Aquifer Storage and Recovery Report: Carrizo-Wilcox Aquifer Characterization for Eastern Gonzales and Parts of Caldwell and Guadalupe Counties, Texas

Andrea Croskrey, P.G., James Golab, Ph.D., P.G., Daniel Collazo

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March 2022

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Cover photo courtesy of Andrea Croskrey

"Carrizo Sand outcrop at the Palmetto State Park scenic overlook, Gonzales County, Texas"

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1. Executive summary

Aquifer storage and recovery (ASR) utilizes injection wells for the local storage and subsequent recovery of water within an aquifer for beneficial use, and aquifer recharge (AR) is the intentional recharge of an aquifer by injection well or other means of infiltration. Interest in both ASR and AR projects has been increasing in the nation and Texas for several reasons, of which the primary reason is the need to store excess water supplies. Implementation of ASR and AR in Texas, however, has been somewhat limited. Presently, there are only two municipal-scale ASR systems and a hybrid municipal-scale ASR-AR system in Texas.

In 2019, the 86th Texas Legislature passed House Bill 721, which tasked the Texas Water Development Board (TWDB) with two legislative mandates: 1) to complete a statewide suitability survey of ASR and AR and 2) conduct ASR or AR studies (Texas Water Code § 11.155). The statewide study created a methodology for surveying the suitability for ASR or AR projects across Texas and was based on mapping the hydrogeological characteristics of the major and minor aquifers, sources of excess water, and water supply needs, as outlined in the house bill. The resulting survey was published as a GIS geodatabase and an interactive web map viewer.

The second mandate was for TWDB to work with appropriate interested persons to conduct studies of ASR and AR projects in the state water plan or identified by others and report the results of these studies to the regional water planning groups and interested persons. A list of ASR or AR projects from the 2017 State Water Plan was developed and the details of each project were researched from the draft 2021 Regional Water Plans, news articles, professional presentations, and correspondence with the project sponsors. The information gathered was scored based on a few criteria: sponsor interest, staff skillset, source water, data availability, planning status, and online decade. Based on this research and scores, TWDB staff determined which projects to initially conduct studies.

The first study selected to fulfill the second legislative mandate was an aquifer characterization of the Carrizo-Wilcox Aquifer to support the Guadalupe-Blanco River Authority (GBRA) in its implementation of the ASR component of the Mid-Basin Water Supply Project. The GBRA plans to inject treated surface water from the Guadalupe River into the Carrizo-Wilcox Aquifer when availability from the river exceeds customer demand and there is available capacity at the new water treatment facility. This project was selected due to its high sponsor interest, match between the project need and staff skillsets, the source water type being treated surface water, availability of data, need for an aquifer characterization, and relatively early online estimate of 2035.

The GBRA needed an aquifer characterization to better understand the storage parameters and options of the aquifers in the vicinity of its Mid-Basin Water Supply Project. This aquifer characterization study describes the hydrogeological characteristics such as stratigraphy, lithology, and salinity of the Carrizo-Wilcox Aquifer in eastern Gonzales County and portions of Caldwell and Guadalupe counties. The GBRA selected the study area due to its proximity to existing infrastructure and the subsurface depth of 2,000 feet below the ground surface because this was the maximum economical drilling depth. The Carrizo-Wilcox Aquifer was considered a viable target zone for ASR in this area as it is not as heavily utilized for water supply compared to the shallower overlying units.

One of the most important aspects of an ASR project is understanding the hydrogeological characteristics of the aquifer to be used to store and recover the excess water supply, which will aid in the selection of a suitable site location and will inform future planning of infrastructure and treatment requirements for the project. For this aquifer characterization study, stratigraphic and lithologic hydrogeological characterization data for the Carrizo-Wilcox Aquifer were collected primarily from geophysical well logs obtained from the TWDB, along with other publicly available databases such as submitted drillers reports. The aquifer was mapped as two separate units: the Wilcox Group and the Carrizo Sand. There are approximately 362 square miles of Wilcox Group strata less than 2,000 feet deep within the study area. Wilcox Group net sands in this area range from zero to 920 feet of accumulated sands. These sand units are often less than 100 feet thick and vertically isolated between shale layers. The Wilcox Group also contains a large shale-filled channel within the study area known as the Yoakum Canyon. The Carrizo Sand is above the Wilcox Group and there are approximately 324 square miles of Carrizo Sand strata that are less than 2,000 feet below the surface in the study area. Net sands in this portion of the Carrizo Sand range from zero to 623 feet of accumulated sands. These porous sand units can be over 500 feet thick and highly productive. Though most of the Yoakum Canyon is below 2,000 feet deep in the study area, it has noticeable effects on the overlying Carrizo Sand. The Carrizo Sand above the Yoakum Canyon contains the thickest accumulated sands in the study area, but the individual sand intervals in this area are commonly thinner, at just over 200 feet.

Refined groundwater salinity mapping as provided in this aquifer characterization facilitates better decision making on well field location, well construction design, water treatment, piloting design, and project costs. For this study, groundwater salinity was obtained from measured water quality data and calculated from resistivity curves of geophysical well logs. The Wilcox Group groundwater in the study area ranges from fresh to very saline. Salinity tends to increase with depth. The stacked and isolated nature of the sand units within the Wilcox Group means that it is common for a single well to have more than one salinity class interval as the well depth increases. Because of these stacked intervals, there were no completely fresh zones in the Wilcox Group mapped in the study area. Carrizo Sand groundwater ranges from fresh to moderately saline in the study area. The area of fresh water in the Carrizo Sand is much more pervasive than in the Wilcox Group due to its higher porosity. The Carrizo Sand also has fewer stacked salinity intervals in a single well, likely due to having higher vertical connectivity than the Wilcox Group. Salinities within both geologic formations appear to be influenced by geologic features such as faults and depositional centers.

Final ratings from the statewide suitability survey of ASR in the study area range from most to least suitable and generally decrease from northwest to southeast. This is due to the distance from and direction to the populated I-35 corridor, as well as the location of potential source water from the Guadalupe and San Marcos rivers. The statewide survey shows the hydrogeology of the Carrizo-Wilcox Aquifer is moderately to most suitable for ASR, primarily because of the well-documented high porosity and permeability of the Carrizo Sand. The Statewide ASR

Suitability Survey is a powerful tool for examining the potential viability of an ASR or AR project but does not replace the need for site-specific studies.

Aquifer characterization is an integral part of planning and developing an ASR system, as all properties of the aquifer affect the potential efficiency of the injection, storage, recovery, system design, material selections, and operations. When we considered the occurrence, quantity, quality, and availability of the Carrizo-Wilcox Aquifer for potential ASR storage in the study area, we identified a 9-mile-wide and 25-mile-long swath of the Carrizo Sand with the most favorable hydrogeological characteristics. In this area the Carrizo Sand is shallower than 2,000 feet, has vertical confinement, and has at least 300 feet of accumulated sands. This almost-200-square-mile area runs diagonally through the middle of the study area, paralleling the outcrop from the southwest to the northeast. Vertical confinement of the Carrizo Sand is provided by the overlying Reklaw Formation and a regional clay layer in the underlying Wilcox Group and helps control the movement of injected water in an ASR project. Intervals of sand are needed to store the injected source water. We chose to highlight an area of the Carrizo Sand with net sands greater than 300 feet in the study area, because presently 29 ASR wells used for the ASR facility at the H2Oaks Center are generally 700 feet deep and have screening intervals starting around 450 feet down the well.

The GBRA drilled three new wells cased in stainless steel as part of the Carrizo Groundwater Supply Project (Phase I) of the Mid-Basin Water Supply. Detailed geochemical data collected show that the native groundwater within the Carrizo Sand in the study area has low total dissolved solids, high iron content, and high manganese concentration. However, the overall low pH and carbonate hardness create corrosive conditions. Additionally, these wells were completed in the portion of the Carrizo Sand mapped as fresh, and it is likely that areas mapped as more saline will be increasingly corrosive to the casing and screen materials.

This aquifer characterization provides hydrogeological expectations inferred from surrounding well information, which the GBRA can use during well site selection. These expectations are conceptual and provisional until data from drilling and testing at the proposed project site can be obtained. Hydraulic gradient, hydraulic conductivity, and geochemical constituents are not provided in this sub-county-scale desktop study and will need to be further evaluated from data collected at the project site. Information gathered on these site-specific hydrogeological characteristics should be considered with source water chemistry and well field design and operations for successful ASR project outcomes.

2. Background

Aquifer storage and recovery (ASR) utilizes injection wells for the local storage and subsequent recovery of water within an aquifer for beneficial use (Texas Water Code § 27.151). Aquifer recharge (AR) is the intentional recharge of an aquifer by injection well or other means of infiltration (Texas Water Code § 27.201). Interest in both ASR and AR projects has been increasing across the United States due to decreasing water levels, increased reliance on vulnerable surface water supplies, and increased need for seasonal or emergency water storage (Pyne, 2005). Aquifer recharge from the surface is feasible in places where sediment near the surface is permeable and surface water can easily reach the water table. In less permeable sediment or for deeper aquifers, an injection well must be used (Pyne, 2005). Most ASR projects typically inject and recover water from the same location as this provides significant engineering and cost advantages to having separate injection and recovery wells. Both ASR and AR can use a variety of treated sources of injected water (Pyne, 2005).

2.1 Aquifer storage and recovery in Texas

In Texas, ASR and AR have been used to store surface water, groundwater, and reclaimed water (Webb, 2015). Presently, there are two municipal-scale ASR systems and a hybrid municipal-scale ASR-AR system in Texas. The City of Kerrville Plant became operational in 1998 and has two ASR wells and a recovery capacity of about 2.6 million gallons per day. The ASR facility at the H2Oaks Center located approximately 30 miles south of San Antonio became operational in 2004 and has 29 ASR wells and a recovery capacity of about 60 million gallons per day. The Fred Hervey Water Reclamation Plant in El Paso became operational in 1985 and has a spreading basin, recharge well field with one shallow vadose well active, and a down gradient Hueco Bolson Aquifer production well field.

The TWDB ASR program is housed under the Innovative Water Technologies Department. It was created in 2009 with the TWDB funding a study, *An Assessment of Aquifer Storage and Recovery in Texas*, to determine why ASR was not being more widely implemented in Texas (Malcolm Pirnie, 2011). As part of the study, 10 entities were surveyed and indicated that the concerns preventing them from implementing an ASR project were related to the recovery and quality of stored water, as well as implementation costs.

Four years later, the TWDB published Technical Note 15-04, *Aquifer Storage and Recovery in Texas: 2015*, which summarized ASR activities in Texas (Webb, 2015). Also, in 2015, the 84th Texas Legislature passed House Bill 655 amending the Texas Water Code to make statute more conducive to implementing ASR projects. The 84th Texas Legislature also passed House Bill 1, Rider 25, which appropriated $1 million from the General Revenue Fund to the TWDB to fund groundwater conservation districts for demonstration projects or feasibility studies that will prove up aquifer storage and recovery or other innovative storage projects. As a result, the TWDB provided funding to the Corpus Christi Aquifer Storage and Recovery Conservation District, the Edwards Aquifer Authority, and the Victoria County Groundwater Conservation District to acquire site-specific hydrogeological conditions for possible ASR projects by either drilling test wells or converting an existing groundwater production well to an ASR test well.

2.2 Legislative mandate

In 2019, the 86th Texas Legislature passed House Bill (HB) 721, which tasked the TWDB with two ASR related legislative mandates (Texas Water Code § 11.155). The first mandate was to conduct a statewide survey to determine the relative suitability of using Texas aquifers for ASR and AR projects based on consideration of: 1) hydrogeological characteristics with a focus on storage potential, transmissivity, infiltration characteristics, storativity, recoverability, and water quality; 2) the frequency, volume, and distance to excess water available for potential storage; and 3) the current and future water supply needs identified in the state water plan. To implement the first mandate, the TWDB funded the *Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects* study that was completed in 2020 (Shaw and others, 2020). The TWDB submitted an overview of the statewide survey to the governor, lieutenant governor, and house speaker by December 15, 2020 (TWDB, 2020). The results of this statewide survey in the study area will be discussed later in the report.

The second mandate was for the TWDB to work with appropriate interested persons to conduct studies of ASR and AR projects in the state water plan or identified by others and report the results of these studies to the regional water planning groups and interested persons. To implement the second mandate, a newly formed ASR team with staff appropriations from the Texas Legislature evaluated all ASR and AR recommended water management strategy projects in the 2017 State Water Plan.

2.3 Study selection process

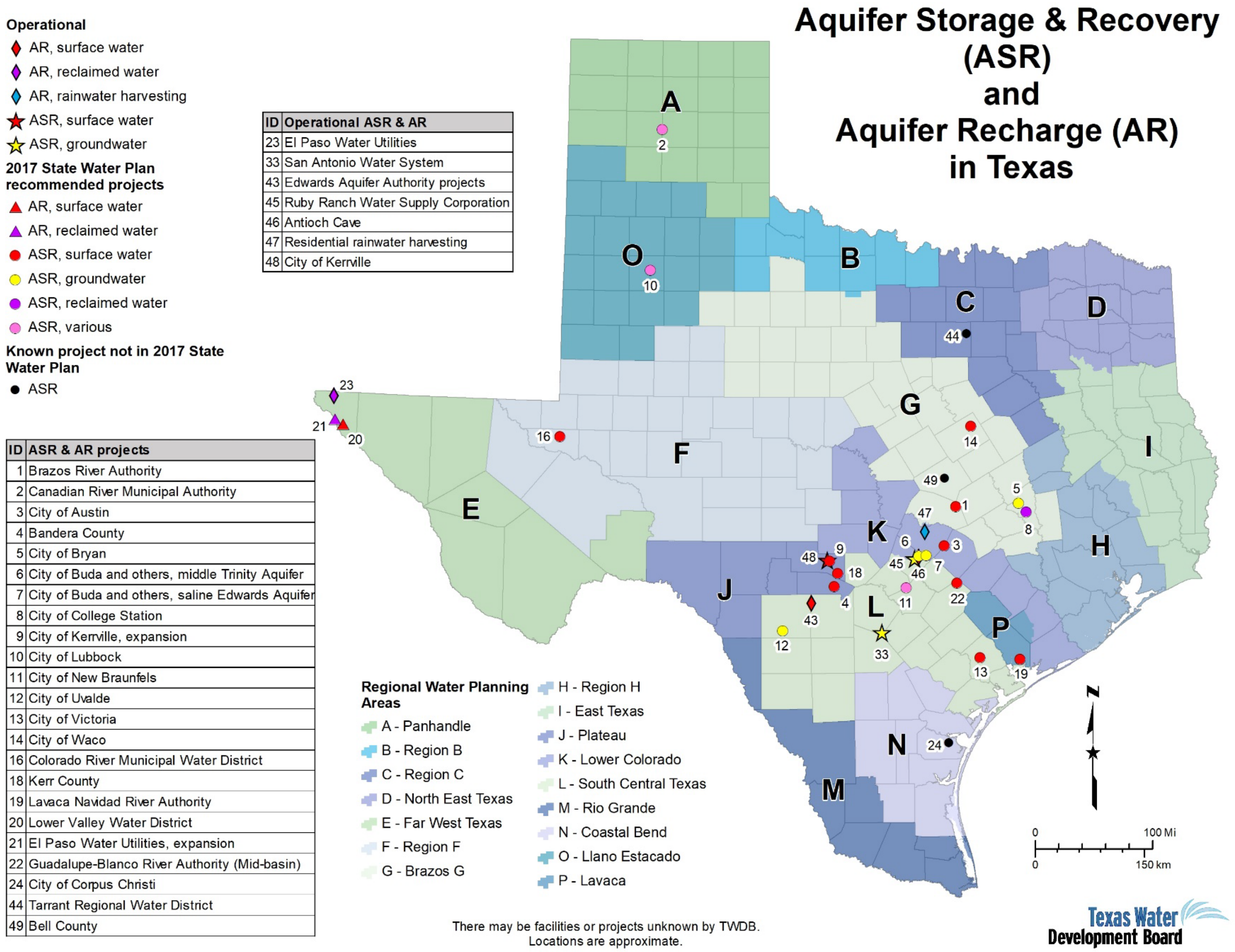
To determine the first studies to initiate and fulfill the second mandate from HB 721, recommended ASR and AR projects from the 2017 State Water Plan were researched. The evaluation of each of the 21 projects included gathering information from the 2017 State Water Plan and draft 2021 regional water plans, calling project sponsors to obtain status of project and interest, and then classifying different components of projects (Figure 2-1). The information gathered for each project was scored according to the following criteria:

1. Sponsor interest: The level of interest a sponsor expressed in having TWDB staff complete a study; a higher score was given to interested sponsors that identified a need for a study by the TWDB. Interest from the project sponsor was the most important criterion since we would not be able to successfully complete a beneficial study that moved a project forward without sponsor support.
2. Matching study type with staff skills and availability: the type of study needed to advance the project had to match the skillset of TWDB staff and the timing of staff being available to complete the study.
3. Source type: The type of water identified for the ASR project's source water (in order of decreasing score): groundwater, surface water, a mix, reuse, or brackish groundwater. In general, higher quality source water is more suitable for an ASR project.
4. Data availability: The relevant data available for the ASR proposed study. Existing data would allow us to quickly get started on and complete the first ASR or AR study per the requirements of HB 721, so a higher score was given to proposed studies that had high quality data readily available to complete them.

5. Planning status: The status of any work or studies related to the ASR project ranged from no studies to a complete facility. A higher score was given to projects with less work completed, because a TWDB study would provide more benefit.
6. Online decade: The decade listed in the regional water plan or state water plan for the water management strategy project. An earlier online decade was given a higher score.

