer, particularly in the moderately saline zone. It is generally considered a negligible contribution to the overall volume of groundwater in the confined portion of the aquifer.

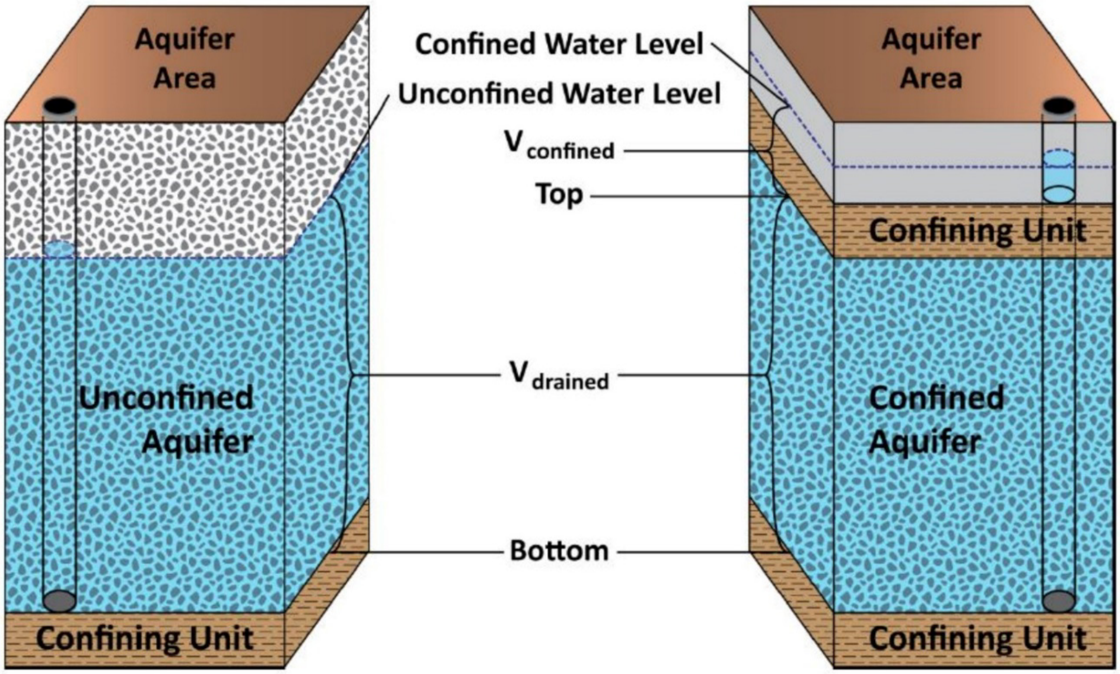


**Figure 15-1** **Schematic image showing the difference between unconfined and confined aquifer storage (Jigmond and Wade, 2013)**

Total aquifer storage volumes for the confined ($V_{drained}$) and unconfined portions of the Woodbine Aquifer were estimated using the following equations within each salinity zone:

For unconfined (outcrop):

$$\text{Volume} = V_{drained} = \text{Area} \times (\text{Water level} - \text{Bottom}) \times \text{Percent sand} \times S_y \quad \textbf{(Eq. 15-1a)}$$

For confined (subcrop):

$$\text{Volume} = V_{drained} = \text{Area} \times (\text{Top} - \text{Bottom}) \times \text{Percent sand} \times S_y \quad \textbf{(Eq. 15-1b)}$$

where:

$V_{drained}$ = storage of volume of water draining from the formation (acre-feet)

Area= aquifer area (acres)

Percent sand = net sand divided by thickness of the unit multiplied by 100

Water level = groundwater elevation (feet above mean sea level)

Top = elevation of aquifer top (feet above mean sea level)

Bottom = elevation of aquifer bottom (feet above mean sea level)

$S_y$ = specific yield (unitless)

The study area was subdivided into cells, and volumes were calculated for individual cells and summed to find the storage volume per salinity zone. Percent sand was calculated for each data location in the study area by dividing the net sand thickness (Figure 8-14) by the total formation thickness (Figure 8-13).

## 15.1 Area calculations

To align with the study rasters (formation elevation and digital elevation model), GIS files built to calculate groundwater volumes were compiled on a 250-foot by 250-foot grid cell basis.

The area of each 250-foot grid cell is 1.434803 acres. This value for the [Area] field in the attribute table was calculated using the Esri ArcGIS Pro® Calculate Geometry tool. To validate the tool result, the simple area equation and conversion factor below were used:

Area per grid cell = $250 \text{ feet } \times 250 \text{ feet } \times \frac{1\, acre}{43{,}560 \text{ feet}^2}$ = 1.434803 acres **(Equation 15-2)**

## 15.2 Saturated thickness

Saturated thickness was calculated in one of two ways depending on whether a cell was in the Woodbine Aquifer outcrop or subcrop. Cells were assigned either an “O” for outcrop or “S” for subcrop. For this study, the TWDB Woodbine Aquifer outcrop outline was used to designate cells that would be assigned as unconfined.

Where the aquifer is under confined conditions, generally downdip from the outcrop, it was assumed to be fully saturated with groundwater. Therefore, the net sand value was used to represent saturated thickness.

Where the aquifer is unconfined, the saturated thickness of each grid cell was based on the static water elevation minus the formation bottom elevation, which was then multiplied by the percent sand to approximate the saturated net sand thickness. Percent sand was calculated by dividing net sand by formation thickness and multiplying this value by 100. As described in Section 8.3, geophysical logs within the outcrop area with less than the full Woodbine stratigraphic interval present were not utilized for net sand mapping. Thus, the net sand in the outcrop area is an interpolation of data from wells down-dip of the outcrop and the zero net sand outcrop points along the up-dip edge. Net sand within the outcrop may be less representative of net sand mapped in the subcrop with more well control.

In areas of the outcrop where the static water level elevation approached the thickness of the aquifer, this calculation technique would sometimes result in saturated thickness values that exceeded the net sand. In these cases, the saturated thickness was set equal to the net sand thickness so as not to exceed it. Net sand analysis is discussed in section 8.3.

## 15.3 Static water level

An interpolated static water level elevation raster (wb_swle_otc) was used to determine the saturated thickness within the TWDB Woodbine Aquifer outcrop extent. Through database queries, we utilized the aquifer determination method to identify wells completed in the Woodbine Aquifer. The TWDB Groundwater Database and SDR Database were the primary sources of static water level data. Additionally, several wells originating from the SDR Database were previously appended to the BRACS Database and pulled from BRACS for this portion of the study. Static water level data from these wells were compiled in a study-specific water level table for interpolation in GIS (wb_swl_2010_pt.shp). To approximate modern static water level conditions, we only included the most recent record for each well with a measurement year greater than or equal to 2010. This process resulted in a total of 531 wells, with 446 from the SDR Database, 81 from the Groundwater Database, and four from the BRACS Database.

Using the Topo to Raster tool in ArcGIS Pro 3.2.0, we interpolated a depth-to-water raster from 1) points along the base of the Woodbine contact with an assigned depth of zero feet water level (wb_swl_otc_zero_pt.shp), and 2) the depth to water points described previously. We converted the static water level depth raster to static water level elevation using the study digital elevation model, then the resulting raster was clipped to the TWDB outcrop extent within the study area to represent the static water level in the unconfined portion of the aquifer. The TWDB outcrop extent encompasses areas of the formation outcrop that are overlain by Quaternary terrace and alluvium deposits but remain unconfined.

For quality control purposes, where the interpolated water level elevations projected above the formation surface in the unconfined portions, the static water level was set to the formation top elevation.

Where the static water level elevation interpolation projected below the formation base, the water level elevation was set to the formation bottom elevation plus one half of the formation thickness. This technique was utilized to avoid designating any grid points as being unsaturated. Adjacent to where the static water level was interpolated below the formation bottom elevation existed a small number of cells with a static water level less than or equal to one foot above the bottom elevation. In these cases, it resulted in a calculated groundwater volume of zero even in the presence of net sand. Because of this, the correction described above was also applied in these areas to alleviate “dry” grid cells.

## 15.4 Specific yield

Specific yield relates to porosity by the general equation:

$$n = S_y + S_r$$ **(Equation 15-3)**

where:

$n$ = porosity

$S_y$ = specific yield

$S_r$ = specific retention

Specific retention represents the ratio of the volume of retained water retained against gravity drainage to the total rock volume. Thus, specific yield is sometimes equated to the effective porosity.

Due to variations in lithology, no single specific yield value will accurately represent the aquifer storage properties throughout the study area. Additionally, we did not identify any recorded specific yields for the Woodbine Aquifer in the TWDB Groundwater Database. Because of this, it was necessary to estimate a relatively conservative specific yield representing similar sandstone lithology and based upon review of literature and previous studies (INTERA, 2014; Morris and Johnson, 1967; Morton, 1992; Nordstrom, 1982; R.W. Harden & Associates, 2004; Walton, 1991). For this study, we selected a specific yield of 15 percent (0.15). In Section 13, we described the process for selecting a porosity value to use for water quality calculations from geophysical well logs. For this study, we utilized a porosity value of 28 percent (0.28). This study's porosity value relied heavily on porosity values calculated from geophysical logs and thus reflects an estimation of total porosity rather than the effective porosity (specific yield).

## 15.5 Volume calculation results

**Important note**

The in-place aquifer storage volumes calculated in this study are estimates to provide insight into the magnitude and distribution of this important resource. We recommend that site-specific studies be conducted to support projects and efforts that will incorporate brackish groundwater resources into water resources planning.

The TWDB uses the information produced from this study to identify potential brackish groundwater production zones, which are areas that can produce brackish groundwater over 30- and 50-year periods without causing significant impacts to water availability or quality for existing users.

In designating brackish groundwater production zones, the TWDB is guided by exclusionary criteria in Texas Water Code § 16.060 that is designed to prevent significant adverse impacts to existing water wells and water quality. These criteria limit production to areas where long-term pumping is unlikely to interfere with fresh groundwater availability or degrade water quality. As a result, the volumes that can be produced from designated brackish groundwater production zones are reduced by orders of magnitude compared to the total in-place storage volumes, underscoring the importance of careful planning and site-specific evaluation for projects within designated zones or in brackish portions of aquifer outside of designated zones.