In addition to the listed criteria, each sponsor was contacted to verify and collect the most recent information on the status of their recommended ASR or AR project. The ASR team provided the project sponsor with background on the legislative mandate, the type of studies that could be completed by the team, and the rough timeline in which we were looking to complete the study.

The first study selected to be completed was an aquifer characterization for the ASR component of the GBRA Mid-Basin Water Supply Project. This project had a relatively early planned online date of 2035 and only had a high-level desktop feasibility study completed. There were high-quality data readily available from an existing TWDB study for an aquifer characterization in the proposed study area (Meyer and others 2020). Also, the GBRA had already obtained water rights for the surface water to be injected, making the project more feasible. Most importantly, the GBRA expressed great interest in having an aquifer characterization done by the TWDB. The GBRA specified site selection as its next step and the need to understand the Carrizo-Wilcox Aquifer's ability to store and retrieve injected water as part of the site selection process. Finally, this study was a good match because the TWDB ASR team had the skills and availability to complete the aquifer characterization in the timeframe GBRA needed.



ID	Operational ASR & AR
23	El Paso Water Utilities
33	San Antonio Water System
43	Edwards Aquifer Authority projects
45	Ruby Ranch Water Supply Corporation
46	Antioch Cave
47	Residential rainwater harvesting
48	City of Kerrville

ID	ASR & AR projects
1	Brazos River Authority
2	Canadian River Municipal Authority
3	City of Austin
4	Bandera County
5	City of Bryan
6	City of Buda and others, middle Trinity Aquifer
7	City of Buda and others, saline Edwards Aquifer
8	City of College Station
9	City of Kerrville, expansion
10	City of Lubbock
11	City of New Braunfels
12	City of Uvalde
13	City of Victoria
14	City of Waco
16	Colorado River Municipal Water District
18	Kerr County
19	Lavaca Navidad River Authority
20	Lower Valley Water District
21	El Paso Water Utilities, expansion
22	Guadalupe-Blanco River Authority (Mid-basin)
24	City of Corpus Christi
44	Tarrant Regional Water District
49	Bell County

Figure 2-1. Aquifer storage and recovery and aquifer recharge projects in Texas and their status from the 2017 State Water Plan.

2.4 **Mid-Basin Water Supply Project**

The ASR component (Phase II) of the GBRA Mid-Basin Water Supply Project (referred to as "GBRA ASR project" in this report) plans to inject treated surface water from the Guadalupe River into the Carrizo-Wilcox Aquifer when availability from the river exceeds customer demand and there is available capacity at the new water treatment facility (Black & Veatch and others, 2020). This stored water would then be recovered to meet customer demand when available surface water supplies are low. The use of surface water in an ASR project will allow peak demand to be met without exceeding local groundwater drawdown limits.

The GBRA ASR project is listed as a recommended conjunctive use water management strategy for the South-Central Texas Regional Water Planning Area (Region L) in the 2017 State Water Plan and a recommended aquifer storage and recovery water management strategy in the 2022 State Water Plan (TWDB, 2017; TWDB, 2021d). In the 2016 Region L Water Plan, the project was listed as an alternative conjunctive use water management strategy and was elevated to a recommended strategy via an amendment to the 2017 State Water Plan (SCTRWPG, 2016). The Region L Water Plan estimates the project to produce an additional 27,000 acre-feet of water annually at an annual unit cost of $1,492 per acre-foot (TWDB, 2021d).

Phase I of the GBRA Mid-Basin Water Supply Project is the development of approximately 15,000 acre-feet per year of groundwater supply from the Carrizo Groundwater Supply Project. In addition to a well field, Phase I will also include new transmission pipeline, a pump station, and storage tanks. Phase II includes an ASR well field, new surface water diversion, water treatment plant, transmission pipeline, and pump station (Freese and Nichols and others, 2017; Black & Veatch and others, 2020). After the completion of the aquifer characterization, the next steps for the GBRA ASR project are to coordinate with the Guadalupe River Habitat Conservation Plan, update the previous desktop study, implement a pilot ASR program, and fully design and construct Phase II infrastructure (Perkins, 2020, personal communication). The project is identified in the state water plan to serve multiple wholesale and regional entities along the I-35 corridor. Planning for the project continues to evolve and the GBRA is beginning the process to fully define the customers (Perkins 2022, personal communication).

3. Study

One of the most important aspects of an ASR project is understanding the hydrogeological characteristics of the aquifer to be used to store and recover the excess water supply. While the GBRA had already identified that the Carrizo-Wilcox Aquifer will be used as the storage zone for its ASR project, it is a widespread aquifer that runs border to border in Texas, averages thousands of feet in thickness, and has characteristics that vary vertically and horizontally. The GBRA had honed into a portion of this aquifer in its service area and needed detailed mapping of the storage potential, transmissivity, storativity, recoverability, and water quality within that area to make an informed well field site selection. These hydrogeological characteristics can be interpreted from maps of the changes in depth, thickness, net sands (sand content), and salinity zones (estimated total dissolved solids) in the aquifer and are parameters that we had the data and skillset to produce. Therefore, the goals of this aquifer characterization were to

1. separately map the Wilcox Group and Carrizo Sand portions of the Carrizo-Wilcox Aquifer to provide the GBRA with greater vertical resolution of the aquifer;
2. provide data and maps on the depth, thickness, net sands, and salinity zones interpreted from every publicly available and applicable well log that we could find in the study area; and
3. assemble information on the regional geology needed for the ASR project authorization application.

The results of this aquifer characterization study will aid the GBRA in the selection of 1) the aquifer to store and recover its injected surface water, 2) the location of the ASR wellfield, and 3) the design of the ASR pilot system.

3.1 **Study location**

The aquifer characterization study area covers approximately 568 square miles across eastern Gonzales County and portions of Caldwell and Guadalupe counties (Figure 3-1). The northern portion of the western boundary is the Guadalupe River Watershed. The GBRA chose the study area to be in proximity to its existing infrastructure, including

- a new Guadalupe River intake and water treatment plant that will be located along the Guadalupe River south of the San Marcos River but north of DeWitt County (per water rights permit);
- the new production well field targeting the Carrizo Sand of the Carrizo Groundwater Supply Project; and
- several existing and planned water pipelines.

The study area is entirely within the South-Central Texas (region L) Regional Water Planning Area and within Groundwater Management Area 13. The study area also contains portions of the Gonzales County Underground Water Conservation District, the Plum Creek Conservation District, and the Guadalupe County Groundwater Conservation District (Figure 3-2). The Edwards Aquifer Authority is also located within a portion of the study area; however, its jurisdiction is limited to the significantly deeper Edwards Aquifer, which is not hydraulically connected to the Carrizo-Wilcox Aquifer.

In addition to the areal study area boundaries described above, a vertical (or depth) boundary of 2,000 feet below ground surface (bgs) was also applied (Figure 3-3). This depth was chosen as the maximum economic limit for drilling an injection well within the study area and was established based on feedback from the GBRA. Elevations are measured from mean sea level, which is a relatively constant and flat reference point. However, the reference point for depth measurements is Earth's surface, which is eroded and irregular. When depth is used as a limit and a measurement in geophysical well logs and drillers logs, the correlated surface is affected by changes in surface topography. For the example, the 2,000-foot depth limit is not a flat surface because it parallels the surface topography. This geometry affects all interpreted surfaces that use depth values. The effects of the depth limit can be seen most clearly in formation top maps near the 2,000-foot depth threshold and where the formation thickness pinches out.

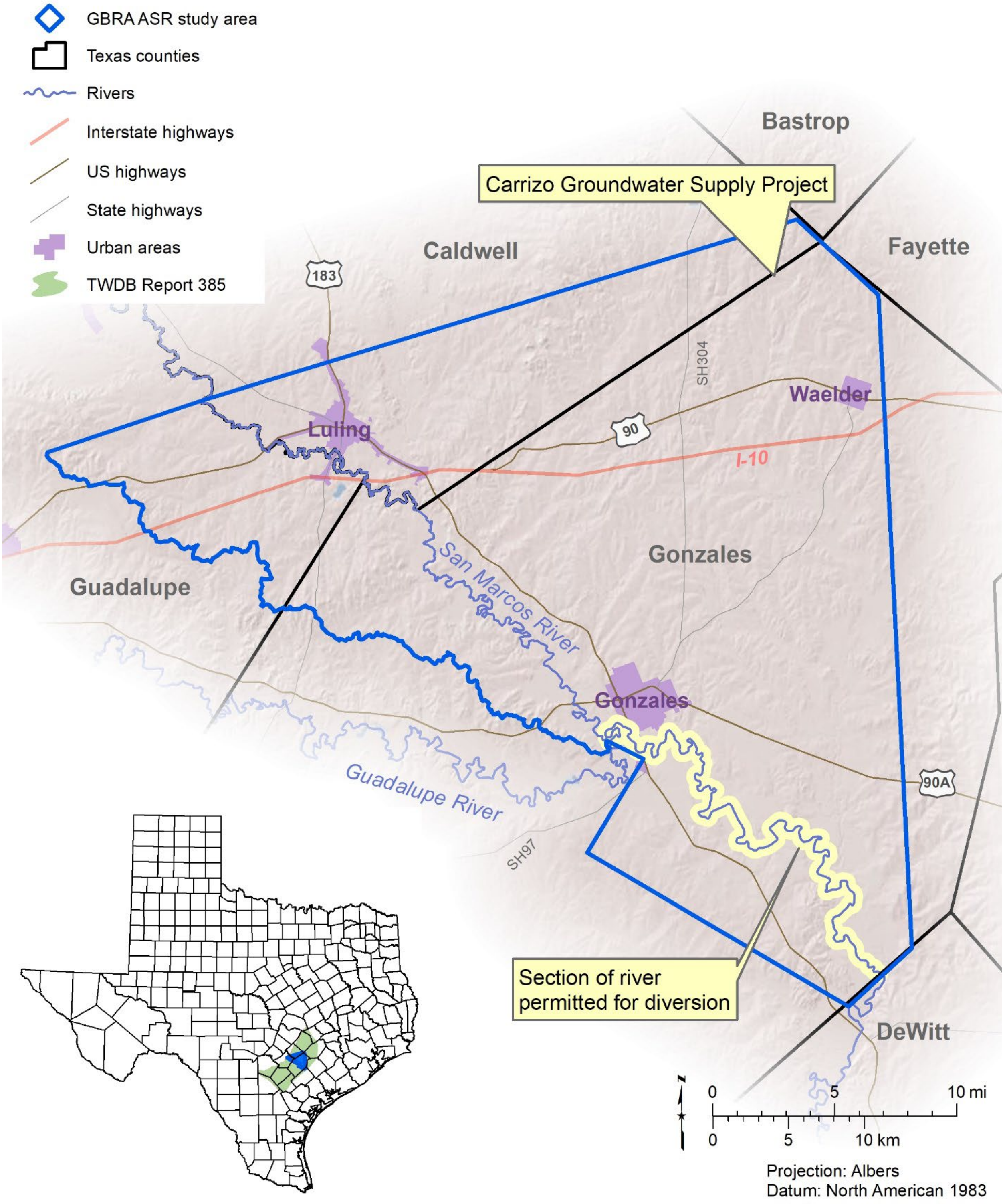


Figure 3-1. **Aquifer characterization study area location map.**

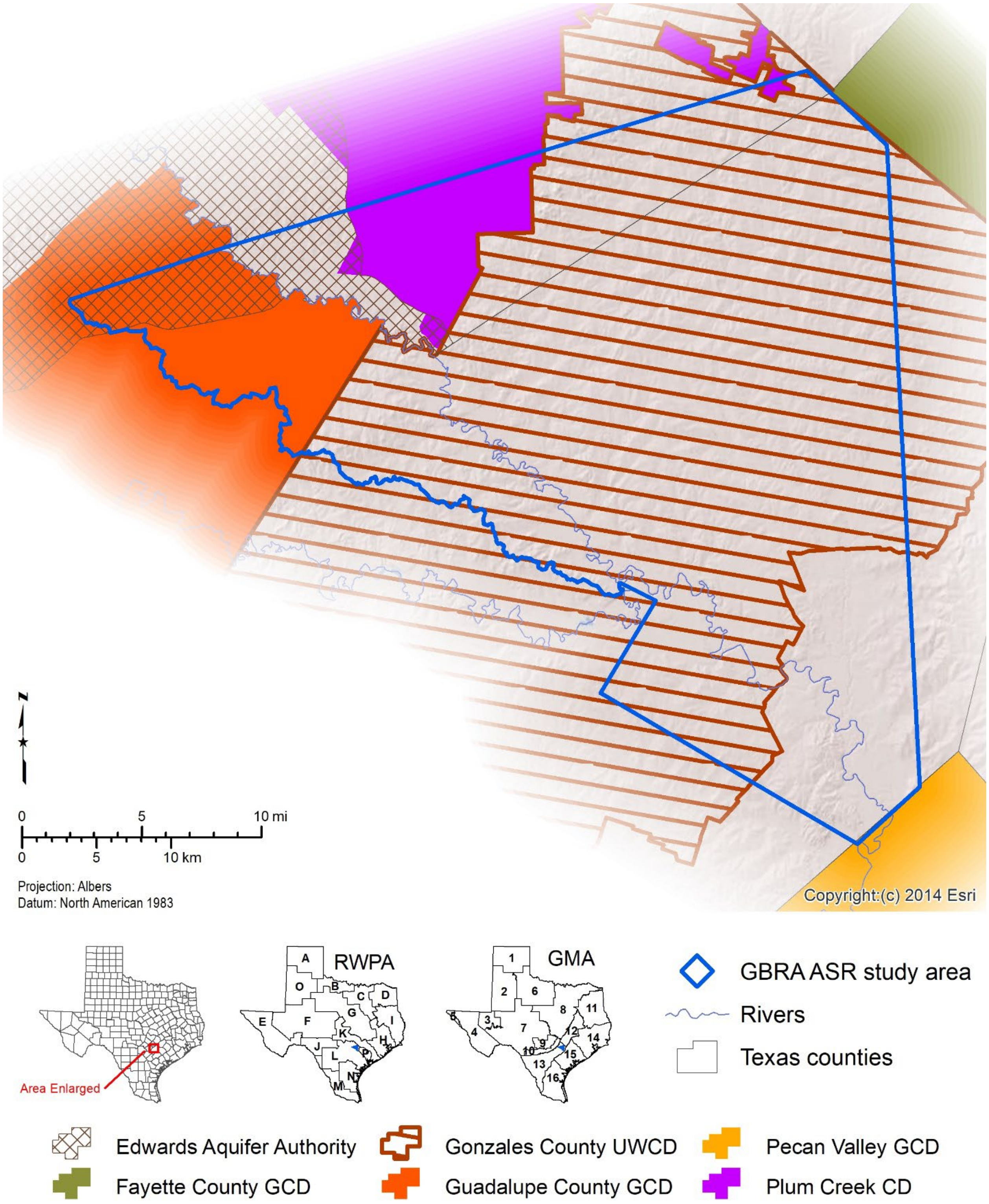


Figure 3-2. **Administrative boundaries map.**

RWPA = regional water planning area
GMA- groundwater management area

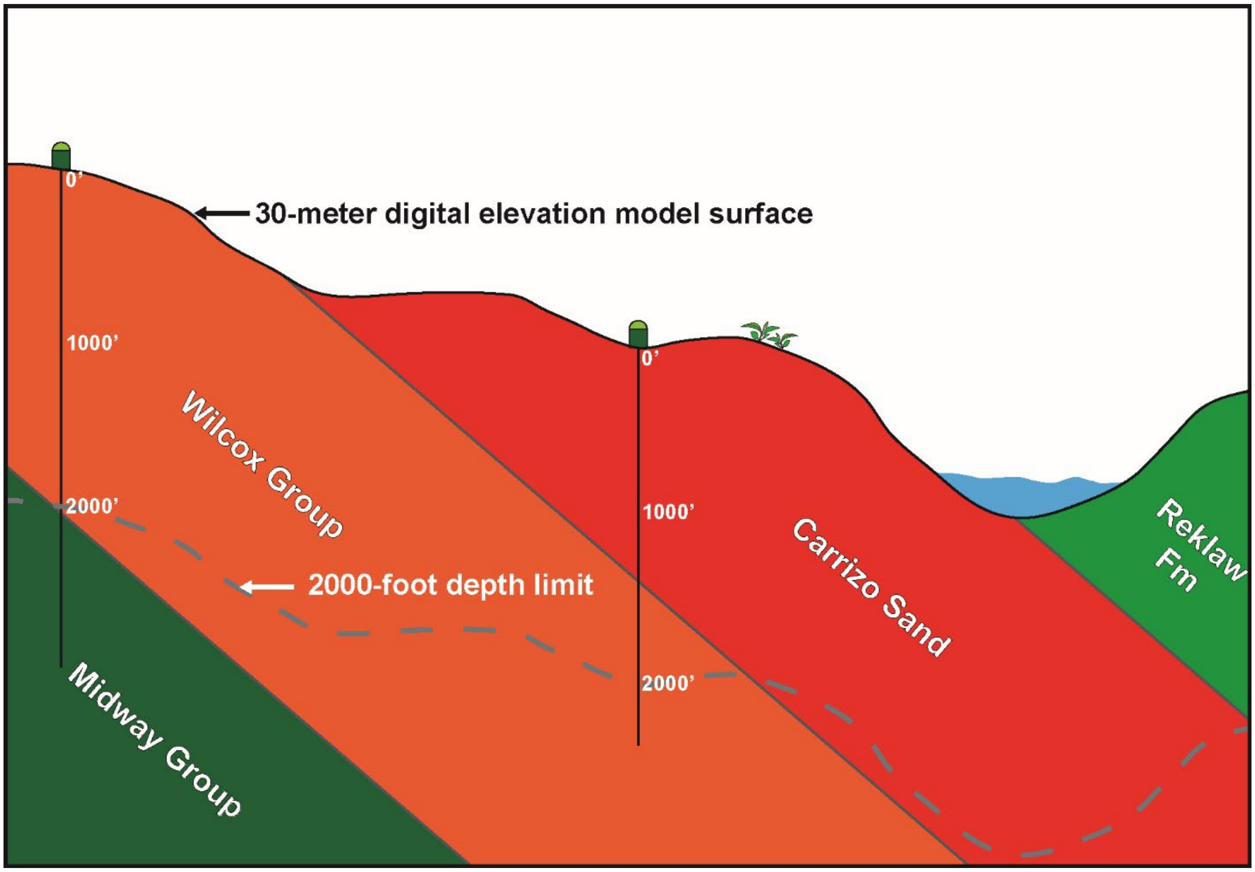


Figure 3-3. **Illustration showing the 2,000-foot depth limitation for the study in profile view. The use of depths for this limit results in a surface that parallels the 30-meter digital elevation model used for surface elevations. Diagram is not to scale and does not represent the extent of the study area.**

3.2 Regional geology

This study focuses on the Carrizo-Wilcox Aquifer, which is part of the Upper Coastal Plains Aquifer System (Ryder, 1996). The Carrizo-Wilcox Aquifer is a major aquifer of Texas that extends from the border of Louisiana southwest to the border of Mexico. The aquifer consists of the Wilcox Group and the Carrizo Sand, which were deposited during the Paleocene and Eocene, 66 to 34 million years ago (Table 3-1). These two geologic units are the result of complex cycles of deposition, compaction, subsidence, erosion, and faulting but some generalizations can be made to establish a fundamental understanding of the aquifers.