It is also important to note that in-place storage volume estimates are not the same as the TWDB-calculated total estimated recoverable storage volumes, which are confined to the aquifer boundaries used by TWDB groundwater availability models and provided to Groundwater Conservation Districts for planning purposes. Furthermore, the area, saturated thickness, and storage parameters used in the calculations for this study are different from those used in total estimated recoverable storage reports (Shi and others, 2014; Wade and others, 2014; Wade and Shi, 2014). Finally, the in-place storage volume estimates are not an estimate of recoverable volume.

Not all brackish groundwater can be produced or economically developed. These volumes do not consider the effects of land surface subsidence, degradation of water quality, or any changes to surface water-groundwater interaction that may result from extracting groundwater from the aquifer. These volumes should not be used for joint planning or evaluation of achieving adopted desired future conditions in the same way total estimated recoverable storage and modeled available groundwater are used according to the joint planning process described in Texas Water Code § 36.108.

The volume calculation method used for this BRACS study varies from that used for the total estimated recoverable storage volumes in three ways: 1) the $V_{drained}$ calculation incorporates the percent sand value to estimate saturated net sand thickness, 2) there is greater data density and stratigraphic control in the downdip portion of the aquifer than what was utilized to calculate the total estimated recoverable storage volumes, and 3) the storage volume attributed to specific storage (reduction in pore space and expansion of water) in the confined portion of the aquifer is not included. Additionally, total estimated recoverable storage does not take water quality into account and therefore cannot be directly compared to BRACS volumes, which are divided by salinity class categories. Further details on the differences between BRACS in-place storage and total estimated recoverable storage volumes can be found on the BRACS webpage (TWDB, 2024b).

Tables 15-1 through 15-4 tabulate volumes by salinity class, by groundwater management area, by regional water planning area, and by groundwater conservation district. Volumes tabulated by county are in Appendix J.

**Table 15-1 Total estimated brackish storage volume in the Woodbine Aquifer per salinity class (in millions of acre-feet).**

| Salinity zone | Slightly saline | Moderately saline | Total brackish volume | Very saline | Total volume including very saline |
|---|---|---|---|---|---|
| **Total** | 72.7 | 47.7 | **120.4** | 49.5 | **169.9** |

**Table 15-2 Total estimated brackish storage volume of the Woodbine Aquifer in each groundwater management area (GMA) by salinity class (in acre-feet).**

| GMA | Slightly saline | Moderately saline | Total brackish volume | Very saline | Total volume including very saline |
|---|---|---|---|---|---|
| **8** | 72,692,600 | 47,260,900 | 119,953,500 | 45,485,300 | 165,438,800 |
| **11** | 0 | 426,000 | 426,000 | 2,464,200 | 2,890,100 |
| **12** | 0 | 0 | 0 | 1,591,300 | 1,591,300 |
| **Total** | 72,692,600 | 47,686,900 | **120,379,500** | 49,540,800 | **169,920,300** |

**Table 15-3 Total estimated brackish storage volume of the Woodbine Aquifer in each regional water planning area (RWPA) by salinity class (in acre-feet).**

| RWPA | Slightly saline | Moderately saline | Total brackish volume | Very saline | Total volume including very saline |
|---|---|---|---|---|---|
| C | 63,876,600 | 30,677,700 | 94,554,200 | 20,744,400 | 115,298,600 |
| D | 6,794,500 | 15,782,000 | 22,576,500 | 26,933,700 | 49,510,200 |
| G | 2,021,600 | 1,227,200 | 3,248,800 | 1,862,800 | 5,111,500 |
| Total | 72,692,600 | 47,686,900 | **120,379,500** | 49,540,800 | **169,920,300** |

**Table 15-4 Total estimated brackish storage volume of the Woodbine Aquifer in each groundwater conservation district (GCD) per salinity class (in acre-feet).**

| GCD | Slightly saline | Moderately saline | Total brackish volume | Very saline | Total volume including very saline |
|---|---|---|---|---|---|
| Mid-East Texas GCD | 0 | 0 | 0 | 1,374,900 | 1,374,900 |
| Neches & Trinity Valleys GCD | 0 | 426,000 | 426,000 | 2,109,700 | 2,535,600 |
| North Texas GCD | 15,897,700 | 2,153,500 | 18,051,300 | 0 | 18,051,300 |
| Northern Trinity GCD | 142,700 | 0 | 142,700 | 0 | 142,700 |
| Prairielands GCD | 14,288,600 | 4,287,100 | 18,575,700 | 175,200 | 18,750,900 |
| Red River GCD | 16,847,700 | 1,194,100 | 18,041,800 | 101,900 | 18,143,700 |
| None | 25,515,900 | 39,626,200 | 65,142,000 | 45,779,200 | 110,921,200 |
| Total | 72,692,600 | 47,686,900 | **120,379,500** | 49,540,800 | **169,920,300** |

# 16 Desalination

Future development of brackish groundwater may require desalination depending on use. Texas now has 43 municipal facilities that desalinate brackish groundwater, with a combined design capacity of 98 million gallons per day (109,774 acre-feet per year) (TWDB, 2024h).

We identified one brackish groundwater desalination plant that may have historically sourced water from the Woodbine Aquifer. The City of Bardwell in Ellis County reported in a 2016 desalination survey conducted by the TWDB that the city produced an average of 50,000 gallons per day from this plant. The most recent groundwater sampling report (2023) available in the TWDB Groundwater Database from the presumed supply well (State Well Number 3343802) indicates that the source water had a concentration of 1,846 milligrams per liter total dissolved solids. However, it has been informally reported to the TWDB that this plant is no longer in use, and that the City of Bardwell now purchases water from other entities that do not operate the plant.

There are no proposed brackish groundwater desalination water management strategies for the Woodbine Aquifer study area in the 2022 State Water Plan (TWDB, 2024a).

## 16.1 Treatment methods

Most brackish desalination plants in the U.S. use reverse osmosis, nano filtration, or electrodialysis reversal. There are only two facilities in the United States that use thermal evaporation and distillation following reverse osmosis (Mickley, 2018). The majority of brackish groundwater plants in Texas use reverse osmosis technology, except for three plants that use electrodialysis reversal (TWDB, 2024d). Both reverse osmosis and nanofiltration use membranes, which require maintenance and replacement. The primary difference between the processes is that reverse osmosis generally uses a high-pressure flow, whereas nanofiltration generally uses a low-pressure flow (Mickley, 2018). Mickley & Associates, LLC were recently awarded funding from the Bureau of Reclamation to conduct an updated survey with information on municipal desalination plants constructed in the U.S. from 2017 through 2024 (U.S. Bureau of Reclamation, 2024).

## 16.2 Concentrate disposal

An important consideration of desalination is the disposal of concentrate, which can be costly and impede a project from moving forward. The five conventional concentrate disposal methods for American desalination plants are 1) discharge to surface water bodies, 2) discharge to sewer or wastewater treatment plants, 3) evaporation ponds, 4) land application, and 5) injection wells (Mickley, 2018). A desalination plant’s site-specific characteristics determine the type of concentrate disposal method(s) that will be used. For desalination facilities in Texas, discharge to surface water bodies is the most common concentrate disposal method, followed by discharge to sanitary sewers and evaporation ponds (Rose, 2023).

# 17 Future improvements

The TWDB collects and disseminates groundwater data and information to help fulfill its mission to lead the state's efforts in ensuring a secure water future for Texas. We have continued interest in obtaining additional study area data and information for inclusion into the BRACS Database. Additional data that can be collected include water quality samples, aquifer tests, and geophysical well logs with complete headers. This additional data will also aid in TWDB's efforts to accurately estimate future potential production volumes in brackish groundwater production zones that will not cause significant adverse impacts to existing water users. We recommend the following to improve the results of this study:

- Acquire more porosity logs, including neutron porosity logs, density porosity logs, sonic logs, and nuclear magnetic resonance logs. These are important to provide insight into porosity and interconnected porosity and were scant in the brackish portions of the Woodbine Aquifer. The lack of these logs is one of the most significant data gaps that exist with old well logs that were used for this study. Additional porosity data may also be beneficial to assess porosity variability in greater detail both laterally and vertically.
- Acquire relevant core data. Woodbine cores were analyzed under TWDB contract number 2348302708. However, upon review of the available core analyses and associated data, it was determined that core samples could not be sourced from the representative sand units within the Woodbine interval due to missing core sections. Thus, it was determined that this data would not be used for establishing input parameters for this study. Key rock property input parameters that may benefit from additional core data include porosity and the cementation exponent.
- Expand the two-tiered (sand and shale) lithology characterization to four-tiered (sand, shaly sand, sandy shale, and shale) to capture local variations in sand and shale content. Although the two-tier approach simplifies characterization of the lithology because this method assumes 100 percent sand within each picked interval, there is some degree of overestimation, since intervals of mixed lithological grain sizes were not identified.
- Acquire more lab-analyzed water quality samples, particularly between 3,000 and 35,000 milligrams per liter total dissolved solids concentration, to build a more robust relationship between total dissolved solids and specific conductance.
- Perform additional review and incorporation of U.S. Geological Survey produced water samples. Forty-five produced water samples were identified within the study area, mainly in Titus County. However, many of these samples were poorly located and not used for salinity analysis.
- Acquire more static water level measurements in the brackish portion of the aquifer, particularly in the less developed moderately saline zone, to extend the mapped static water level downdip from the outcrop. This would allow for improved storage volume estimates by calculating the confined storage volume.

# 18 Conclusions

The purpose of this study is to provide a technical evaluation of the salinity distribution of groundwater within the Woodbine Aquifer. To accomplish this, we first collected and analyzed available data, primarily geophysical well log information, to map the structure and net sand of the Woodbine Formation. The formation surfaces were utilized in the aquifer determination process to identify wells completed in the aquifer to compile a measured water quality data set for mapping the salinity distribution. The measured water quality data was combined with salinity estimations calculated from geophysical well logs in the down dip portion of the aquifer where sampling data is usually sparse or absent. The Woodbine Aquifer groundwater storage volumes were estimated for each salinity classification within certain administrative boundaries (counties, groundwater conservation districts, groundwater management areas, and regional water planning groups).