Table 3-1. Stratigraphic column showing the epochs, formations, and hydrogeologic units of the Upper Coastal Plains aquifers.

Epoch	Group	Formation	USGS aquifer name	Texas aquifer name	Aquifer system
Eocene	Jackson	Caddell	Vicksburg-Jackson confining unit	Yegua-Jackson Aquifer	Upper Coastal Plains
		Moodys Branch			
		Hiatus			
	Claiborne	Yegua	Upper Claiborne Aquifer		
		Cook Mountain	Middle Claiborne confining unit	Confining unit	
		Hiatus			
		Sparta Sand	Middle Claiborne Aquifer	Sparta Aquifer	
		Weches		Confining unit	
		Hiatus			
		Queen City Sand		Queen City Aquifer	
		Reklaw	Lower Claiborne confining unit	Confining unit	
		Hiatus			
		Carrizo Sand	Lower Claiborne – upper Wilcox Aquifer	**Carrizo-Wilcox Aquifer**	
	Wilcox Group	Hiatus			
		Sabinetown			
		Rockdale			
Paleocene		Seguin	Middle Wilcox Aquifer		
	Midway	Wills Point	Midway confining unit	Confining unit	

Notes: Formation and aquifer names used in this report are in bold text. Yellow represents aquifers and green highlights confining units. The United States Geological Survey (USGS) nomenclature is based on Ryder (1996). Texas hydrogeologic units are based on TWDB (2007a) and George and others (2011). This table does not reflect the entire Jackson or Midway group stratigraphy. This table is not scaled vertically in uniform units of time.

Units within the Upper Coastal Plains Aquifer System, including the Wilcox Group and Carrizo Sand, parallel the Gulf Coast and consist of interbedded gravel, sand, silt, clay, and occasionally lignite (Galloway and others, 2000) (Figure 3-4). These beds dip below the ground surface in wedges that are thinnest near the outcrops and thicken toward the Gulf of Mexico. The depositional environments that deposited these sediments include fluvial, strandplain, marsh and swamp, delta, prodelta, barrier island, lagoon, and open marine (Meyer and others, 2020). Regional geologic structures that overlap with the study area include the Yoakum Canyon, Luling and Karnes Trough Fault Zones, the San Marcos Arch, and the northwest limit of the Louann Salt (Figure 3-5). These structures formed before, during, and after the rock units in the study area and have varying influences on the characteristics of the aquifers.

The Louann Salt was deposited during the Middle Jurassic, 176 to 161 million years ago, and may lie deep below some of the aquifers in the extreme southeast corner of the study area (Ewing, 1991). Salt deposits create an unstable platform that will shift and warp under the weight of overlying sediments. That movement resulted in faults and deformation of the overlying rock units that host the Upper Coastal Plains aquifers.

The fault systems in the study area are the Karnes Trough and Luling fault zones (Ewing, 1991; TWDB, 2007b). Both are extensional faults that strike southwest to northeast that resulted from stresses pulling the rocks apart. The Karnes Trough Fault Zone lies in the southernmost portion of the study area and the Luling Fault Zone is in the westernmost portion of the study area. Offsets of 20 and 305 feet were measured on geophysical logs in Gonzales County in the Karnes Trough Fault Zone (Meyer and others, 2020). No measured offsets from stratigraphic markers were available for the Luling Fault Zone in the study area, but there appears to be an effect on the base and thickness of the Wilcox Group. Because some of the faulting occurred while sediments were still being deposited, they are often buried and difficult to map. The faults are meant to highlight areas of faulting and do not capture all the faults that may exist in the Carrizo-Wilcox Aquifer. A few volcanic features are also aligned with the Luling Fault Zone in the western corner of the study area and probably occurred during the Late Cretaceous and are about 80 million years old (Ewing, 1991).

The San Marcos Arch is a subsurface structural high. The axis of the high trends northwest to southeast between the San Antonio and Guadalupe rivers. This structure began development during the Cretaceous as a topographic high. In general, most overlying formations such as the Eagle Ford Group and the Upper Coastal Plains Aquifer System strata thin as they approach the central axis of the San Marcos Arch, and this feature affects the stratigraphic and lithologic features of the strata on either side of the arch (Ewing, 1991).

The Yoakum Canyon is the structure in the study area with the greatest influence on the sand and clay deposits in the Carrizo-Wilcox Aquifer. The Yoakum Canyon is a prevalent feature in the Middle Wilcox Group and spans over 60 miles from southwest Bastrop County to the Wilcox Growth Fault zone downdip of the paleoshelf margin (Figure 3-6). The Yoakum Canyon is one of several large submarine canyons that were downcut into the Wilcox Group with a maximum width of over 10 miles and a total thickness of over 3,500 feet (Chuber and Begeman, 1982; Dingus, 1987). There are several competing hypotheses to outline the development of the Yoakum Canyon within the primarily progradational Wilcox Group (e.g., Winkler, 1982; Chuber and Begeman, 1982; Dingus, 1987; Olariu and Ambrose, 2016). The creation of the canyon is generally considered to be caused by slumping along the Gulf Coast margin causing a transgressional sequence (Galloway, 1989; Olariu and Ambrose, 2016). This downcutting event occurred as the Rockdale Delta System continued to deposit thick sediments along the paleoshelf margin. More recent studies show that tectonic uplift influenced the location of these large canyons along the Gulf Coast (Olariu and Ambrose, 2016; Clayton, 2017). The lithology within the canyon is primarily shale but does contain some isolated units of sand in the upper portions of the group.

The presence of the Yoakum Canyon also affected the thickness and lithology of the overlying Carrizo Sand. The Carrizo Sand units that overlie the Yoakum Canyon are thicker than the surrounding strata. The added thickness was likely caused by increased accommodation space created above the Yoakum Canyon deposits due to compaction of the clay and silt layers (Galloway, 1989). This accommodation likely occurred at the same time as deposition of the Carrizo Sand and created a surface low where more material could be deposited.

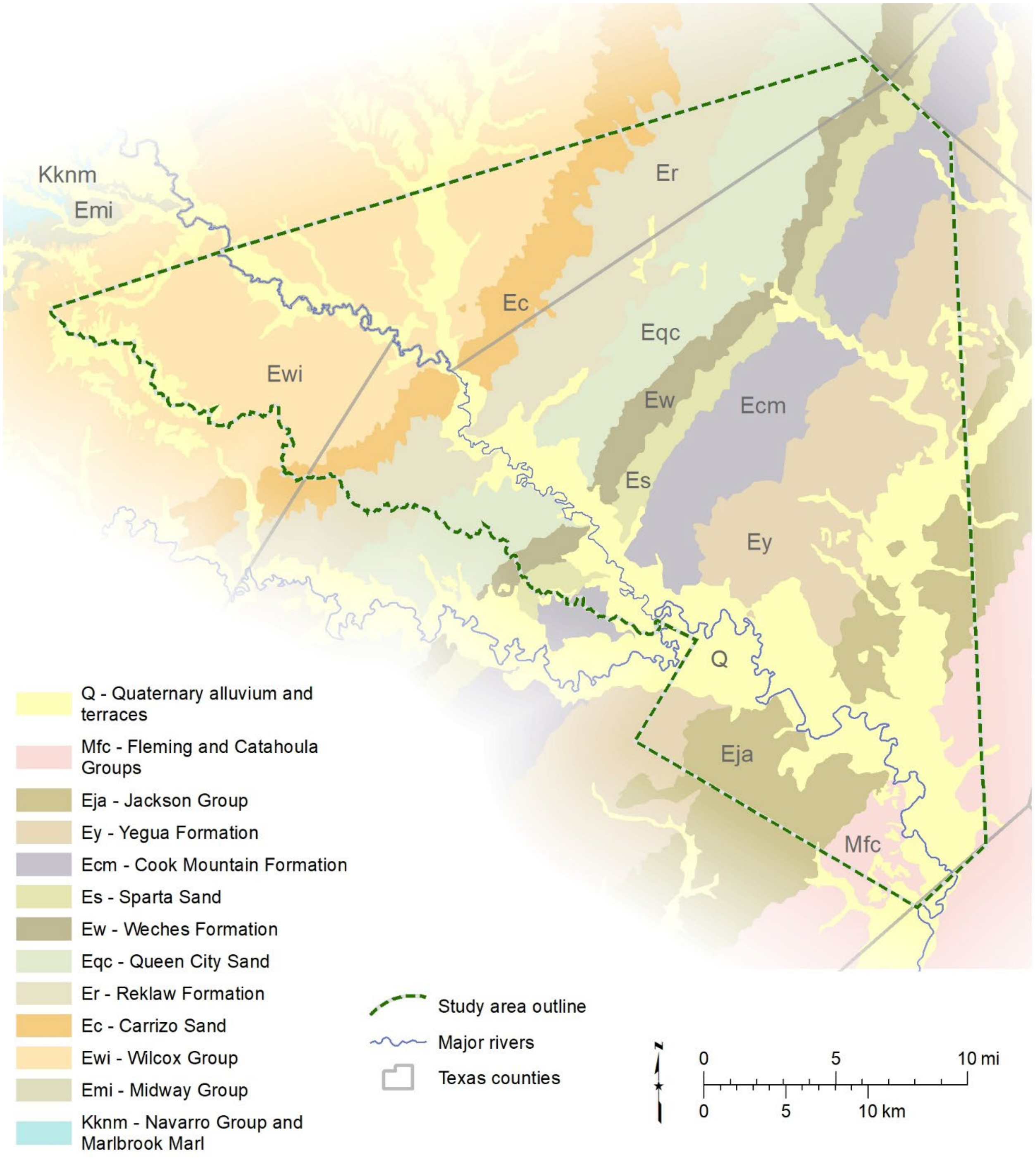


Figure 3-4. **Surface geologic map for the study area with features from digital Geologic Atlas of Texas (TWDB, 2007b).**

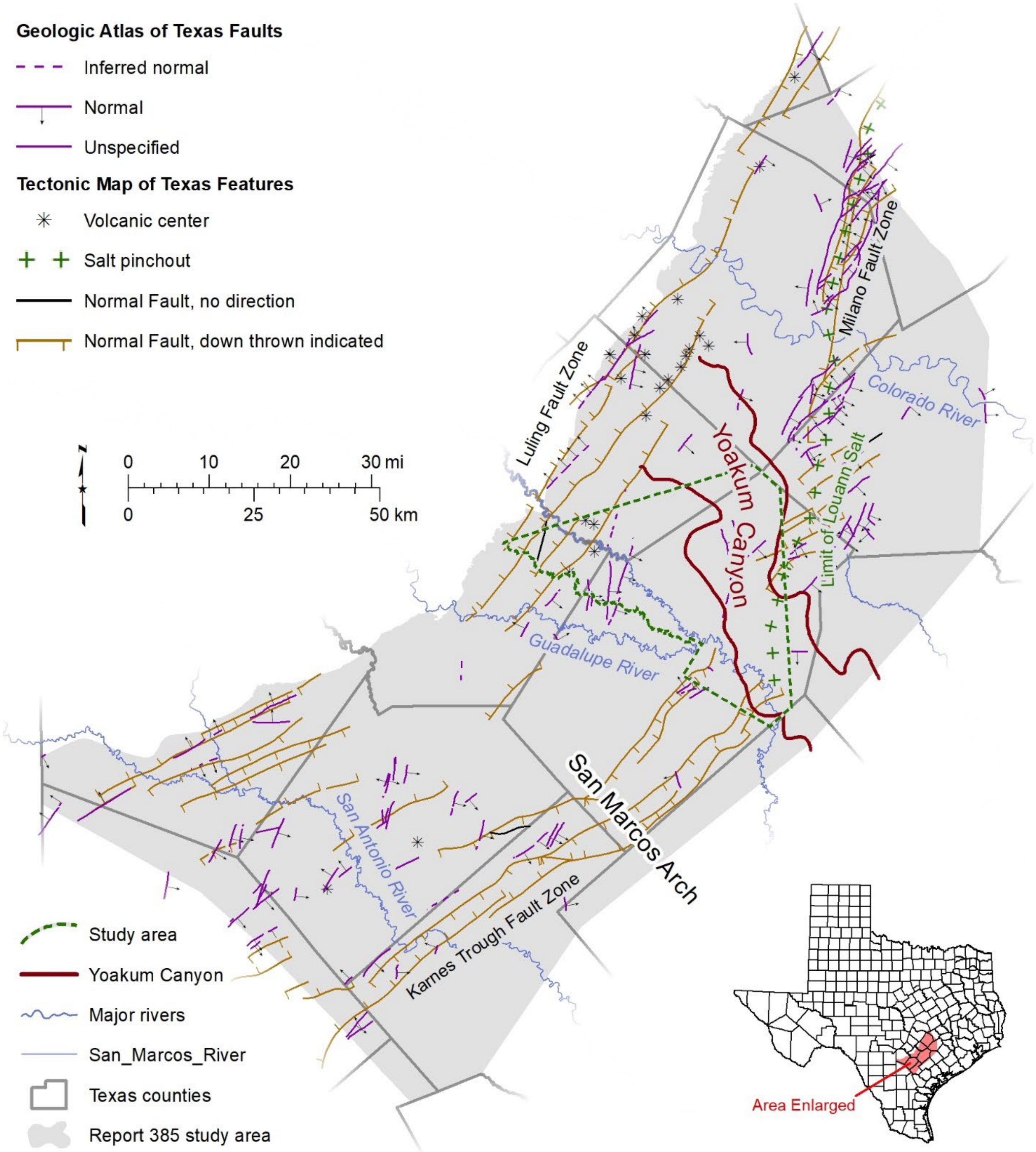


Figure 3-5. Regional geologic structure map showing the extent of the Yoakum Canyon based on Meyer and others (2020), faults from the digital Geologic Atlas of Texas (TWDB, 2007b), and faults and other structural features from the Tectonic Map of Texas (Ewing, 1991; Breton, 2013).

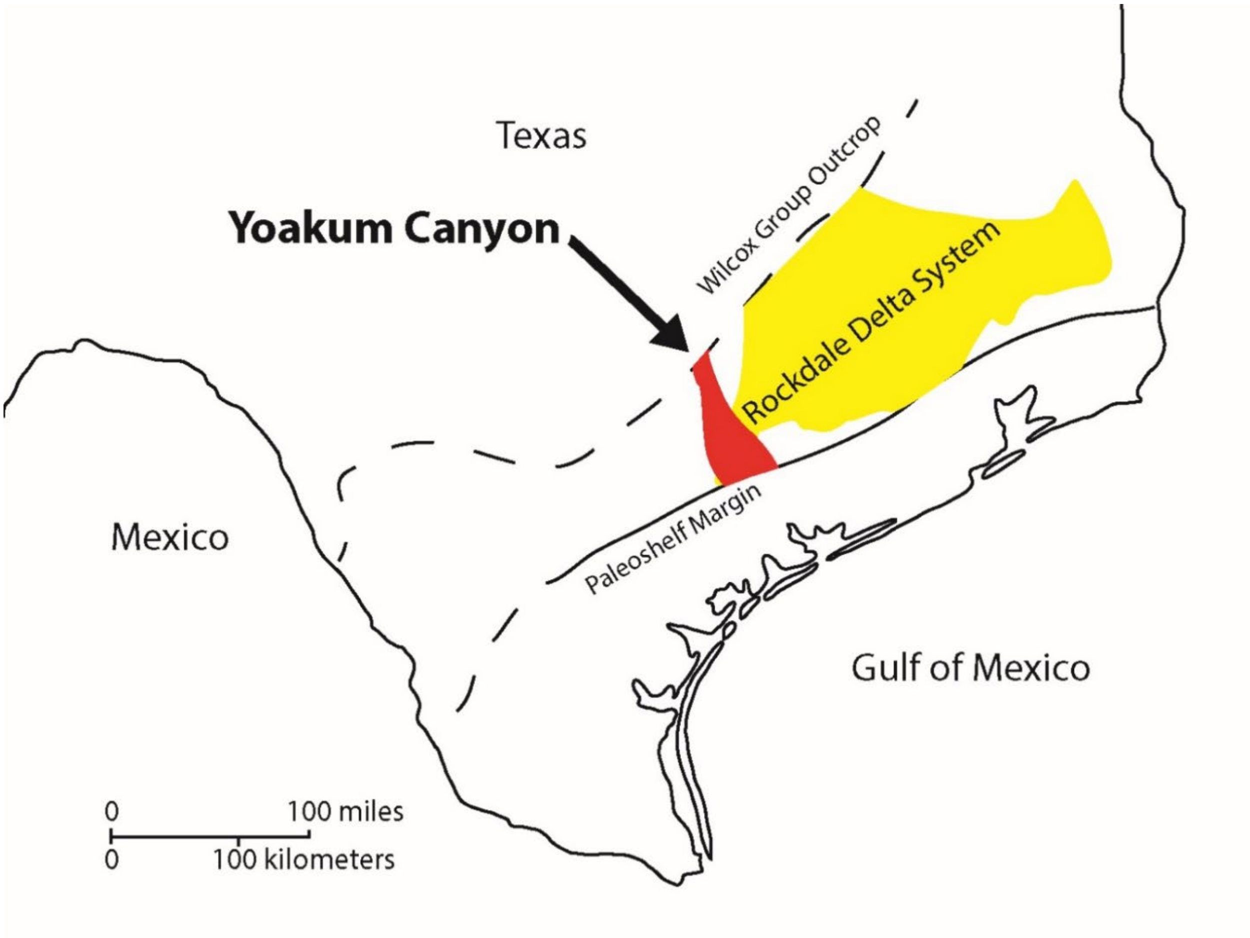


Figure 3-6. **Location of the Yoakum Canyon within Texas. Modified from Galloway and others (1991).**

4. Methodology

This study utilized data mined from public well records, databases, and maps to interpret the stratigraphy, lithology, and salinity classes in the study area for a total of 662 wells. Sources of public well data included

- TWDB Brackish Resources Aquifer Characterization System (BRACS) Database (TWDB, 2021a);
- TWDB Groundwater Database (TWDB, 2021b);
- Texas Department of Licensing and Regulation State Driller Reports Database (TWDB, 2021c);
- Railroad Commission of Texas Groundwater Advisory Unit Q-log geophysical well log collection (Railroad Commission of Texas, 2020a); and
- Railroad Commission of Texas Wellbore Database (Railroad Commission of Texas, 2020b).

Some wells had all the information needed for stratigraphic, lithologic, and salinity analysis. Others only had adequate information for one or two of these analyses. Of the 662 wells used for this aquifer characterization, 583 were used for stratigraphic mapping (including 119 that were imported and used outside of the study area to reduce edge effects of interpolation of surfaces), 328 wells were used in the lithologic mapping, and 271 wells were used for the salinity class mapping (including 20 wells from outside of the study area that were used as high salinity samples). Analyses were a combination of new interpretations and updates on a number of wells previously used in TWDB studies, such as Meyer and others (2020). All well record data, analytical methods, interpretations, and results are summarized in this report, provided in Appendix A – Detailed Methodology (see Section 11), Appendix B – Geographic Information System (GIS) files (see Section 12), and stored as tables in the Appendix C – BRACS Database (see Section 13).

To map the stratigraphic extent of the Wilcox Group and Carrizo Sand within the study area, top and bottom depths of the units were interpreted from geophysical well logs and driller's reports. In addition, stratigraphic depth interpretations from Meyer and others (2020) were reviewed and refined as necessary. These stratigraphic depth interpretations were converted to elevations and then interpolated in ArcGIS to create raster surface models for the top and bottoms of both formations. These stratigraphic surfaces were used to assign lithologic interpretations, water quality samples, and total dissolved solids (TDS) calculations to either the Carrizo Sand or the Wilcox Group.

Lithology within the study area was interpreted using both geophysical well logs and drillers' logs. It was described using a four-tier nomenclature system used in Meyer and others (2020). These four tiers are defined as sand (100 percent sand), sand with clay (65 percent sand), clay with sand (35 percent sand), and clay (0 percent sand). Net sand values at well locations were interpolated in ArcGIS to create maps for the Wilcox Group to a depth of 2,000 feet bgs, the Carrizo Sand to a depth of 2,000 feet bgs, and the total thickness of the Carrizo Sand.

Salinity class maps for the Wilcox Group and Carrizo Sand were created using both measured and calculated TDS values. Charge balance calculations were used to review measured TDS values from water sample data. Where measured water quality samples were not available for either the Wilcox Group or Carrizo Sand, TDS values were calculated using the relationships between groundwater TDS, specific conductance, and the measured resistivity of fluid filled rocks. These calculated TDS values make up the majority of TDS values in the study area for both formations. A salinity class was assigned to the formation based on the calculated TDS values. In cases where a formation had more than one salinity class, multiple intervals within the formation were assigned their corresponding salinity class. Cutoffs for the salinity classes are listed in Table 4-1.

Table 4-1. Groundwater salinity classification (Winslow and Kister, 1956).

Salinity class	Total dissolved solids concentration (mg/l)
Fresh	0 to 1,000
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	Greater than 35,000

5. Results

For this aquifer characterization study, we divided the Carrizo-Wilcox Aquifer into two stratigraphic units, the Wilcox Group and the Carrizo Sand. The following aquifer characterization results include maps for the stratigraphy, lithology, and salinity classes for both the Wilcox Group and Carrizo Sand. The stratigraphy results provide the depths that would need to be drilled to access the aquifers, the lithology results provide the cumulative intervals of sand that would be available for screened well sections, and the salinity class results provide the general water quality of the aquifer in the study area to guide decisions on well construction and operation considerations.

5.1 Stratigraphy results

The Wilcox Group and Carrizo Sand have distinct geophysical log responses that were used to correlate the elevation of contacts between the

1. bottom of the Wilcox Group with the top of the Midway Group,
2. bottom of the Carrizo Sand with the top of the Wilcox Group, and
3. bottom of the Reklaw Formation with the top of the Carrizo Sand.

In addition to the elevation picks from geophysical well logs, outcrop elevation points and guide points were used to create the contact elevation maps. The outcrop elevation points were created along the downdip boundary of the Midway Group, Wilcox Group, and Carrizo Sand outcrops and were assigned values from the ground surface 30-meter digital elevation model (DEM). We used these points to bring the interpolated elevation values from the subsurface to the outcrop. Guide points were created to help guide the surface interpolations to better reflect best professional judgement where no well control was available. The resulting correlated elevation maps were then used to map the depth and thickness of the Carrizo-Wilcox Aquifer in the study. Results for both units of the aquifer follow.

5.1.1 Wilcox Group

The Wilcox Group is the lowermost unit this study examines. Like in Meyer and others (2020), this study characterizes the group as a single undifferentiated unit. As noted in Section 3.2, the units were only characterized to a depth of 2,000 feet bgs.

Top of the Wilcox Group

The Wilcox Group underlies the Carrizo Sand so there is a shared surface between the top of the Wilcox Group and the bottom of the Carrizo Sand. The Meyer and others (2020) study originally had 81 picks for this contact. This study added 69 more for a total of 150 elevation points for the top of the Wilcox Group. In addition to the 150 elevation picks from geophysical well logs, 53 outcrop elevation points, and 4 guide points were used to map the Wilcox Group top elevation.

The top of the Wilcox Group is an unconformity commonly interpreted to have been caused by tectonic uplift, which lead to changes in drainage patterns along the Gulf Coast (Meyer and others, 2020; Ambrose and others 2020). The top of the Wilcox Group was identified in geophysical well logs by the presence of a regional shale that is prevalent in the eastern half of the study area (Figure 5-1). The contact can also be identified by the change in sandstone character between the Wilcox Group and Carrizo Sand (see Section 5.2).

The top of the Wilcox Group covers the entire extent of the study area (Figure 5-2). The outcrop, or where the top of the Wilcox Group is exposed and eroded at the surface, is in the northwest corner. Elevations for the top of the Wilcox Group range from 658 feet above mean sea level to 5,182 feet below mean sea level. The contact between the bottom of the Carrizo Sand and the top of the Wilcox Group decreases in elevation to the southeast towards the Gulf Coast. Therefore, the lowest elevation for this contact is in the very southeast corner of the study area and the highest elevations are in the outcrop in the northwest corner. Lines of parallel elevation run from southwest to northeast.

The depth map for the top of the Wilcox Group was created by subtracting the Wilcox Group top elevation from the elevation of Earth’s surface (the DEM) (Figure 5-3). Depth of the contact between the Carrizo Sand and the Wilcox Group ranges from 0 to 5,517 feet in the study area. It has the same general extent and geometry as the elevation map but with the more detailed texture of the eroded ground surface embossed on it. Looking at the 2,000-foot limit for the top of the Wilcox Group, we see it trends southwest to northeast, just a bit past halfway from the outcrop to the southeast limit of the study area. The extent of the Wilcox Group top that is less than 2,000 feet deep makes up 362 square miles, or 64 percent of the study area.

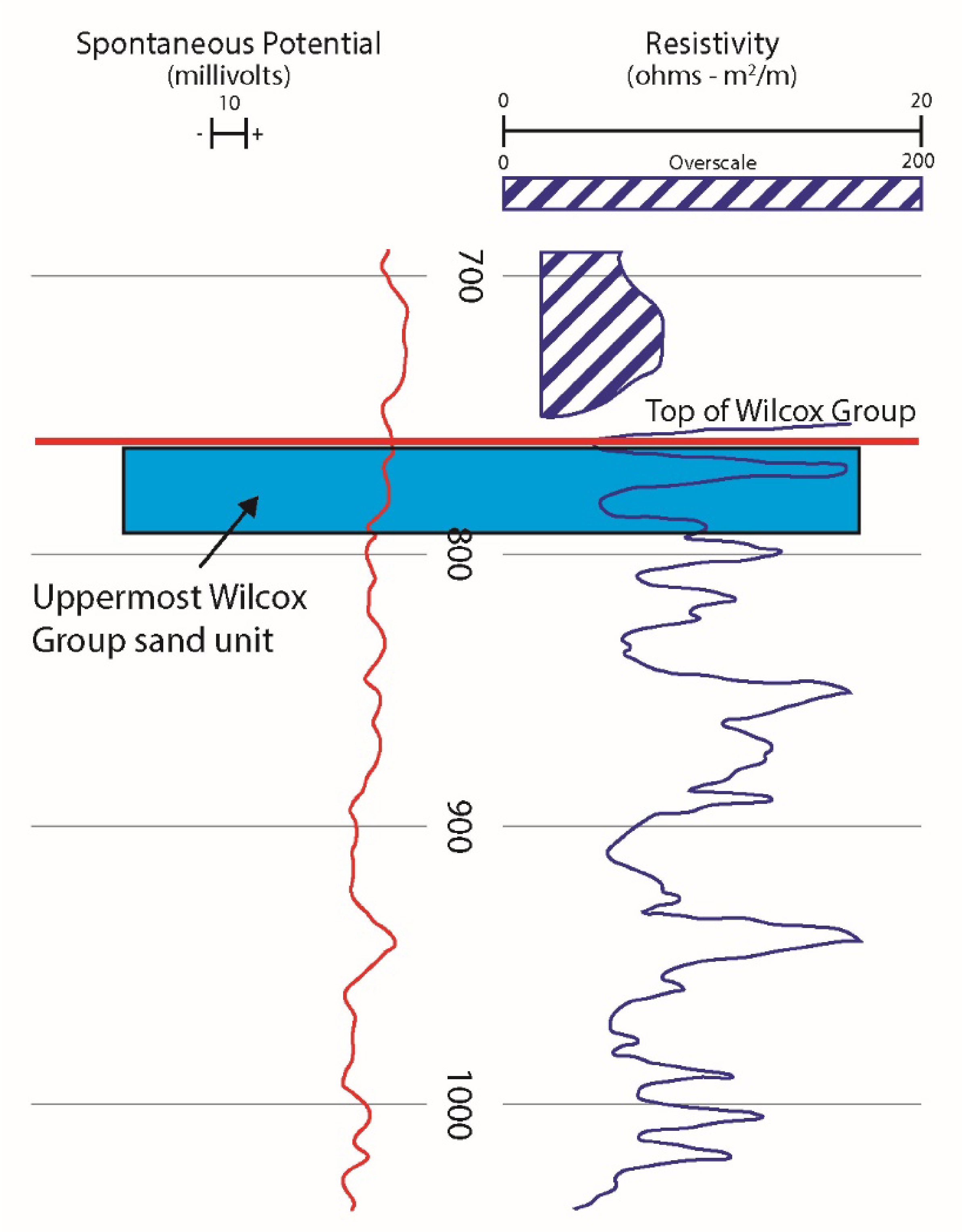


Figure 5-1. Illustration of the spontaneous potential and resistivity curve signatures used to select the top of the Wilcox Group for BRACS Database Well ID 15281 (Gonzales County).

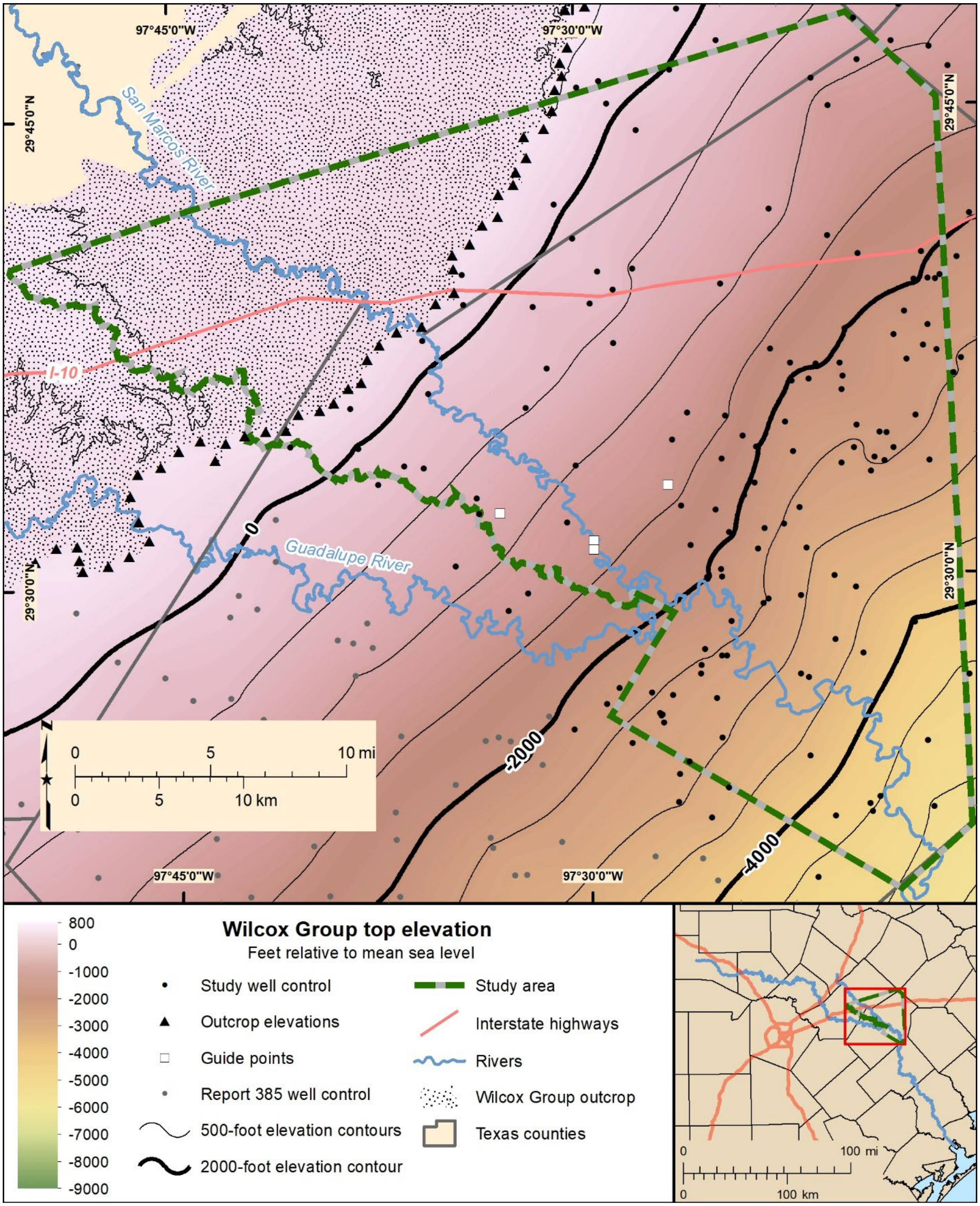


Figure 5-2. **Wilcox Group top elevation surface (feet relative to mean sea level).**