We estimated groundwater volumes for salinities ranging from 1,000 to 34,999 milligrams per liter total dissolved solids which includes slightly saline, moderately saline, and very saline groundwater. However, it should be noted that we consider brackish groundwater to represent the slightly saline and moderately saline salinity classes (1,000 to 9,999 milligrams per liter total dissolved solids). We did not calculate volume for the fresh or brine salinity classes.

Our estimated total in-place storage volume of brackish groundwater in the Woodbine Aquifer is approximately 120.4 million acre-feet. This comprises approximately 72.7 million acre-feet of slightly saline and 47.7 million acre-feet of moderately saline groundwater. The estimated volume of very saline groundwater (10,000 to 34,999 milligrams per liter total dissolved solids) is approximately 49.5 million acre-feet.

Not all brackish groundwater can be produced or economically developed. However, these estimates and associated salinity mapping provide stakeholders with a beneficial tool to evaluate potential sites for brackish groundwater well fields. These volumes do not consider the effects of land surface subsidence, degradation of water quality, or any changes to surface water-groundwater interaction that may result from extracting groundwater from the aquifer. These volumes should not be used for joint groundwater planning or evaluation of achieving adopted desired future conditions in the same way total estimated recoverable storage (TERS) and modeled available groundwater are used according to the joint planning process described in Texas Water Code § 36.108.

The information contained in this report is not intended to serve as a substitute for site-specific studies that are required to evaluate local aquifer characteristics and groundwater conditions for a desalination plant. Well-field-scale data collection using test and monitoring wells is strongly recommended to evaluate the brackish groundwater resource at a particular site. Collection and evaluation of additional well control and aquifer properties in a prospective site area is essential in understanding potential target zones for groundwater development.

Publicly available study deliverables include 1) this report, 2) geographic information system (GIS) files, 3) BRACS Database and associated Data Dictionary, and 4) water well and geophysical well log files.

# 19 Acknowledgements

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## A. Public water supply systems

This appendix provides a table for the public water supply systems (PWS) in the Woodbine Aquifer study area (TWDB, 2024f). Section 4 references this appendix is and Figure 4-3 displays the associated data.

**Table A-1** **Public water supply table cross-referenced between map identification number and the public water supply in Figure 4-3.**

| Map ID | PWS ID | PWS name |
|---|---|---|
| 1 | 1260066 | Mansfield South |
| 2 | 700080 | Coming of Christ Full Gospel Church |
| 3 | 700059 | Lakeview Water System |
| 4 | 700064 | Spanish Grant Subdivision |
| 5 | 700006 | City of Milford |
| 6 | 1260116 | Triple H Estates |
| 7 | 700028 | City of Italy |
| 8 | 1260039 | Blue Water Oaks Estates |
| 9 | 1090069 | Tres Vidas Subdivision |
| 10 | 1260073 | Cahill Country Water System |
| 11 | 1090024 | City of Mertens |
| 12 | 1090003 | City of Itasca |
| 13 | 700057 | Lakeview Ranchettes |
| 14 | 700067 | City of Ovilla |
| 15 | 700058 | Emerald Forest |
| 16 | 700071 | Chambers Meadow Estate Water |
| 17 | 610051 | Boyd Acres Water System |
| 18 | 570036 | City of Cedar Hill |
| 19 | 430003 | City of Celina |
| 20 | 910139 | Heritage Estates |
| 21 | 700034 | Sardis Lone Elm WSC |
| 22 | 700070 | Buffalo Hills Water System |
| 23 | 1260078 | Rancho Villa Subdivision |
| 24 | 700063 | Grande Casa |
| 25 | 1260123 | Mauka |
| 26 | 1260006 | City of Venus |
| 27 | 2200186 | Forest Acres Gardens |
| 28 | 2200079 | Westside Rural WSC |
| 29 | 1260094 | Southern Acres Water System |
| 30 | 2200115 | Spring Creek Circle WSC |
| 31 | 910022 | Two Way SUD |
| 32 | 610070 | Rocky Point Water System |

| Map ID | PWS ID | PWS name |
|---|---|---|
| 33 | 610035 | Town of Little Elm |
| 34 | 2200018 | City of Mansfield |
| 35 | 700031 | City of Red Oak |
| 36 | 610163 | Saratoga Estates |
| 37 | 610068 | Knob Hill Water System |
| 38 | 1260077 | West Park Village |
| 39 | 1260004 | City of Grandview |
| 40 | 610112 | Hilltown Addition |
| 41 | 1260074 | Metroplex Homesteads Water Supply |
| 42 | 430005 | City of Frisco |
| 43 | 910014 | City of Sadler |
| 44 | 700007 | City of Palmer |
| 45 | 700033 | Rockett SUD |
| 46 | 570097 | Parkerville East Mobile Home Park |
| 47 | 430009 | Town of Prosper |
| 48 | 910007 | City of Tioga |
| 49 | 430050 | Weston WSC |
| 50 | 700056 | Red Oak Community Water Service |
| 51 | 610214 | Spanish Oaks Addition |
| 52 | 610091 | City of Hackberry |
| 53 | 610037 | Wynnwood Haven Estates |
| 54 | 1160002 | City of Celeste |
| 55 | 610212 | Willow Wood Addition Meadow Vista |
| 56 | 570013 | City of Lancaster |
| 57 | 700020 | City of Bardwell |
| 58 | 700019 | Avalon WSC |
| 59 | 700002 | City of Ferris |
| 60 | 570032 | City of Balch Springs |
| 61 | 430002 | City of Blue Ridge |
| 62 | 740006 | City of Savoy |
| 63 | 430039 | City of Mckinney |
| 64 | 910006 | City of Sherman |
| 65 | 910060 | Kentuckytown WSC |
| 66 | 740008 | City of Windom |
| 67 | 740007 | City of Ector |
| 68 | 910072 | 3-D Mobile Home and RV Park |
| 69 | 430040 | City of Melissa |
| 70 | 430049 | Westminster SUD |
| 71 | 740027 | Randolph WSC |

| Map ID | PWS ID | PWS name |
|---|---|---|
| 72 | 740038 | City of Bailey |
| 73 | 910032 | Luella SUD |
| 74 | 740034 | West Leonard WSC |
| 75 | 1160005 | City of Wolfe City |
| 76 | 1160039 | North Hunt SUD |
| 77 | 570094 | Cottonwood Creek Mobile Home Park |
| 78 | 700023 | Rural Bardwell WSC |
| 79 | 740002 | City of Dodd City |
| 80 | 570016 | City of Seagoville |
| 81 | 430048 | Verona SUD |
| 82 | 430035 | Frognot SUD |
| 83 | 430027 | City of Anna |
| 84 | 910009 | City of Van Alstyne |
| 85 | 430032 | Desert WSC |
| 86 | 910052 | Tanglewood On Texoma |
| 87 | 910008 | City of Tom Bean |
| 88 | 910064 | South Grayson SUD |
| 89 | 910003 | City of Denison |
| 90 | 910034 | Pink Hill WSC |
| 91 | 910011 | City of Whitewright |
| 92 | 740019 | Arledge Ridge WSC |
| 93 | 740031 | Southwest Fannin County SUD |
| 94 | 740005 | City of Leonard |
| 95 | 740044 | Bois D Arc MUD |
| 96 | 740003 | City of Honey Grove |
| 97 | 1390012 | Petty WSC |
| 98 | 430025 | City of Allen |
| 99 | 910004 | City of Pottsboro |
| 100 | 910001 | City of Bells |
| 101 | 1260010 | Oakview Farms Subdivision |
| 102 | 1750004 | City of Frost |
| 103 | 700004 | City of Maypearl |
| 104 | 610029 | Lake Cities Municipal Utility Authority |
| 105 | 1090070 | City of Carls Corner |
| 106 | 1160062 | Hickory Creek SUD |
| 107 | 570085 | City of Glenn Heights |
| 108 | 740009 | City of Trenton |
| 109 | 570012 | City of Hutchins |
| 110 | 1160029 | Caddo Basin SUD |

| Map ID | PWS ID | PWS name |
|---|---|---|
| 111 | 910055 | Marilee Elmont |
| 112 | 740021 | Bartley Woods WSC |
| 113 | 610032 | Town of Lakewood Village |
| 114 | 570014 | City of Mesquite |
| 115 | 1290043 | Kaufman County FWSD 1A |
| 116 | 740024 | Gober MUD |
| 117 | 570098 | Matthew Road WSC |
| 118 | 740035 | White Shed WSC |
| 119 | 910045 | City of Southmayd |
| 120 | 740036 | Ravenna Nunnelee WSC |
| 121 | 570006 | City of Desoto |
| 122 | 2200043 | City of Colleyville |
| 123 | 1090048 | City of Bynum Blackland System |
| 124 | 910012 | City of Gunter |
| 125 | 910048 | City of Southmayd Westview Subdivision |
| 126 | 910013 | City of Howe |

*Notes:* ID = identification number; SUD = Special Utility District; WSC = Water Supply Corporation; MUD = Municipal Utility District, FWSD = Fresh Water Supply District.

## B. BRACS Database

This appendix contains a brief overview of the BRACS Database. Descriptions of selected tables housed in the BRACS Database are included for general reference. For additional information, please refer to the latest edition of the BRACS Database Data Dictionary (TWDB, 2025a), which is available for download from the BRACS Database webpage.

Figure 21-1 shows the BRACS Database table relationships. Each rectangle represents a unique category of information in a primary table linked to the other tables based on key fields represented by colored lines. The well location table, in the upper left, is the primary table where the well record identification number, Well_ID (also referred to as BRACS ID), is assigned.

**Well location: tblWell_Location** – The well location table contains one record per well. When a new well record is appended into the BRACS Database, the record is first added to this table, which assigns its unique identification number using an autonumber data type in the field [WELL_ID]. The table contains attributes about the well, such as owner, location, source of well information, and well depth information.

**Elevation: tblBracs_Elevation** – The elevation information resides in a separate table to handle the one-to-many relationship between a well record and site elevation. The elevation values may differ depending on the elevation model used. The two primary sources of elevation information used are digital elevation models, one with a 30-meter grid cell and the other with a 10-meter grid cell. The table contains attributes about the well elevation such as method, elevation datum, agency, and date collected.

**Foreign keys: tblBracs_ForeignKey** – The foreign key table has one-to-many relationship between the BRACS well ID and unique well identification names or numbers assigned to it (for example, state well number and American Petroleum Institute number). These identifiers, also known as foreign keys, permit database linkage to the supporting databases developed from external agencies and other TWDB project databases with geophysical well logs and stratigraphic pick information.

**Well geology: tblWell_Geology** – The well geology table contains records of 1) well site lithology, 2) simplified lithologic descriptions, 3) stratigraphic picks, 4) faults, 5) salinity zones, and 6) hydrogeologic units. The information resides in a separate table to handle the one-to-many relationship between a well record and well site geology.

**Aquifer hydraulic properties: tblBracs_AquiferTestInformation** – The aquifer test table contains records of hydraulic properties such as well yield, specific capacity, and transmissivity. The information resides in a separate table to handle the one-to-many relationship between a well record and aquifer test results. Sources of information include, but are not limited to: 1) TWDB aquifer test spreadsheet, 2) TWDB Groundwater Database (TWDB, 2024e), 3) compilations of aquifer test data (Myers, 1969) and 4) Christian and Wuerch 2012), 5) Texas Department of Licensing and Regulation Submitted Driller's Report Database (TDLR, 2024), 6) scanned State of Texas Water Well Reports (TCEQ, 2024), 7) TWDB published reports, 8) U.S. Geological Survey published reports, 9) Bureau of Economic Geology published reports, and 10) miscellaneous published and unpublished reports.

**Geophysical well log, header: tblGeophysicalLog_Header** – This table contains geophysical well log attributes, file names and types, and digital file locations for each log in the TWDB BRACS collection. The information resides in a separate table to handle the one-to-many relationship between a well record and a geophysical well log. The top page of a geophysical well log is commonly called the header and contains the operator's name, well lease and number, location, dates, depths, logging parameters, and other attributes essential in understanding the conditions under which the logging was performed.

**Geophysical well log, log runs: tblGeophysicalLog_Header_LogRuns** – This table contains geophysical well log attributes from each log run for each geophysical well log used for log analysis. An oil or gas well may be drilled and logged in different depth stages. Attributes (for example top and bottom depth of the log run, temperature of bottom hole, drilling mud resistivity) will be different and must be recorded in a separate table to handle the one-to-many relationship between a geophysical well log and each log run.

**Well construction: tblBracs_Casing** – The well construction table contains the diameter, top and bottom depths, and construction interval (casing, well screen, open hole). The design of the table is exactly like the table in the original TWDB Groundwater Database (Rein and Hopkins, 2008) except the state well number field is replaced with the BRACS [Well_ID] field. The information resides in a separate table to handle the one-to-many relationship between a well record and the well construction.

**Digital water well reports: tblBracsWaterWellReports** – This table contains file names and types, file locations, and hyperlinks for each digital well report in the BRACS Database collection. The majority of reports are for water wells. However, any non-geophysical well log report for oil and gas wells (such as a scout ticket) is contained in this table and filing system. The information resides in a separate table to handle the one-to-many relationship between a well record and the digital well report.

**Water quality: tblBracsWaterQuality** – The water quality table contains records of water chemistry data organized with one record per well per date sampled with constituents in separate fields. The design of the table is almost exactly like the table in the original TWDB Groundwater Database (Rein and Hopkins, 2008). The information resides in a separate table to handle the zero-to-many relationship between a well record and water quality sample.

**Porosity: tblGeophysicalLog_Porosity** – The geophysical log porosity table holds records of geophysical well log types and the calculated porosity for specific geologic intervals. There may be multiple inputs for one well ID given the number of logs or formations with calculated porosity.

**Static water level: tblBRACS_SWL** – Static water level information is contained in this table which is designed similarly to its equivalent in the original Groundwater Database. Information includes dates, water levels, and source of measurement.

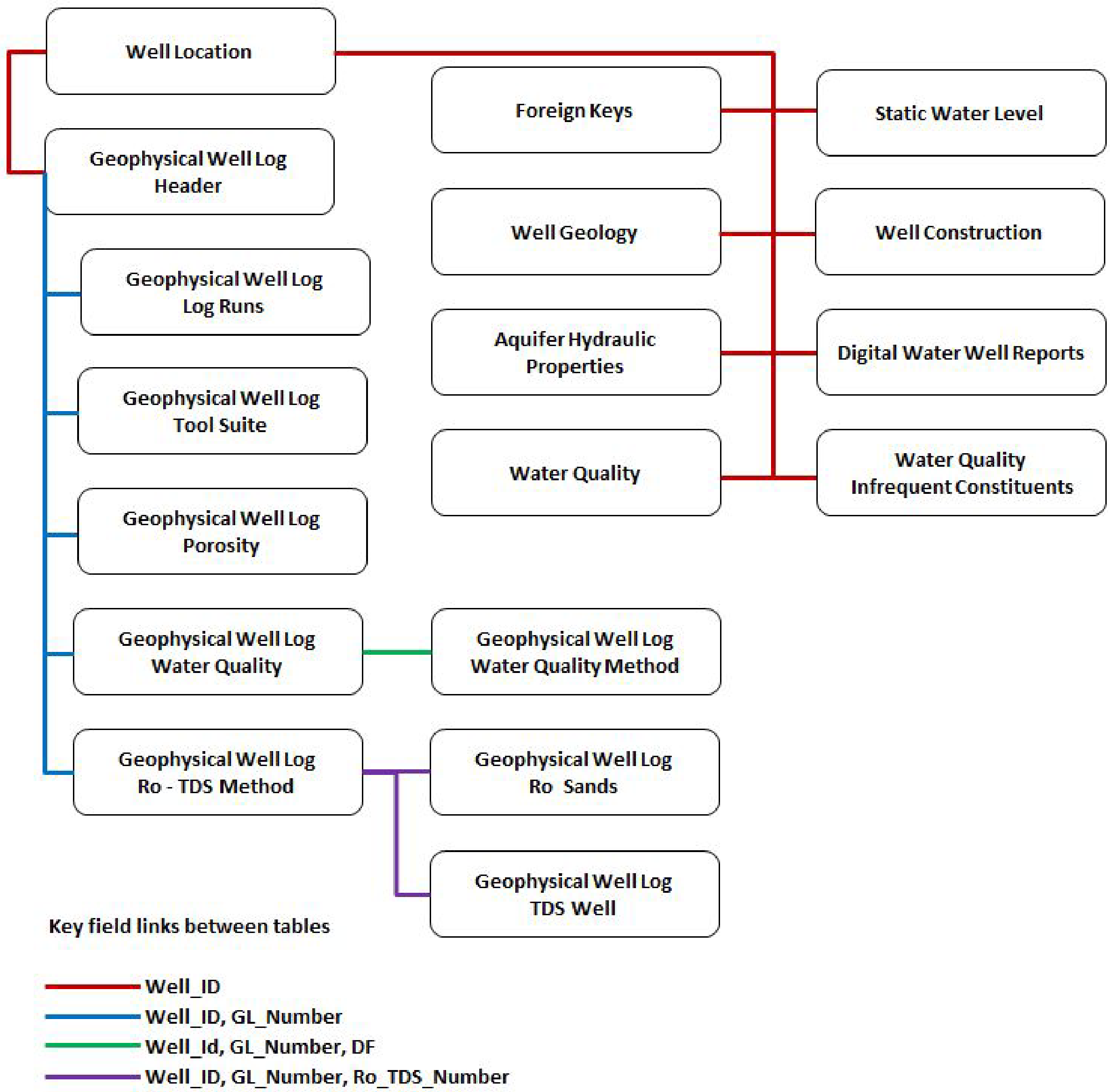


**Figure B-1** **Table relationships in the BRACS Database. Each rectangle represents a primary data table. The lines connecting the tables represent key fields: red represents the primary key Well_ID, blue represents the second key, green represents the third key, and purple represents the fourth key. New well records must be appended to the well location table to set the unique Well_ID. The tables, fields, and key fields are described in more detail in the Data Dictionary (TWDB, 2025a).**

## C. Geophysical logging tools

Geophysical logging enables geoscientists to characterize downhole physical properties to gain understanding of geologic materials, groundwater and/or other fluids, and the mechanical integrity of boreholes. Geophysical logging tools may be passive or active, and each measure specific rock and fluid properties. These tools are typically dropped to the lowest depth of the hole to be logged and are lifted at a constant rate until the logging tool passes the desired section of the hole. Interpretations of geophysical well logs are conducted using the combination of several geophysical well logging techniques. Common geophysical logs used in this study include:

**Spontaneous-potential (SP) logs** – results from naturally occurring electrical currents flowing between borehole mud and formation. SP curve deflection occurs opposite permeable bed (Schlumberger, 2009), and depending on the salinity of the mud filtrate vs salinity of the formation water, deflection of SP curve appears as negative or positive. Spontaneous-potential logs can be used in the interpretation of lithology and water quality.

**Resistivity logs** – record the electrical resistivity of the formation consisting of rock and fluid adjacent to the borehole as measured by variably-spaced potential electrodes on the logging probe (logs measure the geological formation at shallow, medium, and deep depths) (Rittgers, 2019). Log response shows separation between deep resistivity and shallow resistivity curves opposite permeable formations due to invasion of drilling mud into the formation (Schlumberger, 2009). This results in differing resistivity values close to the borehole wall compared to deeper in the formation. Resistivity logs can be useful in indicating permeable zones, comparing different lithologies and fluid resistivity which reflect difference in dissolved solids concentration of water.