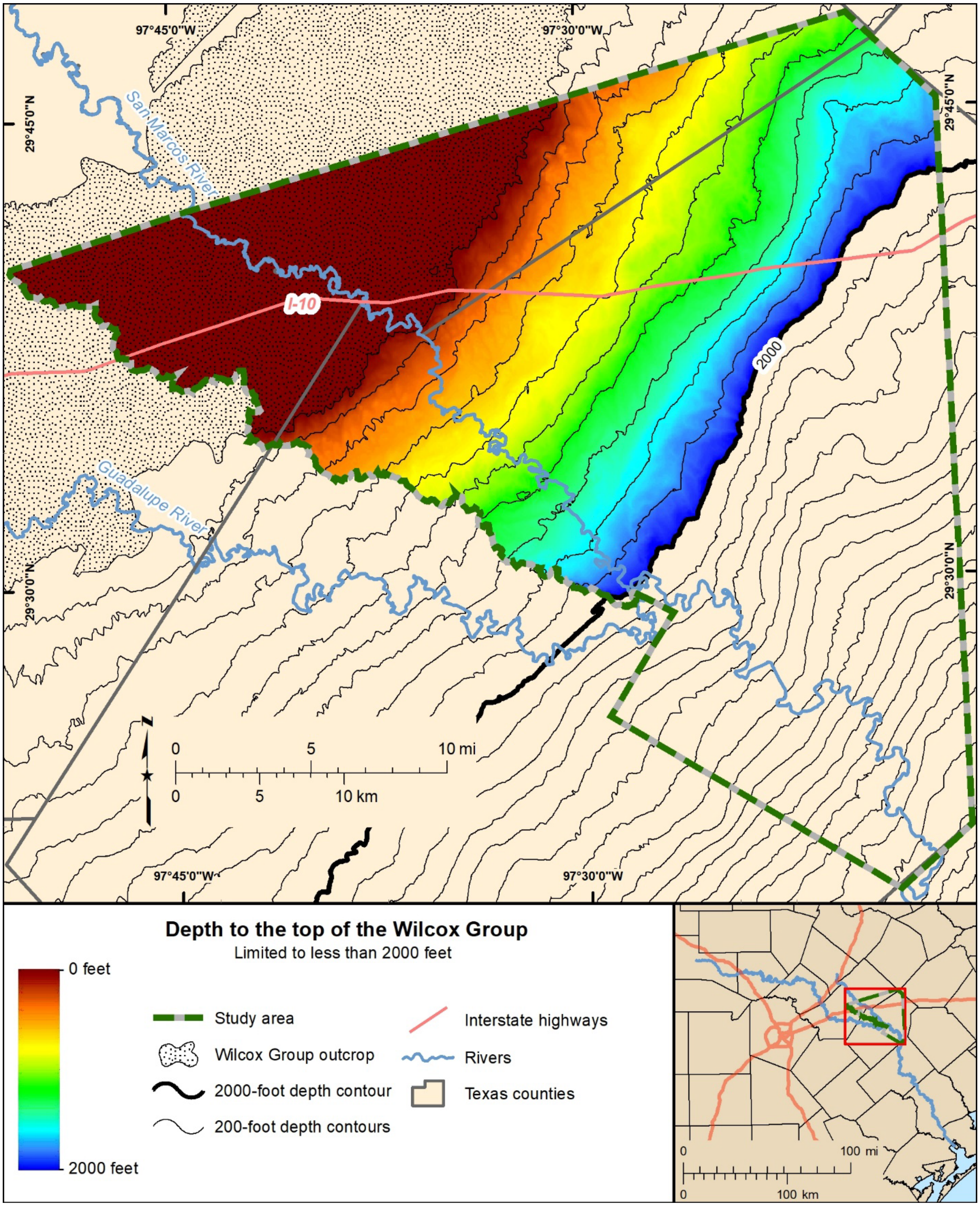


Figure 5-3. Wilcox Group top depth in feet. The map is limited to an area where the top of the Wilcox Group is less than 2,000 feet below the ground surface.

Bottom of the Wilcox Group

The bottom of the Wilcox Group overlies the Midway Group. The Meyer and others (2020) study had 110 picks for this contact. This study added 284 more for a total of 394 elevation points for the bottom of the Wilcox Group. In addition to the 394 elevation picks from geophysical well logs, 127 outcrop elevation points and 6 guide points were used to map the Wilcox Group bottom elevation.

The bottom of the Wilcox Group is a gradational contact within the study area and can be challenging to identify on geophysical well logs (Meyer and others, 2020). The contact between the Midway Group to the Wilcox Group is interpreted to represent a transition from a deeper inner-shelf environment to shallower coast-plain environment (Ambrose and others, 2020). Identification of this surface was done with best professional judgement, particularly in areas where faulting is present (Figure 5-4).

The bottom of the Wilcox Group is found throughout the study area (Figure 5-5). The elevation ranges from 392 to -7,853 feet, relative to mean sea level. The contact between the Wilcox Group and Midway Group is at its highest in the outcrop of the Wilcox Group in the western corner of the study area. The contact is at its lowest in the southeast corner of the study area. As with the top of the formation, lines of parallel elevation run southwest to northeast.

The depth map for the top of the Wilcox Group was created by subtracting the Wilcox Group bottom elevation from the ground surface elevation (DEM). The contact between the Wilcox Group and the Midway Group ranges in depth from 121 to 8,167 feet below the ground surface. To limit the formation to both the areal and vertical limit of the study area, it was clipped to the footprint of the 2,000-foot limit of the top of the Wilcox Group and then cut off at a depth of 2,000 feet (Figure 5-6). Above the 2,000-foot cutoff, the Wilcox Group bottom depth map reflects the same geometry as the bottom elevation but with the added details of the ground surface topography.

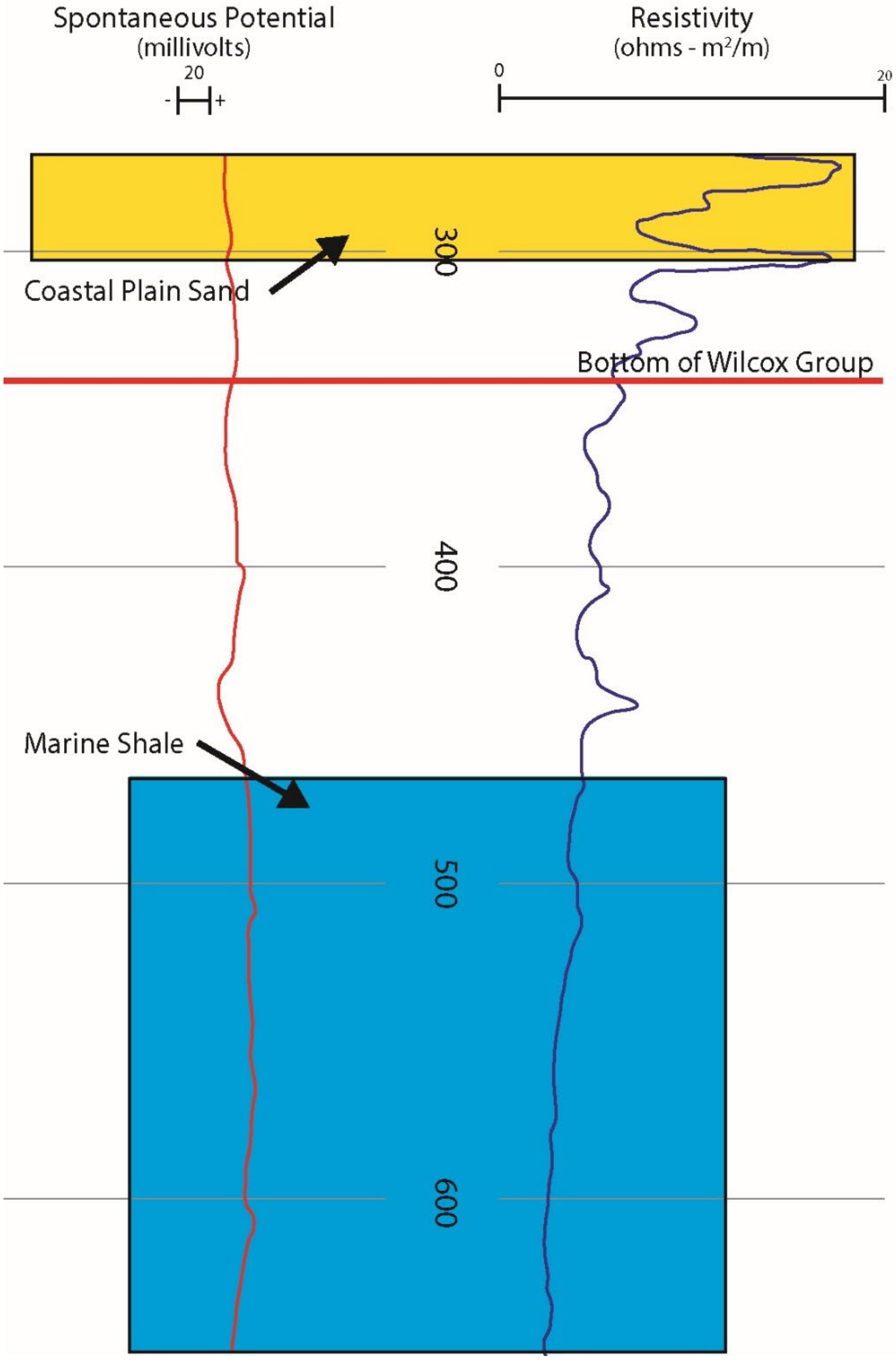


Figure 5-4. Illustration of the spontaneous potential and resistivity curve signatures used to select the bottom of the Wilcox Group for BRACS Database Well ID 19318 (Guadalupe County).

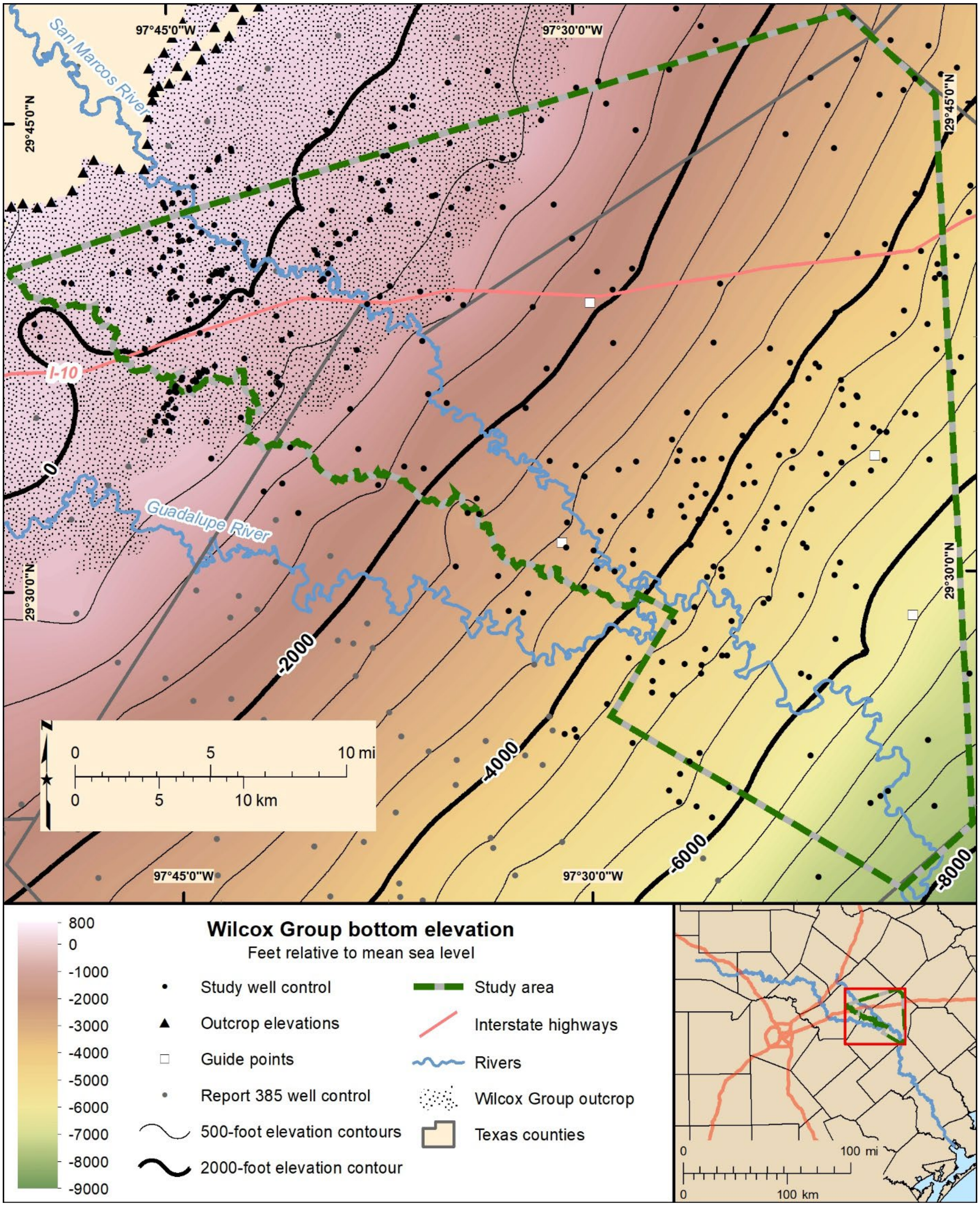


Figure 5-5. Wilcox Group bottom elevation surface (feet relative to mean sea level).

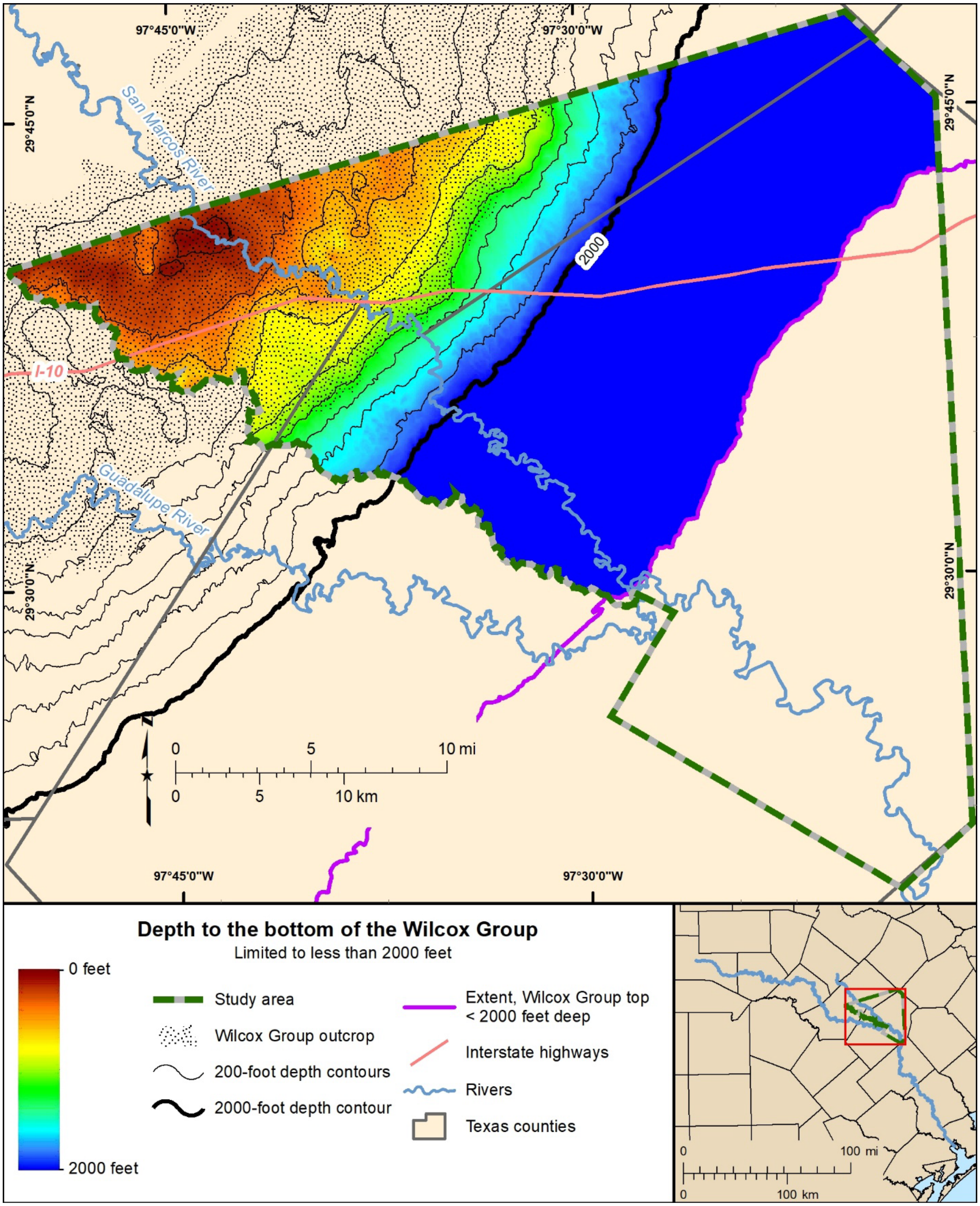


Figure 5-6. **Wilcox Group bottom depth in feet. The map is limited to an area where the top of the Wilcox Group is less than 2,000 feet below the ground surface.**

Thickness of Wilcox Group

The thickness of the Wilcox Group was calculated by subtracting the Wilcox Group bottom elevation from the Wilcox Group top elevation. The thickness of the entire Wilcox in the entire study area increases in depth and thickness toward the Gulf of Mexico, ranging from 121 to 2,990 feet thick. When limited to less than 2,000 feet deep in the study area, the thickness maxes out at 1,528 feet thick (Figure 5-7). Limiting the formation to 2,000 feet deep or less essentially creates a pinch out in the subsurface, giving the thickness of the formation a symmetrical geometry. It is thickest in a middle band running southwest to northeast and thins both toward the outcrop to the northwest and the subcrop to the southeast.