**Gamma Ray logs** – record the amount of natural gamma radiation emitted by the rocks surrounding the borehole. The most significant naturally occurring sources of gamma radiation are potassium-40 and daughter products of the uranium- and thorium-decay series (Williams and others, 2002). Clay- and shale-bearing rocks commonly emit relatively high gamma radiation because they include weathering products of potassium feldspar and mica and tend to concentrate uranium and thorium by ion absorption and exchange. The gamma log is often used to define lithology and correlate geologic units between boreholes.

**Caliper logs** – provide a continuous record of average borehole diameter. Used to identify fractures, water-bearing openings, and changes in lithology. Changes in borehole diameter are related to drilling and construction procedures, caving in of rocks, and the presence of fractures (Williams and others, 2002).

**Acoustic logs** – provide record of formation’s interval transit time and are commonly referred to as sonic logs. Acoustic logs have become a widely used porosity tool in formation evaluation (Pickett, 1963).

**Nuclear logs (neutron and density logs)** – provide a record of formation porosity variations, bulk density, types of pore fluids, and rock characteristics by measuring the intensity of scattered radiation induced by radioactive sources (Oliveira and others, 2011).

# D. Geographic information system (GIS) datasets

Many GIS datasets were created for this study and each of the GIS files are available for download from the Texas Water Development Board BRACS studies web page. GIS techniques used to build the files are noted in the GIS file metadata. For further information on GIS raster interpolation methodology, see Section 8 and Appendix 21.5. ArcGIS® and the Spatial Analyst® extension software by Environmental Systems Research Institute, Inc. (Esri) were used to create the GIS files.

**GIS file name codes**

We have developed a file naming scheme for all GIS files created for this study. The full list of naming codes can be found in the BRACS Database in the table called tblGisFile_NamingConventions, and a shortened list of codes specific to this study are presented in Table D-1.

**Study GIS files**

All raster files (for example elevation, depth, net sand) are in the Tag Image File Format (tif) with Albers projection and the North American Datum 1983 as the horizontal datum. All raster files are snapped (coincident cell boundaries) to the study snap grid raster with a cell size of 250 by 250 feet.

Polygon, polyline and point files are in the ArcGIS® shapefile (shp) format with Albers projection and the North American Datum (NAD) 1983 as the horizontal datum. Various tables are provided in dBASE table file format (dbf), which represents dBase database file.

Unique GIS datasets, subdivided into the folders Study Area, Geology, Stratigraphy, Salinity, Lithology, and Volume, are presented in Tables 21-3 through 21-8.

**Table D-1 GIS file naming codes applied to the BRACS Woodbine Aquifer study.**

| Code | Code type | Code description |
|---|---|---|
| BRACS | General | Brackish Resources Aquifer Characterization System |
| TWDB | General | Texas Water Development Board |
| RWPA | General | Regional Water Planning Area |
| GCD | General | Groundwater Conservation District |
| GMA | General | Groundwater Management Area |
| PWS | General | Public Water System |
| GAT | General | Geologic Atlas of Texas |
| TDLR | General | Texas Department of Licensing and Regulation |
| GWDB | General | Groundwater database |
| DEM | Value | Digital Elevation Model, ground surface elevation in feet relative to mean sea level |
| wb | Stratigraphic | Woodbine Group |
| ns | Net sand analysis | Net sand in cumulative feet |
| te | Surface position | Top elevation in feet relative to mean sea level |
| be | Surface position | Bottom elevation in feet relative to mean sea level |
| td | Value | Top depth in feet below ground surface |
| bd | Value | Bottom depth in feet below ground surface |
| tk | Value | Isochore thickness in feet |
| tds | Value | Total dissolved solids in milligrams per liter |
| swl | Value | Static water level in feet below ground surface |
| swle | Value | Static water level in feet relative to mean sea level |
| guide | Value | Guide point value |
| 50ft | Contour interval | Contour interval of 50 feet |
| i | Raster data value | Integer |
| nd | Raster data value | Null data values |
| snap | Snap raster | All raster files are snapped to the project snap raster |
| con | Data type | Contour |
| ext | Data type | Extend |
| pt | Data type | Point |
| pl | Data type | Polyline |
| pg | Data type | Polygon |
| 250K | Data type | Shapefile was digitized from a 1:250,000 original |
| otc | Data type | Outcrop |
| sbc | Data type | Subcrop |
| AD | Data type | Aquifer determination |
| AT | Data type | Aquifer test |
| ft | Data type | Feet |
| nf | Data type | Normal fault |

**Table D-2 GIS study support files in the Woodbine Aquifer study area.**

| File type | Point file name | Polyline file name | Polygon file name | Raster |
|---|---|---|---|---|
| Project snap grid | | | | wb_snap |
| Project elevation | wb_te_otc_DEM_pt | | | wb_i_dem |
| | wb_be_otc_DEM_pt | | | |
| Study area | | wb_study_area_pg | | wb_sa_ext_nd<br>wb_otc_ext_nd |
| Texas counties | | TX_counties_pg | | |
| | | wb_TX_counties_pg | | |
| Texas urban areas | | | urban_areas_pg | |
| PWS | | | wb_PWS_pg | |
| Well control | wb_AD_pt<br>wb_BRACS_pt<br>wb_GWDB_pt | | | |
| Aquifer test | wb_AT_pt | | | |
| GMA | GMA_pg | | | |
| RWPA | RWPA_pg | | | |
| GCD | GCD_pg | | | |

**Table D-3 GIS files for stratigraphic analysis in the Woodbine Aquifer study area.**

| File type | Point file name | Polyline file name | Raster |
|---|---|---|---|
| Top elevation | wb_te_pt<br>wb_te_guide_pt<br>wb_te_alluvium_guide_pt<br>wb_te_be_fault_area_gude_pt | wbte_con_1000ft_pl | wbte |
| Bottom elevation | wb_be_pt<br>wb_be_guide_pt<br>wb_be_alluvium_guide_pt | wbbe_con_1000ft_pl | wbbe |
| Bottom depth | | wbbd_con_1000ft_pl | wbbd |
| Top depth | | wbtd_con_1000ft_pl | wbtd |
| Thickness | | wbtk_con_100ft_pl | wbtk |
| Outcrop control | wb_te_otc_DEM_pt<br>wb_be_otc_DEM_pt | | |

**Table D-4 GIS files for lithologic analysis in the Woodbine Aquifer study area.**

| File type | Point file name | Polyline file name | Raster |
|---|---|---|---|
| Net sand | wb_ns_pt | wb_ns_con_50ft_pl | wbns |
| Outcrop control | wb_ns_otc_zero_pt | | |

**Table D-5 GIS files for groundwater volumes in the Woodbine Aquifer study area.**

| File type | Point file name | Polygon | Raster |
|---|---|---|---|
| Static water level | wb_swl_2010_pt | | wb_swle_otc |
| Static water level outcrop control | wb_swl_otc_zero_pt | | |
| Volume grid | wb_master_grid_pt | wb_master_grid_pg | |
| Volumes by county | wb_volumes_by_county.dbf | | |
| Volumes by GCD | wb_volumes_by_GCD.dbf | | |
| Volumes by GMA | wb_volumes_by_GMA.dbf | | |
| Volumes by RWPA | wb_volumes_by_RWPA.dbf | | |
| Volumes by salinity class | wb_volumes_by_salinity_zone.dbf | | |

**Table D-6 GIS files for salinity class delineation in the Woodbine Aquifer study area.**

| File type | Point file name | Polyline file name | Polygon |
|---|---|---|---|
| Salinity class | | wb_salinity_class_pl | wb_salinity_class_pg |
| Measured water quality | wb_tds_measured_pt | | |
| Calculated water quality | wb_tds_calculated_pt | | |
| Produced water samples | wb_produced_water_pt | | |
| Salinity cutoff | | wb_salinity_class_cutoff_pg | |

**Table D-7 GIS files for regional geology in the Woodbine Aquifer study area.**

| File type | Polyline file name | Polygon file name |
| --- | --- | --- |
| Outcrop | | TWDB_wb_otc_pg<br>GAT_wb_otc_pg<br>TWDB_sbc_pg |
| Mapped faults | wb_nf_study_area_pl<br>wb_nf#_pl | |
| Surface geology | | wb_rock_unit_pg_250K_GAT |

## E. Raster interpolation documentation

This appendix contains additional details of the raster interpolation process discussed in Section 8 of this report, including stratigraphic surfaces and the net sand map. Individual raster files and shapefiles are listed in Appendix 21.4.

### i. Stratigraphic surface interpolation

**Input data descriptions for elevation rasters**

Geologic formation boundary

We extracted formation outcrop polygons from the Geologic Atlas of Texas (TWDB, 2007). These outcrop polygons were combined with the study area boundary and used to create extent shapefiles for selecting and clipping data.

Outcrop elevation points

Digital elevation model outcrop points were created along the formation outcrop contacts to support raster interpolation. When possible, points along the contacts were sampled at 250 feet to reflect the accuracy of the modeled surfaces more closely. We then used the Extract Values to Points tool to attribute the points with the elevation value from the study digital elevation model.

Stratigraphic elevation points

We mapped the stratigraphic units in the subsurface primarily based on geophysical well log characteristics utilizing S&P Global Kingdom™ geological software as described earlier in this report. The use of well logs from both water wells and deeper oil and gas wells allowed us to correlate the stratigraphic units consistently throughout the study area. We used the kelly bushing height and surface elevation from the well location table to correct the stratigraphic depths and elevations for interpolation. Stratigraphic picks for the top of the Woodbine and the top of the Washita Group (representing the base of the Woodbine) were exported to Microsoft Excel for input into Esri ArcMap® mapping software which was used to interpolate the geologic surfaces. The elevation points were also imported into the BRACS Database and compiled in table gBRACS_ST_WB.

Faults

We created 22 fault polylines from within the Mexia-Talco Fault Zone for input as “Cliff” features in the Topo to Raster interpolation tool in Esri ArcMap®. All faults used for raster surface interpolation are normal faults modified and digitized from Ewing (1991).

**Quality control, errors, and anomalies**

Visual inspection

Stratigraphic picks that appeared to fall outside of the expected structural features were evaluated for errors such as location, elevation, and geologic interpretation.

<u>Guide points</u>

During the formation surface interpolation process, anomalies such as under- and overthickening, and inversion may occur. In these cases, the well attributes, including location and stratigraphic picks, are reviewed for accuracy, and corrections are made if necessary. If these attributes appeared reliable, an attempt to acquire additional well control was made. When the well attributes appeared accurate and additional well control was unavailable, guide points were created to encourage the interpolation in these areas to a more geologically defensible result. Guide points were divided between multiple point shapefiles depending on the need they satisfied (see Appendix 21.4). Guide points were utilized in both top and bottom elevation surfaces at certain locations where well control was inadequate, particularly in areas near faulting. Guide points were also utilized in areas where the upper or lower formation contacts were overlain by laterally extensive alluvial sediments. These point locations are estimated to be near the location of the contacts and calculated to the DEM depth minus 39 feet to allow for accommodation of sediments. While these points did not eliminate inversion, their purpose was to guide the interpolations in this area to reduce inversion, which was corrected as described herein.

<u>Layer inversions</u>

Layer inversion occurs when underlying raster surfaces extend in elevation above the overlying surface, creating negative thickness values. These errors typically occurred in the following locations: the outcrop area where thickness decreases, outcrop areas that are overlain by surface water features or alluvium, areas of sparse well control or only a top or bottom control point, and in areas with irregular topography.

Layer inversion in the top elevation raster occurred predominantly in outcrop areas underlying Quaternary alluvial deposits. An abbreviated evaluation of the alluvial deposits within outcrop study area indicated an average thickness of 39 feet. Areas of negative thickness values were identified, and these raster cell values were adjusted to the digital elevation model elevation value minus 39 feet. An evaluation of hydraulic connectivity between alluvium and the Woodbine Aquifer is outside of the scope of this study.

Areas of negative thickness values that were identified in the bottom elevation raster were adjusted to the inversion corrected top elevation minus 1 foot.

Steps to correct top elevation inversion:

Use the Raster Calculator tool to subtract the top elevation raster from the study digital elevation model.

> Example: “wb_i_dem.tif” – “wbtetrxo__i15.tif”
>
> Example output: “qcwbteiDEM_15.tif”

For every cell with a negative thickness value, change the geologic formation top elevation value to the digital elevation model minus 39 (feet).

Example syntax: Con("qcwbteiDEM_15.tif "<0, " dem_i_WB"-39,"wbtetrxo__i15.tif ")

Example output: "wbteifixed15.tif," finalized as "wbte.tif"

Steps to correct bottom elevation inversion:

Use the Raster Calculator tool to subtract the bottom elevation raster from the study top elevation raster.

Example: "wbte.tif" – "wbbetrxo__i19.tif"

Example output: "qcwbbei_19.tif"

For every cell with a negative thickness value, change the geologic formation bottom elevation value to the top elevation raster value minus 1.

Example syntax: Con("qcwbbei_19.tif "<0, " wbte"-1,"wbbetrxo__i19.tif")

Example output: "wbbeifixed19.tif," finalized as "wbbe.tif"

**Elevation raster finalization**

To finalize the stratigraphic raster surfaces, we performed the following steps:

1. Check that cells coincide with the snap grid
2. Check that the raster is in the GAM projection
3. Ensure rasters have integers values
4. Correct interpolated values that go above or below corresponding surfaces (inversion)
5. Overwrite precise elevation point values into raster cells

**Depth rasters**

The raster for the depth to the top of the Woodbine was created by subtracting the finalized top elevation raster from the study digital elevation model raster. The raster for the depth to the base of the Woodbine was created by subtracting the finalized bottom elevation raster from the study digital elevation model raster.

**Isochore thickness raster**

The isochore thickness raster was created by subtracting the finalized formation bottom elevation raster from the finalized top elevation raster.

**ii. Net sand thickness raster interpolation**

We selected the Topo to Raster tool for interpolating net sands. This tool reasonably honored input point values while creating a raster that resembled our best professional judgement. The net sand interpolation input features included the net sand point and zero value outcrop point (net sand value set to zero) shapefiles.

Zero value net sand outcrop points were created along the updip outcrop line. These zero value points forced the interpolated raster to smaller values towards the outcrop. Guide points were not utilized for net sand interpolation.

In the Woodbine outcrop, geophysical well logs were unable to capture the entirety of the formation present since they are often not logged to the surface and were not used to characterize net sand in this area. Additionally, formation contacts were difficult to discern in the available driller's logs and they were not helpful in characterizing net sands in the outcrop area. Because of this, net sand interpolation in the outcrop is interpolated from the closest well logs with complete sections to the zero value outcrop points described above. The net sand in the outcrop area may be less representative due to lack of interpolation control. However, this part of the study area is largely characterized by fresh groundwater and will have little impact on the evaluation of brackish groundwater volume.

**Quality control, errors, and anomalies**

Visual inspection

Net sand points that appeared to fall outside of the expected features were evaluated for errors such as location, elevation, and lithologic interpretation.

Thickness inversions

The net sand thickness raster was subtracted from the formation thickness raster to identify any cells where the net sand exceeded the formation thickness. In these areas, the net sand raster value was set equal to the formation thickness.

Steps to correct top elevation inversion:

Use the Raster Calculator tool to subtract the net sand raster from the study formation thickness raster.

> Example: "wbtk.tif" – "wbns_07_clip.tif"
>
> Example output: "wbns_07_tkchk.tif"

For every cell with a negative value, change the net sand value to the formation thickness.

> Example syntax: Con("wbns_07_tkchk.tif"<0, "wbtk.tif" ," wbns_07_clip.tif ")
>
> Example output: "wbns_07_fixed.tif," finalized as "wbns.tif"

**Raster finalization**

To finalize the net sand raster, we performed the following steps:

1. Check that cells coincide with the snap grid
2. Check that the raster is in the GAM projection
3. Ensure rasters have integers values
4. Correct interpolated net sand values that are greater than formation thickness values
5. Overwrite precise net sand point values into raster cells

## F. Aquifer test data

This section contains figures of locations of available aquifer test data, including specific capacity, hydraulic conductivity, transmissivity, and well yield. Additional information regarding aquifer hydraulic properties can be found in Section 10 of this report.