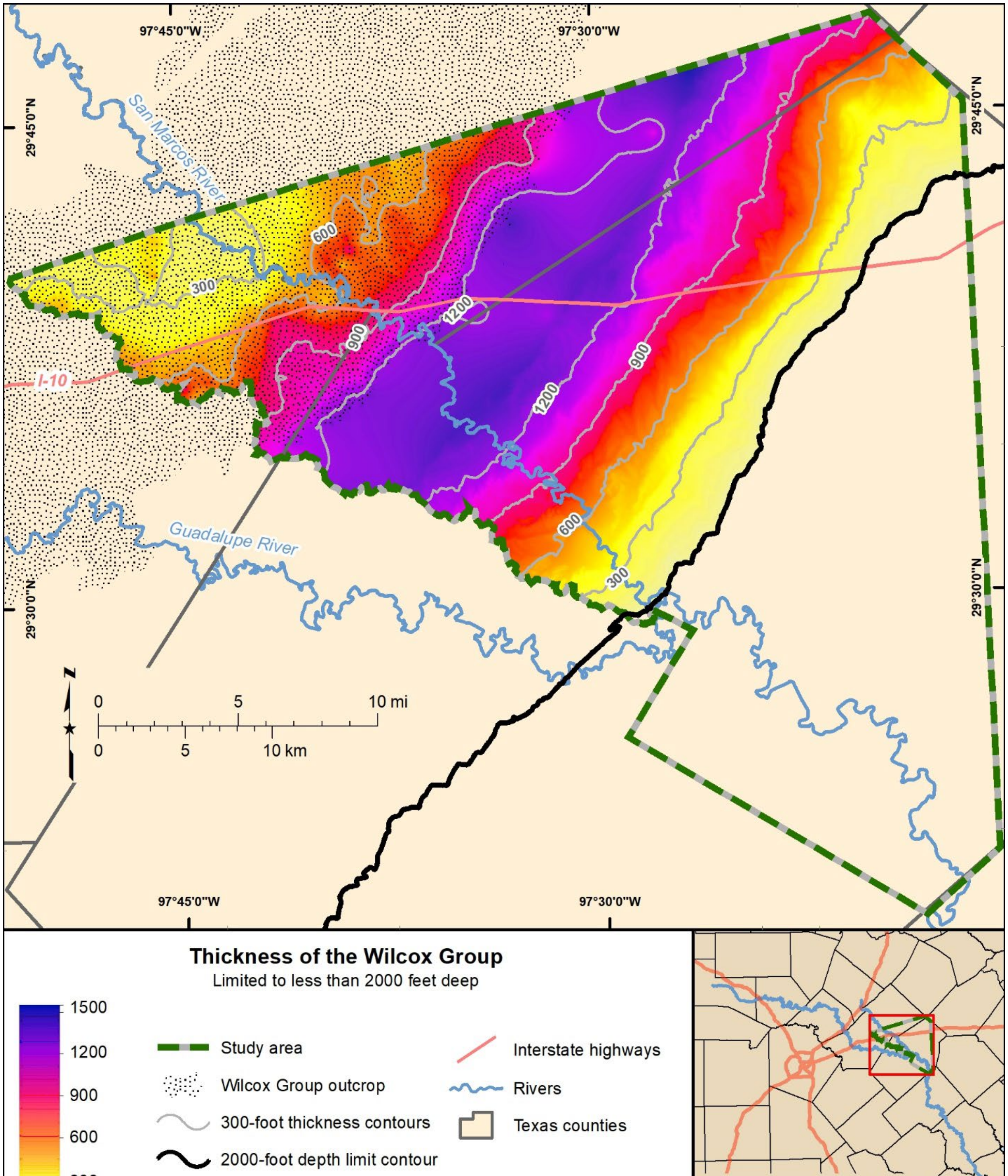


Figure 5-7. **Wilcox Group thickness in units of feet. The map is limited to an area where the top of the Wilcox Group is less than 2,000 feet below the ground surface.**

5.1.2 Carrizo Sand

The Carrizo Sand is the uppermost unit this report examines. The Carrizo Sand is often considered to be the lowermost unit of the Claiborne Group, but some authors may also consider it to be a separate formation.

Top of the Carrizo Sand

To create the Carrizo Sand top elevation map, 75 stratigraphic picks from Meyer and others (2020), and 70 stratigraphic picks added during this study were used (145 picks total). Additional 66 stratigraphic elevation points in from outside of the study area buffer were used to help eliminate GIS raster edge effects. In addition to the stratigraphic elevation points, 10 guide points and 82 outcrop elevation points were also used.

The top of the Carrizo Sand was placed at the top of the uppermost distinct high-resistivity massive sand interval (Figure 5-8). This surface represents a marine transgression, and the Carrizo Sand is distinct from the shale-dominated overlying Reklaw formation (Meyer and others, 2020; Ambrose and others, 2020) The base of the Reklaw formation commonly contains some sands that where reworked during this transgression, but commonly have much higher clay content and therefore lower resistivity valuers (Meyer and others, 2020).

The elevation of the Carrizo Sand top ranges from 670 feet above mean sea level in the outcrop area to 4,254 feet below mean sea level in the farthest downdip corner (southeast) of the study area (Figure 5-9). The Carrizo Sand top depth map was created by subtracting the elevation raster from the study area DEM (Figure 5-10). In the study area, the depth to the top of the Carrizo ranges from 0 feet, where the formation outcrops, to 4,547 feet in the farthest downdip corner of the study area. The top of the Carrizo reaches a depth of 2,000 feet approximately 15 miles downdip of the outcrop. In approximately 57 percent of the study area (324 square miles), the top of the Carrizo is less than 2,000 feet deep.

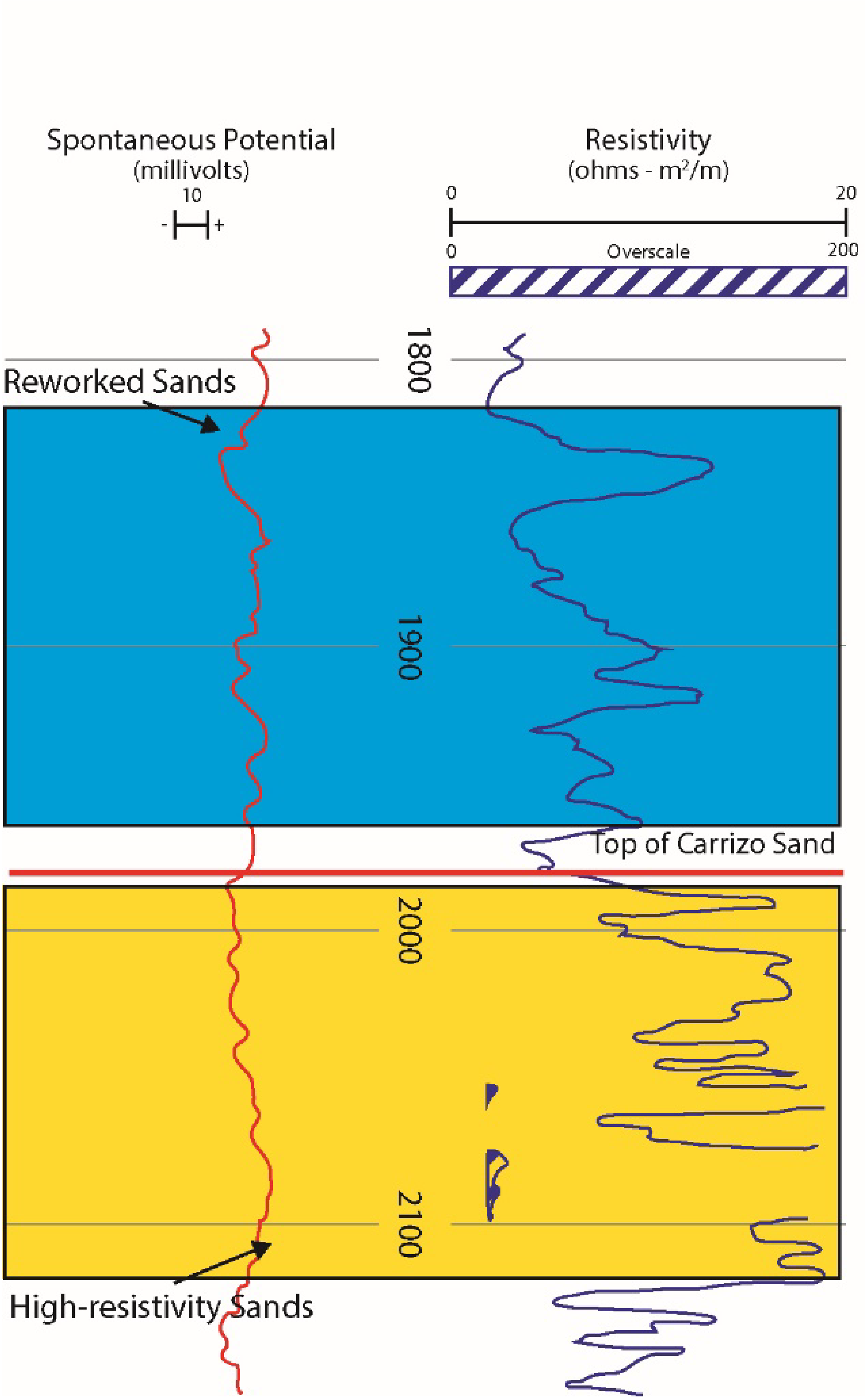


Figure 5-8. **Illustration of the spontaneous potential and resistivity curve signatures used to select the top of the Carrizo Sand for BRACS Database Well ID 15383 (Gonzales County).**

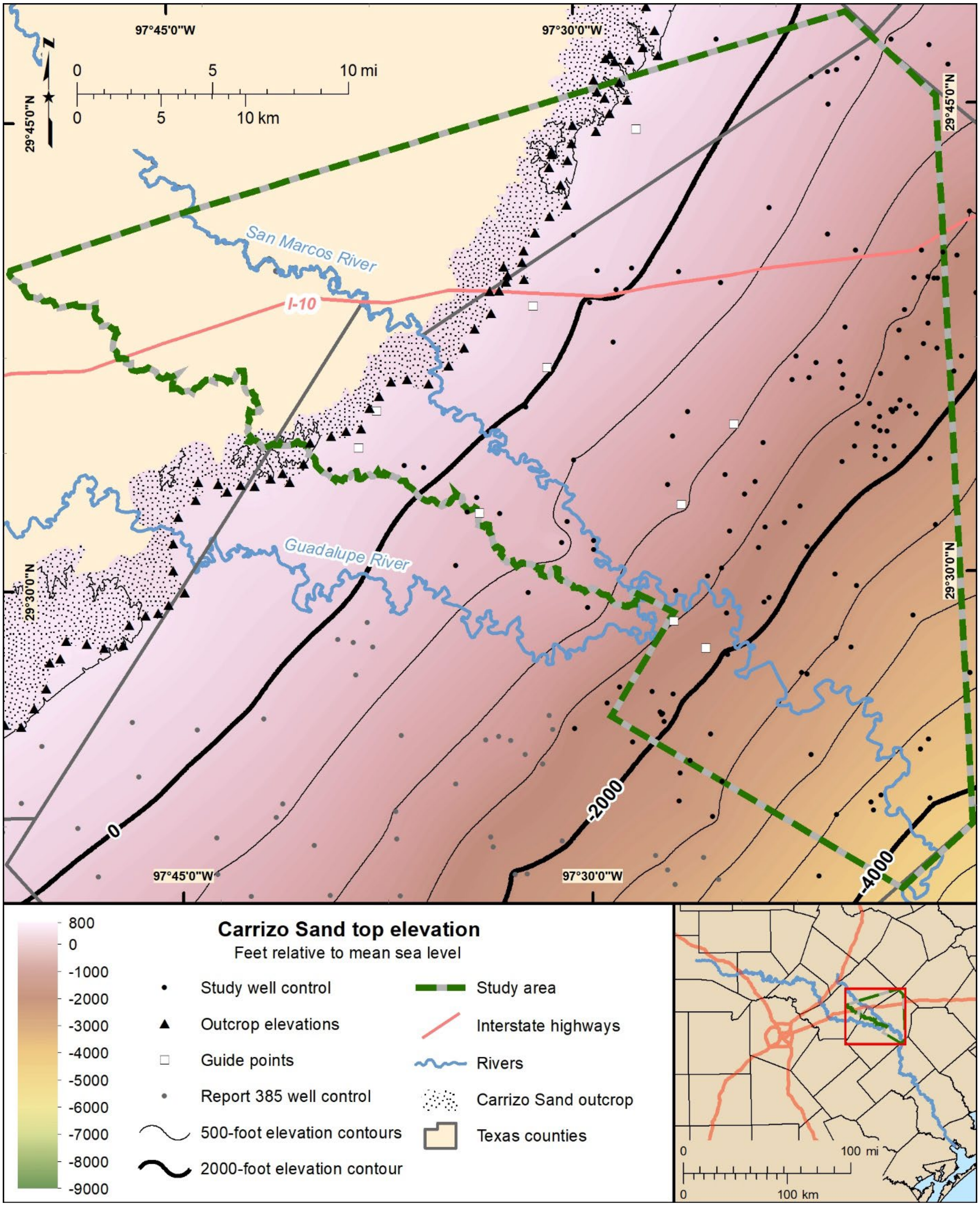


Figure 5-9. **Carrizo Sand top elevation surface (feet relative to mean sea level).**

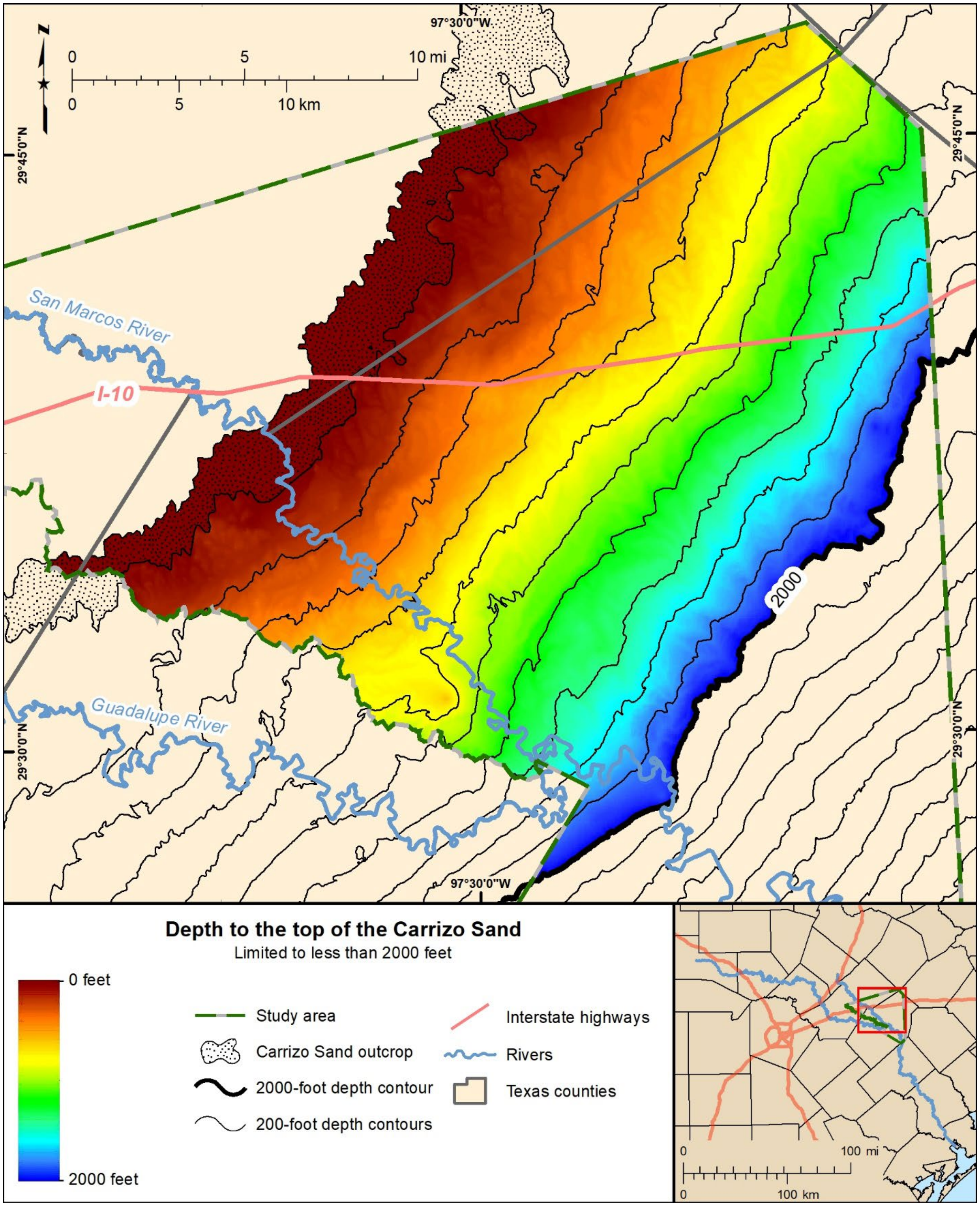


Figure 5-10. Carrizo Sand top depth in feet. The map is limited to an area where the top of the Carrizo Sand is less than 2,000 feet below the ground surface.

Bottom of the Carrizo Sand

To create the Carrizo Sand bottom elevation map, 81 stratigraphic picks from Meyer and others (2020) and 69 stratigraphic picks added during this study were used (150 picks total, Figure 5-11). An additional 76 stratigraphic elevation points from outside of the study area buffer were used to help eliminate GIS raster edge effects. Four guide points and 53 outcrop elevation points were also used in addition to the stratigraphic elevation points.