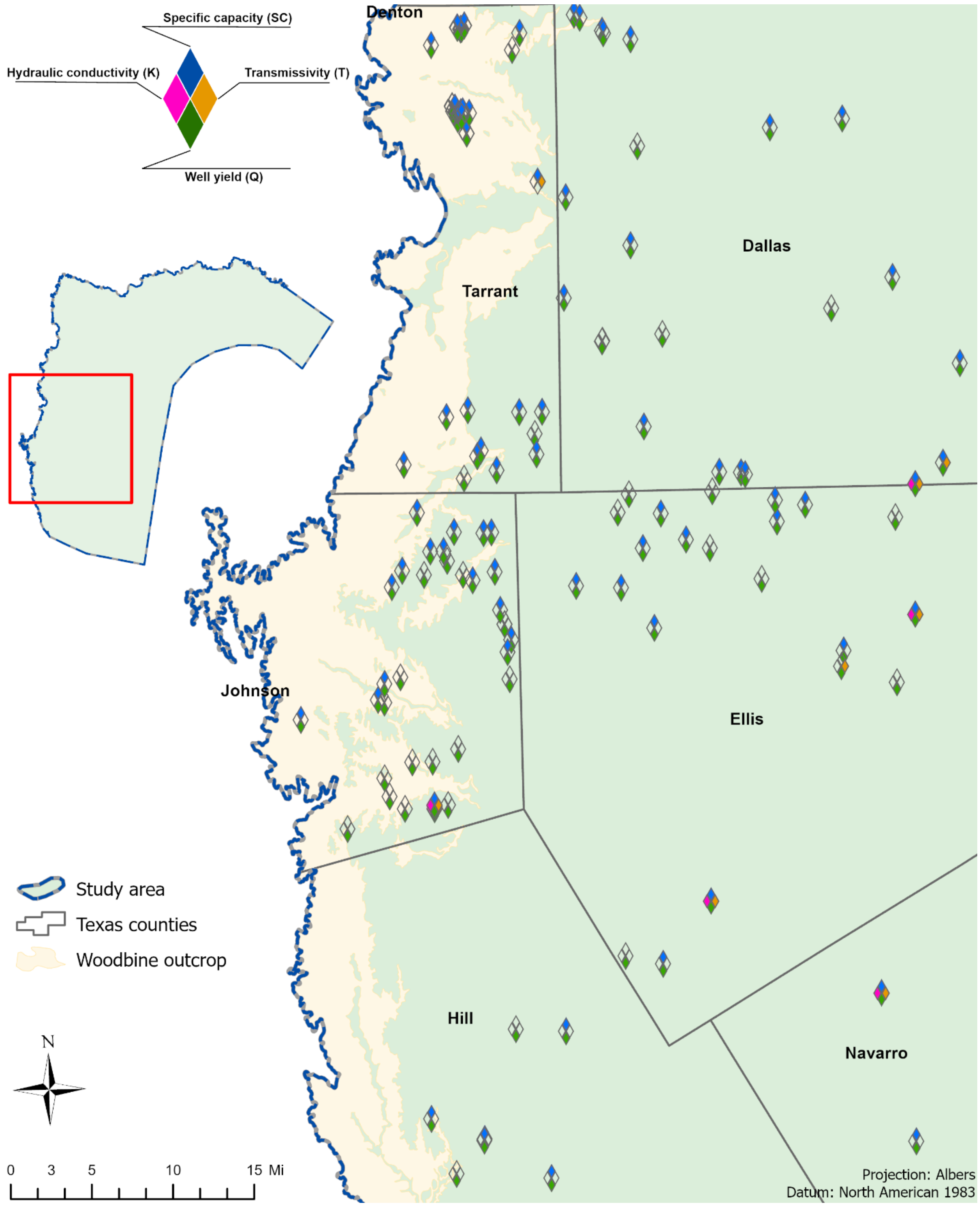


**Figure F-1 Aquifer test availability in the southern portion of the study area.**

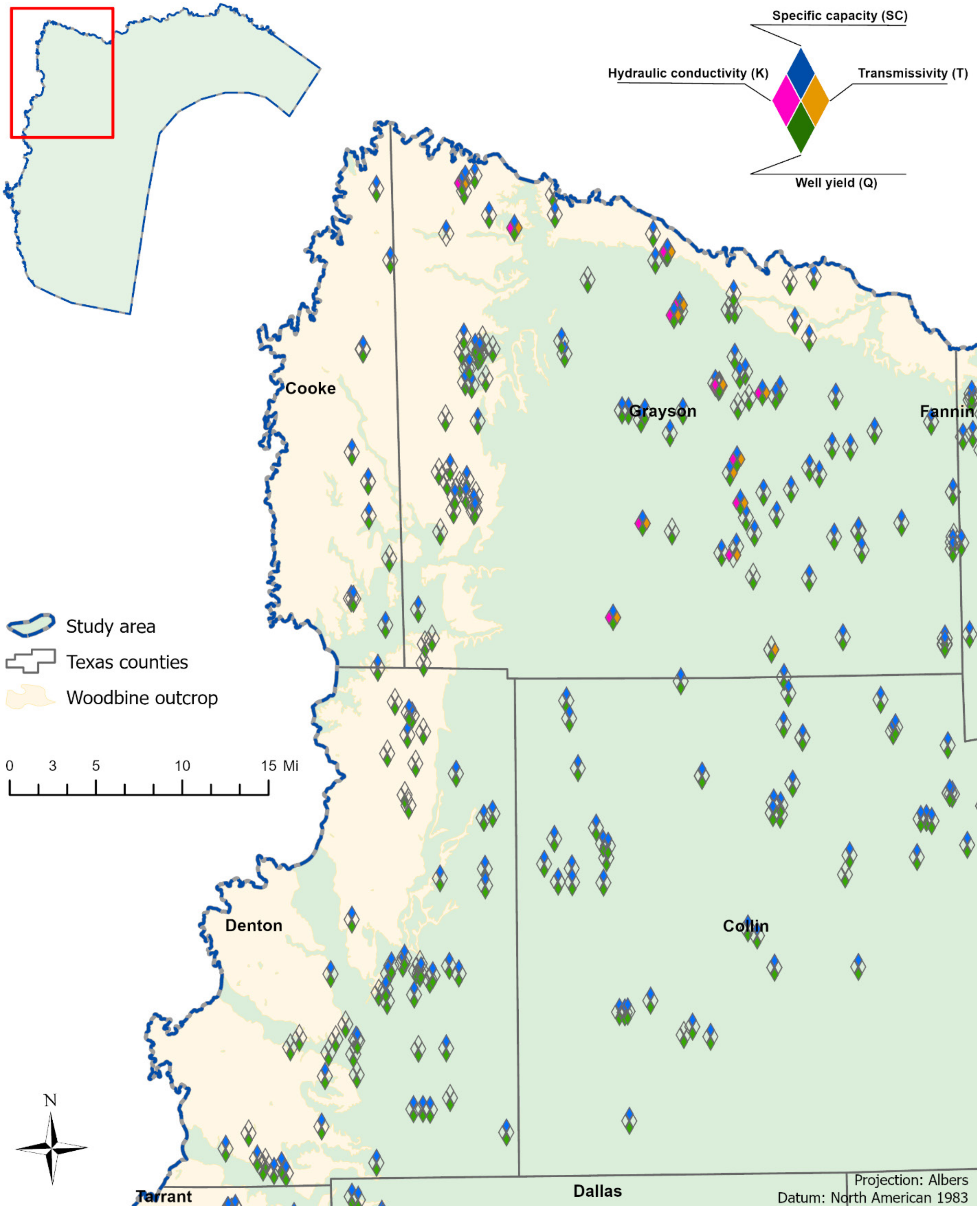


**Figure F-2** **Aquifer test availability in the northwestern portion of the study area.**

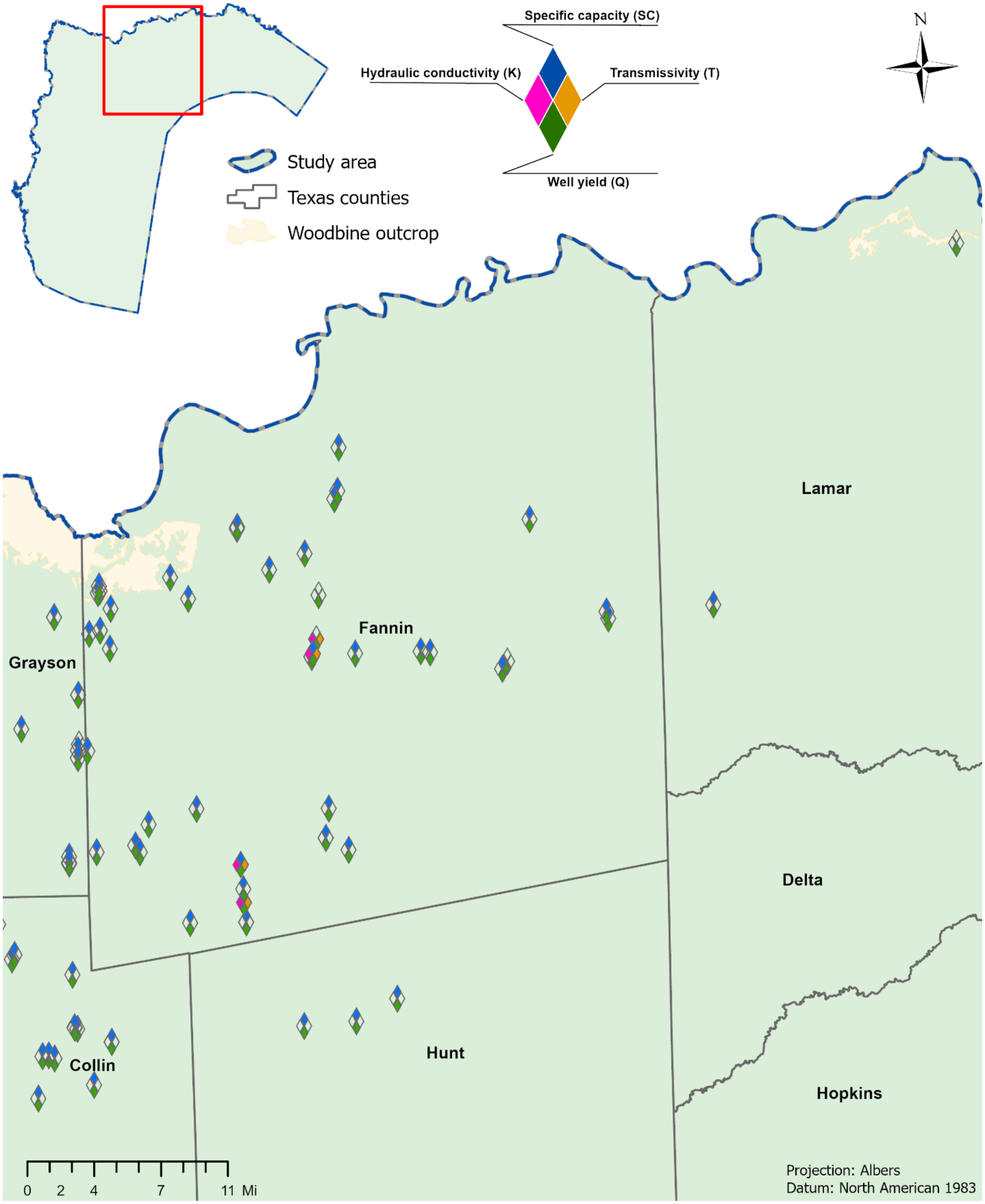


**Figure F-3 Aquifer test availability in the northeastern portion of the study area.**

## G. Cation-anion balance equations

We calculated the total cation and anion milliequivalents per liter (mEq/L) with the following formulas (the chemical constituents are in milligrams per liter (mg/L), and the decimal fraction in the formulas is the conversion from milligrams per liter to milliequivalents per liter for each individual constituent):

Total cations in mEq/L = $[(Ca^{2+} \times 0.0499) + (Mg^{2+} \times 0.08229) + (Na^{+} \times 0.0435) + (K^{+} \times 0.02557) + (Sr^{2+} \times 0.0228)]$ **(Equation G-1)**

where:

$Ca^{2+}$ = calcium concentration (mg/L)

$Mg^{2+}$ = magnesium concentration (mg/L)

$Na^{+}$ = sodium concentration (mg/L)

$K^{+}$ = potassium concentration (mg/L)

$Sr^{2+}$ = strontium concentration (mg/L)

Total anions in mEq/L = $[(CO_3^{2-} \times 0.03333) + (HCO^{-} \times 0.01639) + (SO_4^{2-} \times 0.02082) + (Cl^{-} \times 0.02831) + (F^{-} \times 0.0228) + (NO_3^{-} \times 0.01613)]$ **(Equation G-2)**

where:

$CO_3^{2-}$ = carbonate concentration (mg/L)

$HCO_3^{-}$ = bicarbonate concentration (mg/L)

$SO_4^{2-}$ = sulfate concentration (mg/L)

$Cl^{-}$ = chloride concentration (mg/L)

$F^{-}$ = fluoride concentration (mg/L)

$NO_3^{-}$ = nitrate concentration (mg/L*)*

The percentage difference between the cation and anion totals in milliequivalents per liter is calculated as follows:

$$Percent\ difference = \frac{|C_{ttl} - A_{ttl}|}{\frac{C_{ttl} + A_{ttl}}{2}} \times 100$$ **(Equation G-3)**

where:

$C_{ttl}$ = total cations in mEq/L

$A_{ttl}$ = total anions in mEq/L

## H. Porosity estimations from geophysical logs

We calculated eight porosity estimates for the Woodbine Formation using the sonic (acoustic) tool. A sonic porosity without compaction correction was calculated using the sonic interval transit time, measured in units of microseconds per foot, directly from the geophysical well log. The calculation follows the equation provided by Asquith (1982):

$$\Phi_S = \frac{(T_{fm} - T_m)}{(T_{fl} - T_m)} \quad \textbf{(Equation H-1)}$$

where:

$\Phi_S$ = sonic porosity

$T_{fm}$= Interval transit time of the formation

$T_m$ = Interval transit time of the matrix

$T_{fl}$ = Interval transit time of the borehole fluid

We also calculated 31 neutron-density porosity estimates for the Woodbine Group. When logged with a sandstone matrix, the apparent neutron and density porosity values were read directly from the geophysical well log. For logs using a limestone matrix, the Porosity Equivalence Curves chart was used to convert neutron porosity (NPHI) from limestone to sandstone matrix, and the recorded density porosity (DPHI) was back calculated (Schlumberger, 2009).

The neutron-density porosity without shale correction was calculated using the apparent neutron and density porosity values with the equation from Asquith (1982):

$$\Phi_{N-D} = \sqrt{\frac{\Phi N^2 + \Phi D^2}{2}}$$

**(Equation H-2)**

where:

$\Phi_{N-D}$ = neutron-density porosity

$\Phi N^2$ = apparent neutron porosity squared

$\Phi D^2$ = apparent density porosity squared

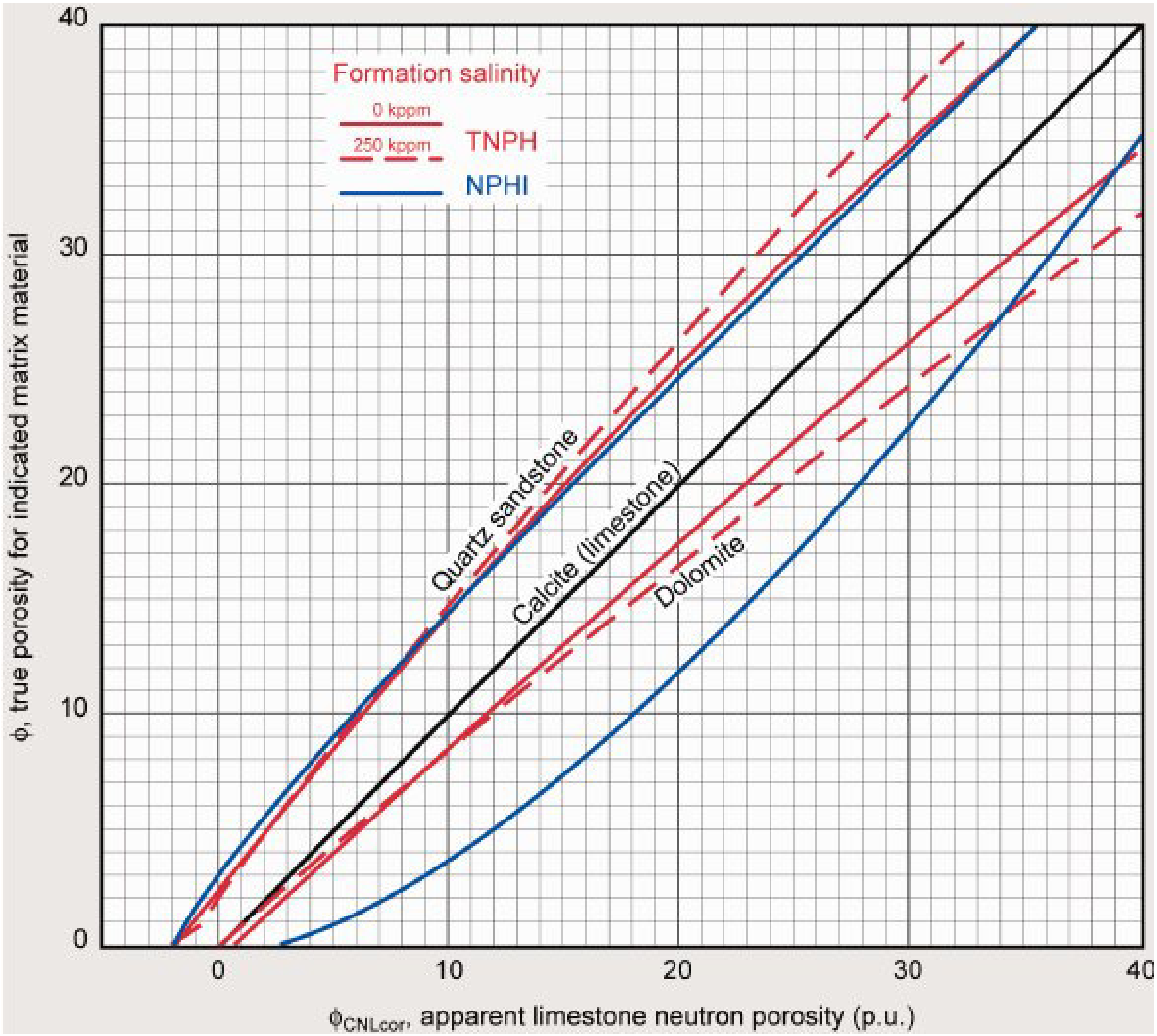


**Figure H-1 Porosity equivalence curves (Schlumberger, 2009)**

# I. Summary of well log-groundwater sample pairs

**Table I-1** **Summary of measured total dissolved solids (TDS)/calculated TDS well pair results. TDS calculations were performed with the $R_{wa}$ minimum method using a cementation exponent of 1.5 and a porosity of 28 percent (0.28). The cementation exponent of 1.5 was determined to provide the best match between measured and calculated TDS, whereas the porosity of 28 percent was derived from geophysical log porosity tools and published porosities throughout the study area.**

| County | BRACS ID | SWN/USGS PWDB [a] | Pair distance (feet) | Measured TDS [b, c] | Calculated TDS [c] |
|---|---|---|---|---|---|
| Johnson | 70457 | 3246209 | 2200 | 1031 | 1491 |
| Tarrant | 70760 | 3216205 | 4000 | 629 | 709 |
| Grayson | 31866 | 1818902 | 2600 | 1064 | 849 |
| Ellis | 33989 | 3240607 | 0 | 764 | 616 |
| Grayson | 70252 | 1834601 | 5500 | 3186-3354 | 2869 |
| Collin | 14570 | 1850304 | 0 | 722 | 1005 |
| Dallas | 38552 | 3327203 | 4280 | 1853 | 1933 |
| Fannin | 21359 | 1839501 | 6000 | 1027-2171 | 1098 |
| Collin | 69671 | 1844902 | 0 | 544 | 542 |
| Ellis | 2533 | 3336201 | 0 | 1999-2616 | 2709 |
| Navarro | 36956 | 3904401 | 5200 | 3754-4085 | 3049 |
| Grayson | 31866 | 1818903 | 2650 | 937-964 | 849 |
| Limestone | 20535 | 90061* | 0 | 28162 | 25417 |
| Navarro | 100432 | 55595* | 5600 | 20026 | 23462 |

[a] State well number or *U.S. Geological Survey Produced Water Database

[b] Measured TDS given as a range if more than one sample was reported

[c] Total dissolved solids (TDS) in milligrams per liter calculated using the $R_{wa}$ minimum method

# J. Groundwater volumes by county

**Table J-1** **Total brackish storage volume of the Woodbine Aquifer in each county by salinity class. Volumes are in acre-feet.**

| County | Slightly saline | Moderately saline | Total brackish volume | Very saline | Total volume including very saline |
|---|---|---|---|---|---|
| **Bowie** | 0 | 61,600 | 61,600 | 1,588,100 | 1,649,700 |
| **Collin** | 14,357,700 | 2,153,700 | 16,511,400 | 0 | 16,511,400 |
| **Dallas** | 15,294,900 | 9,300 | 15,304,200 | 0 | 15,304,200 |
| **Delta** | 0 | 110,400 | 110,400 | 4,633,900 | 4,744,300 |
| **Denton** | 1,540,000 | 0 | 1,540,000 | 0 | 1,540,000 |
| **Ellis** | 12,265,100 | 3,111,400 | 15,376,500 | 0 | 15,376,500 |
| **Fannin** | 14,129,600 | 1,194,100 | 15,323,700 | 101,900 | 15,425,500 |
| **Freestone** | 0 | 0 | 0 | 1,374,900 | 1,374,900 |
| **Grayson** | 2,718,100 | 0 | 2,718,100 | 0 | 2,718,100 |
| **Henderson** | 0 | 426,000 | 426,000 | 2,109,800 | 2,535,800 |
| **Hill** | 1,862,900 | 1,175,700 | 3,038,700 | 175,200 | 3,213,900 |
| **Hopkins** | 0 | 0 | 0 | 1,000 | 1,000 |
| **Hunt** | 4,136,100 | 7,366,700 | 11,502,800 | 9,496,500 | 20,999,200 |
| **Johnson** | 160,500 | 0 | 160,500 | 0 | 160,500 |
| **Kaufman** | 1,051,300 | 10,215,300 | 11,266,600 | 8,423,600 | 19,690,200 |
| **Lamar** | 2,658,400 | 6,360,800 | 9,019,200 | 2,995,200 | 12,014,400 |
| **Limestone** | 0 | 52,400 | 52,400 | 1,687,500 | 1,739,900 |
| **Navarro** | 2,287,000 | 9,512,700 | 11,799,600 | 8,734,200 | 20,533,900 |
| **Red River** | 0 | 1,882,500 | 1,882,500 | 7,995,200 | 9,877,700 |
| **Rockwall** | 88,200 | 4,054,400 | 4,142,600 | 0 | 4,142,600 |
| **Tarrant** | 142,700 | 0 | 142,700 | 0 | 142,700 |
| **Titus** | 0 | 0 | 0 | 105,000 | 105,000 |
| **Van Zandt** | 0 | 0 | 0 | 118,800 | 118,800 |
| **Total** | 72,692,600 | 47,686,900 | **120,379,500** | 49,540,800 | **169,920,300** |