The elevation of the Carrizo Sand bottom ranges from 514 feet above mean sea level in the outcrop area to 5,182 feet below mean sea level in the farthest downdip corner (southeast) of the study area (Figure 5-12). The Carrizo Sand bottom depth map was created by subtracting the elevation raster from the study area DEM (Figure 5-13). In the study area, the depth to the bottom of the Carrizo ranges from 0 at the outcrop contact between the Carrizo and the Wilcox to 5,517 feet in the farthest downdip corner of the study area. Approximately 12 miles downdip of the outcrop, the bottom of the Carrizo reaches a depth of 2,000 feet.

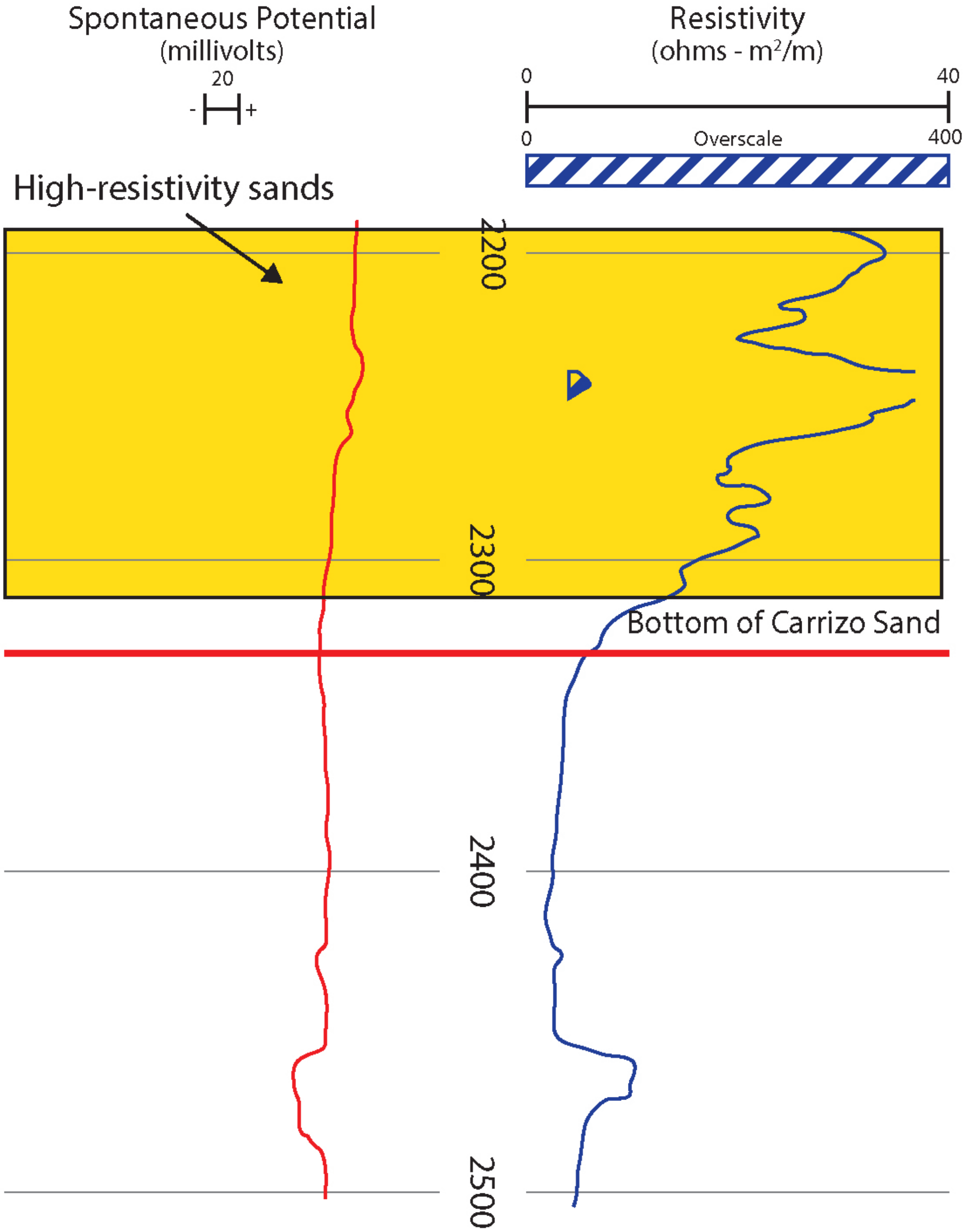


Figure 5-11. Illustration of the spontaneous potential and resistivity curve signatures used to select the bottom of the Carrizo Sand for BRACS Database Well ID 15379 (Gonzales County).

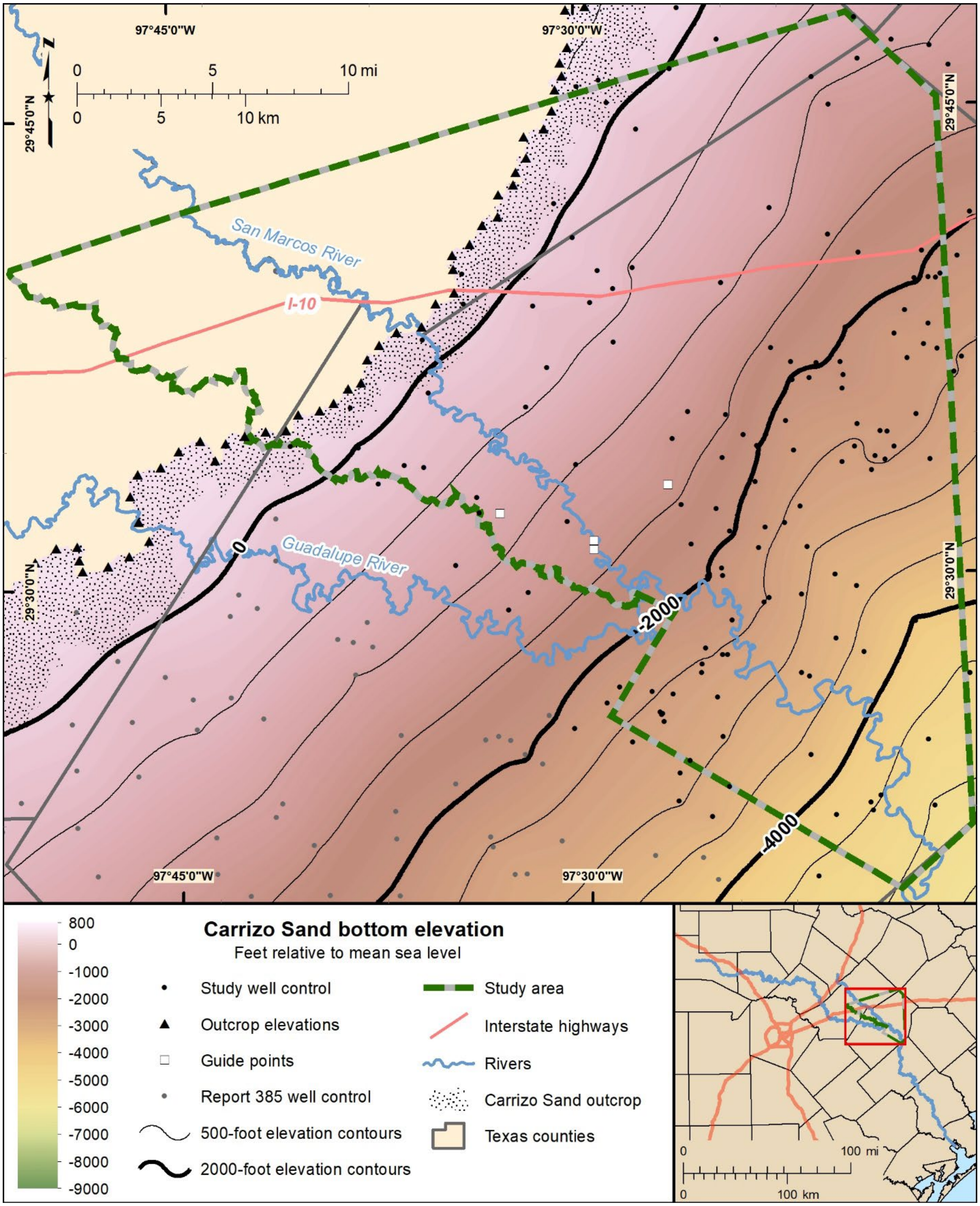


Figure 5-12. Carrizo Sand bottom elevation surface (feet relative to mean sea level).

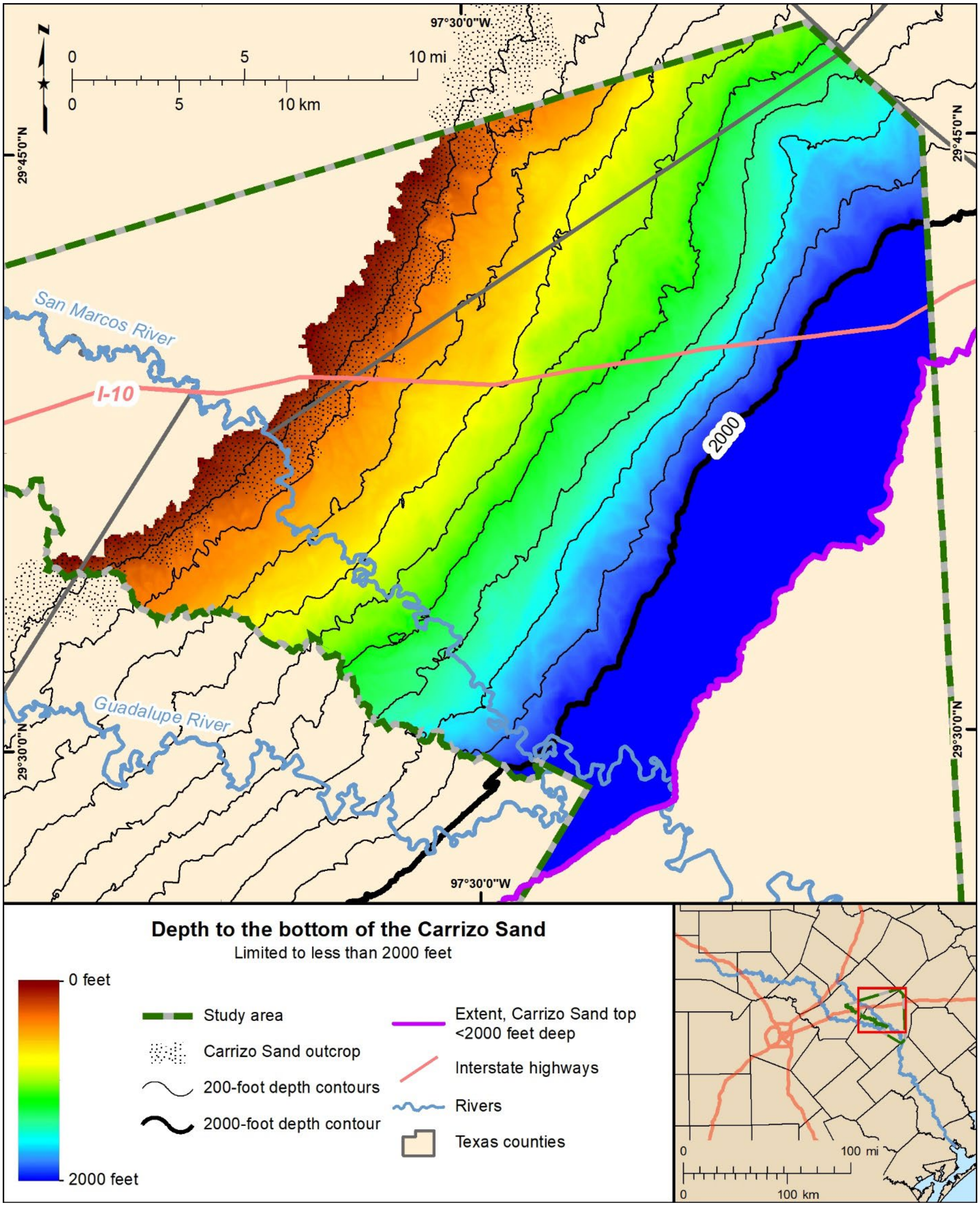


Figure 5-13. Carrizo Sand bottom depth in feet. The map is limited to an area where the top of the Carrizo Sand is less than 2,000 feet below the ground surface.

Thickness of Carrizo Sand

The Carrizo Sand thickness map (Figure 5-14) was created by subtracting the bottom elevation raster from the top elevation raster. The Carrizo Sand thickness ranges from 0 at the surficial contact between the Carrizo and the Wilcox to 1,173 feet in the southeast corner of the study area. In Figure 5-14, the Carrizo thickness map was limited to a depth of 2,000 feet to the top of the formation. In this depth-limited extent, the Carrizo maximum thickness is 904 feet. The thickness is 0 at the updip outcrop limit and at the 2,000-foot depth limit and is thickest at the southwest edge of the study area and the northeast corner of the study area.

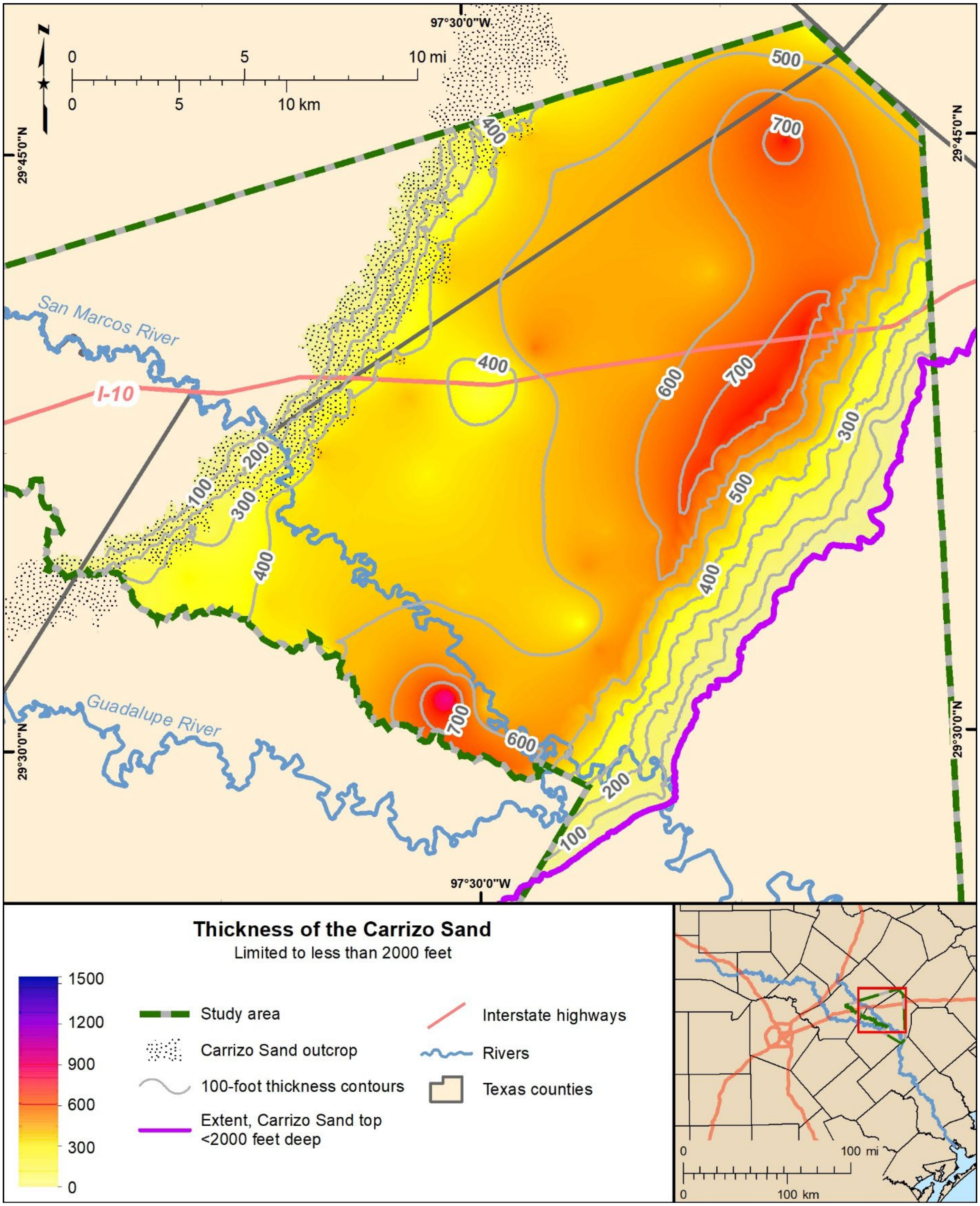


Figure 5-14. **Carrizo Sand thickness in units of feet. The map is limited to an area where the top of the Carrizo Sand is less than 2,000 feet below the ground surface.**

5.2 **Lithology**

This study is concerned with suitable and economic locations for a potential ASR project and therefore focused on the lithology of the Carrizo-Wilcox Aquifer to a total depth of 2,000 feet bgs, as this was considered to be the maximum economically viable depth to drill an injection well for this project. Additionally, the suitability of strata for an ASR project depends on several hydrogeological factors that affect its recharge, storage, and recoverability, all of which are required for a successful ASR project (Shaw and others, 2020).

5.2.1 Wilcox Group

The Paleocene–Eocene Wilcox Group consists primarily of heterogeneous deposits of clay, silt, sand, gravel, and lignite that were deposited a range of fluvial, deltaic, and marine environments. The Wilcox Group was deposited in a progradational sequence along the northwestern Gulf of Mexico (Galloway, 1989). Wilcox Group sandstones within the study area are very fine to fine-grained and poorly to moderately sorted (Fisher and McGowen, 1967; Bebout and others, 1982; Fisher, 1982). These sandstones are primarily feldspathic litharenite containing 64 percent framework quartz grains, 10 percent feldspar grains, and 14 percent rock fragments (primarily silicified igneous fragments, shale fragments, and clay clasts) on average (Fisher and McGowen, 1967; Fisher, 1982). The study area contains a portion of the Yoakum Canyon, which is a prevalent feature in the Middle Wilcox. The lithology within the canyon is primarily shale but does contain some isolated units of sand in the upper portions of the group.

A total of 206 logs were used to interpret the net sands of the Wilcox Group within the study area. This included 195 geophysical well logs where the majority included spontaneous potential (SP) and dual-induction resistivity measurements. Additionally, 11 driller's descriptions of lithology were used for the analysis. The top of the Wilcox Group was identified as a regional shale within the study area that is immediately below the lowest sharp-based sand unit of the Carrizo Formation (Meyer and others, 2020). The lithology for the Wilcox Group was interpreted to a maximum depth of 2,000 feet bgs. The lower Wilcox Group contract with the Midway Group was only used within the Wilcox Group outcrop in the western portion of the study area.

The lower Wilcox Group contact with the Midway Group is gradational and challenging to identify on geophysical logs. This pick was only used within the Wilcox Group outcrop in the western portion of the study area. As with Meyer and others (2020), stratigraphic contact picks were conducted using geophysical log signatures. Stratigraphic interpretations of the Wilcox Group have been debated by many authors (e.g., Hutto and others, 2009; Demchuk and others, 2019). Other controls, such as paleontological and chronological markers, were not readily available and not considered necessary for the goals of this study (Brown and Loucks, 2009; Meyer and others, 2020).

Between the surface and 2,000 feet below ground level there are between 0 and 920 feet of net sands (Figure 5-15). The thickest sands are located immediately downdip of the boundary of the Wilcox Group outcrop and in the northern portion of the study are. This region is dominated by isolated clean sand units interbedded with clay and mixed clay and sand units (Figure 5-16). These sands increase in thickness in the uppermost 500 feet of the Wilcox Group but are lithologically distinct from the sands of the overlying Carrizo Sand.

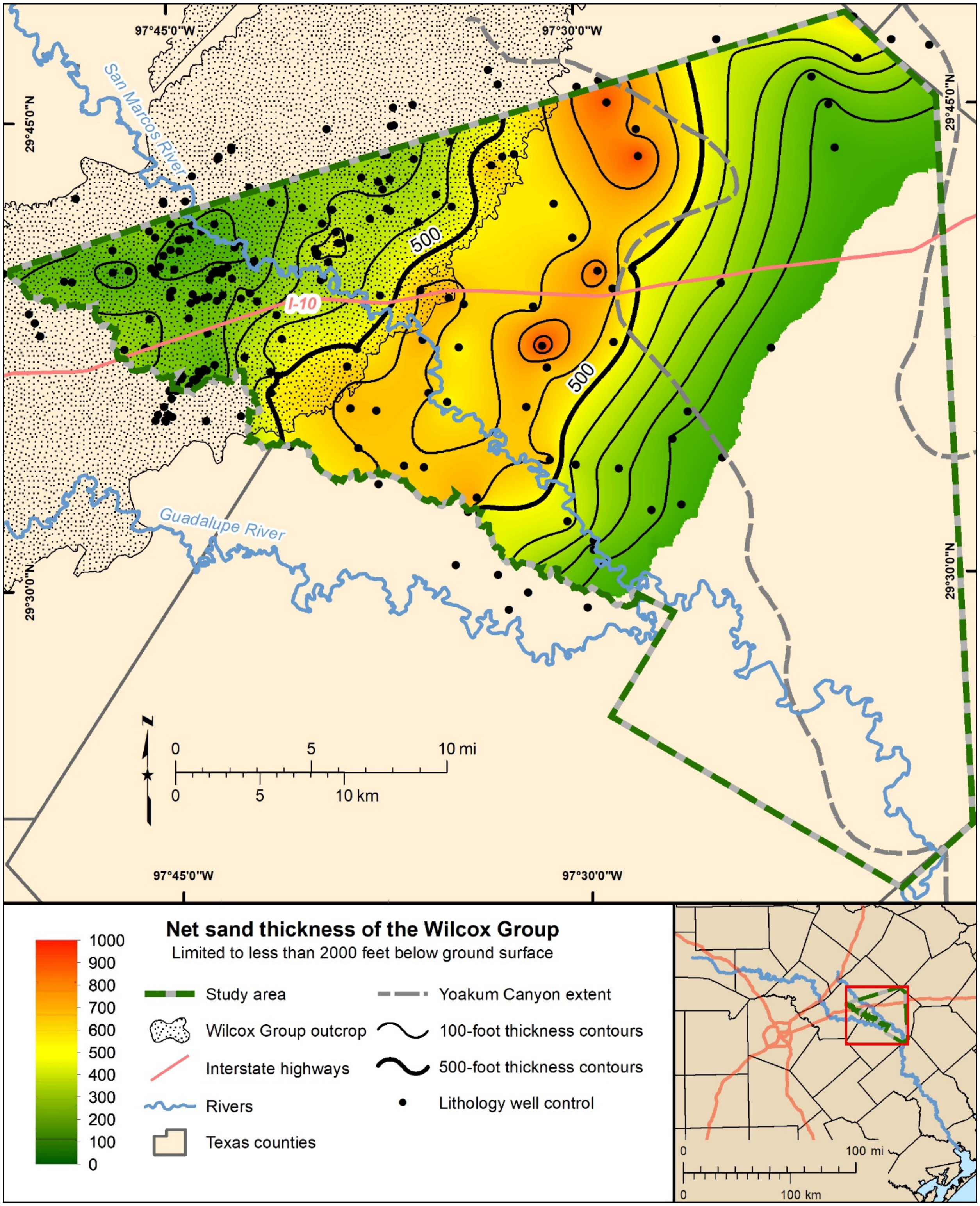


Figure 5-15. **Net Sand thickness (feet) of the Wilcox Group limited to 2,000 feet below ground surface prepared using 206 wells for control (black dots). Extent of the shale-filled Yoakum Canyon is outlined.**

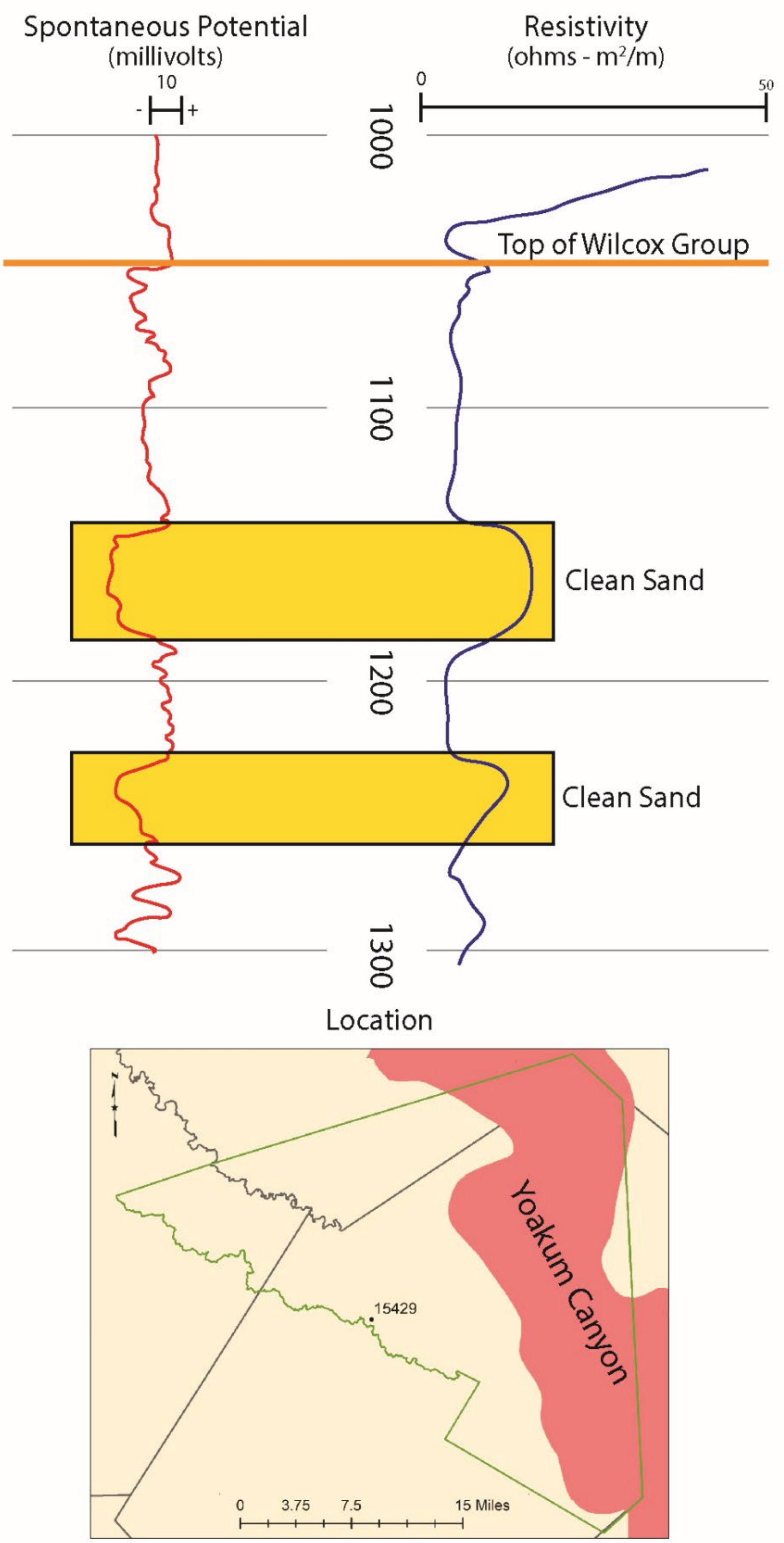


Figure 5-16. **Lithology of the sandstone units in the upper Wilcox Group interpreted from a geophysical well log in Gonzalez County, Texas (BRACS ID 15429). Spontaneous potential and deep resistivity values shown. Sandstone units with little to no clay content are highlighted.**

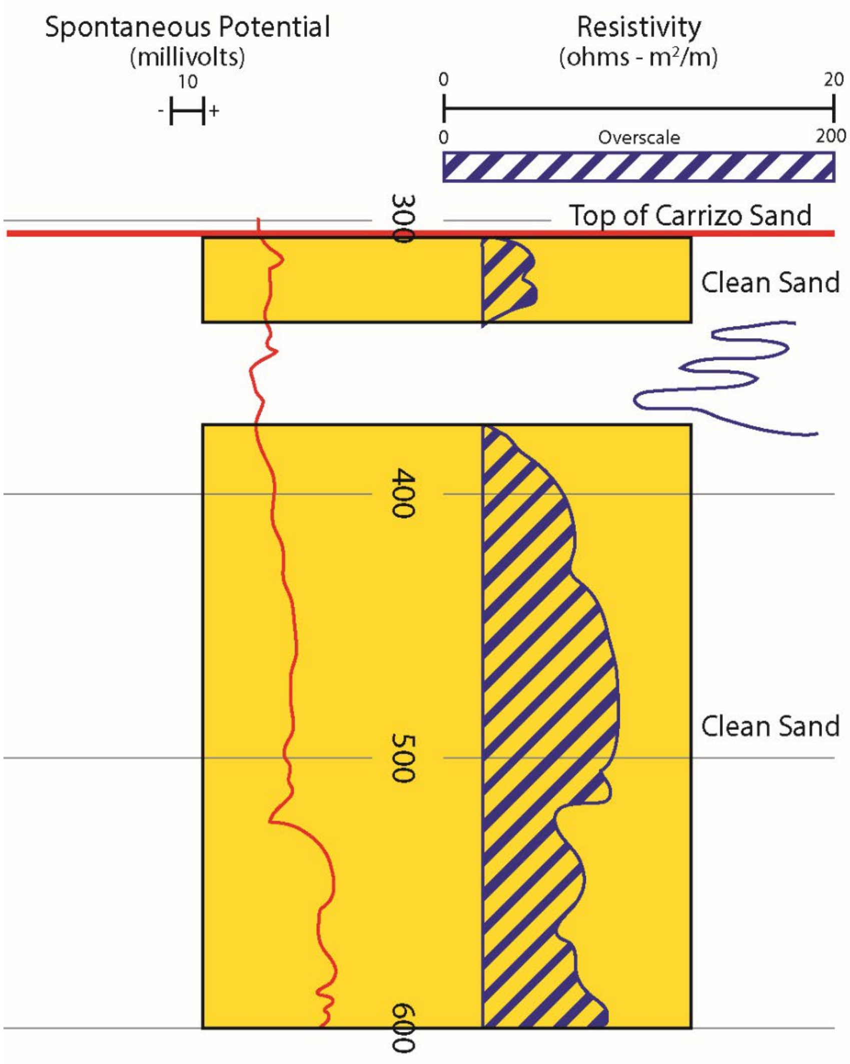
5.2.2 Carrizo Sand

The Eocene Carrizo Sand unconformably overlies the Wilcox Group and contains distinct thick, sharp-based, high-resistivity sand units. The Carrizo Sand contains an average of 80 percent sand over its entire distribution from south-central Texas to Mississippi (Payne, 1975; Ambrose and others, 2020). Within the study area, the basal sandstones of the Carrizo Sand are crossbedded with some areas containing clay-dominated rip-up clasts (Demchuk and others, 2019; Ambrose and others, 2020). These crossbedded sands are overlain by massive, quartz-rich ferruginous sand with some sparse carbonaceous clays (Adams and Smith, 1980; Demchuk and others, 2019). Lithologic analysis done for this study shows that these massive, high-porosity sandstones are identified by their high-resistivity and can be over 500-feet thick across much of the study area (Figure 5-17). These sandstones have previously been interpreted as an alluvial system (e.g., Payne, 1975; Dickey and Yancey, 2010), however more recent sedimentological and ichnological studies show that the basal Carrizo Sand was deposited in a marine environment, specifically the identification of a continuous *Glossifungites* surface directly above the Wilcox Group and the presence of *Ophiomorpha,* burrows of callianassid shrimp, in the basal sands of the Carrizo that cross into the Wilcox Group (Demchuk and others, 2019; Ambrose and others, 2020).

As stated above, the Yoakum Canyon is a prominent subsurface feature in the Wilcox Group, where it is characterized by thick shales and clays. The Carrizo Sand that overlies the Yoakum Canyon is distinctly thicker than the surrounding strata, and the sandstones within this region have a distinctly different character as seen in geophysical well logs. The sands overlaying the Yoakum Canyon have much more interbedded clay and the clean, quartz-rich sandstones are more vertically isolated. On average the resistivity of these sands is also slightly lower than the massive sands found elsewhere in the study area (Figure 5-18).

Due to the high productivity of the Carrizo Sand, lithologic analysis was completed for the entire thickness of the unit within the study area. The entire Carrizo Sand contains up to 854 feet of net sands within the study area with the thickest portions overlying the Yoakum Canyon (Figure 5-19). Thickness of these sands increases to the east where they are below the 2,000-foot depth limit. The net sands for the entire Carrizo Formation within the study area were interpreted using 148 well logs, which included 126 geophysical well logs where the majority included SP and resistivity measurements. Additionally, 22 driller's descriptions of lithology were used for the analysis.

Within 2,000 feet below ground surface the Carrizo Sand contains up to 623 feet of net sands with the thickest sands overlying the Yoakum Canyon shales and in the southern portion of the study area near the City of Gonzalez (Figure 5-20). This depth-limited net sands value was interpreted using data from 100 wells, which included 75 geophysical well logs where the majority included SP and resistivity measurements. Additionally, 25 driller's descriptions of lithology were used for the analysis. The process of depth limiting the analysis eliminated 60 wells in the downdip section of the unit from analysis. However, an additional 12 wells that had total depths greater than 2,000 feet but did not completely penetrate the Carrizo Sand were able to be added from the BRACS Database. This process also creates a subsurface wedge that pinches out to the east as the top of the Carrizo Sand reaches 2,000 feet bgs (Figure 5-20).



Location

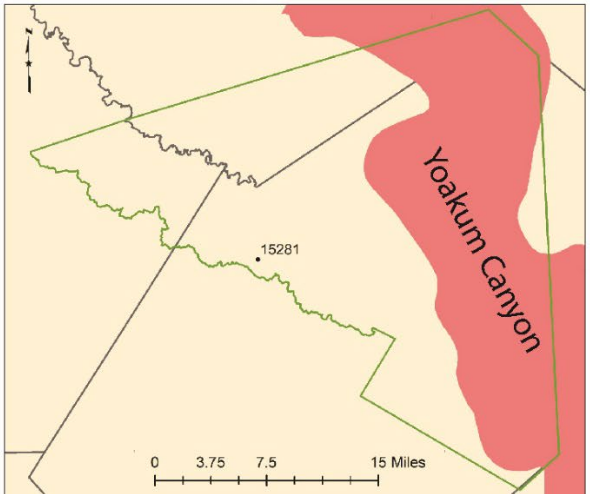


Figure 5-17. Lithology of the sandstone units in the Carrizo Sand interpreted from a geophysical well log in Gonzalez County, Texas (BRACS ID 15281). Spontaneous potential and deep resistivity values shown. Typical high-resistivity massive sandstone units are highlighted.

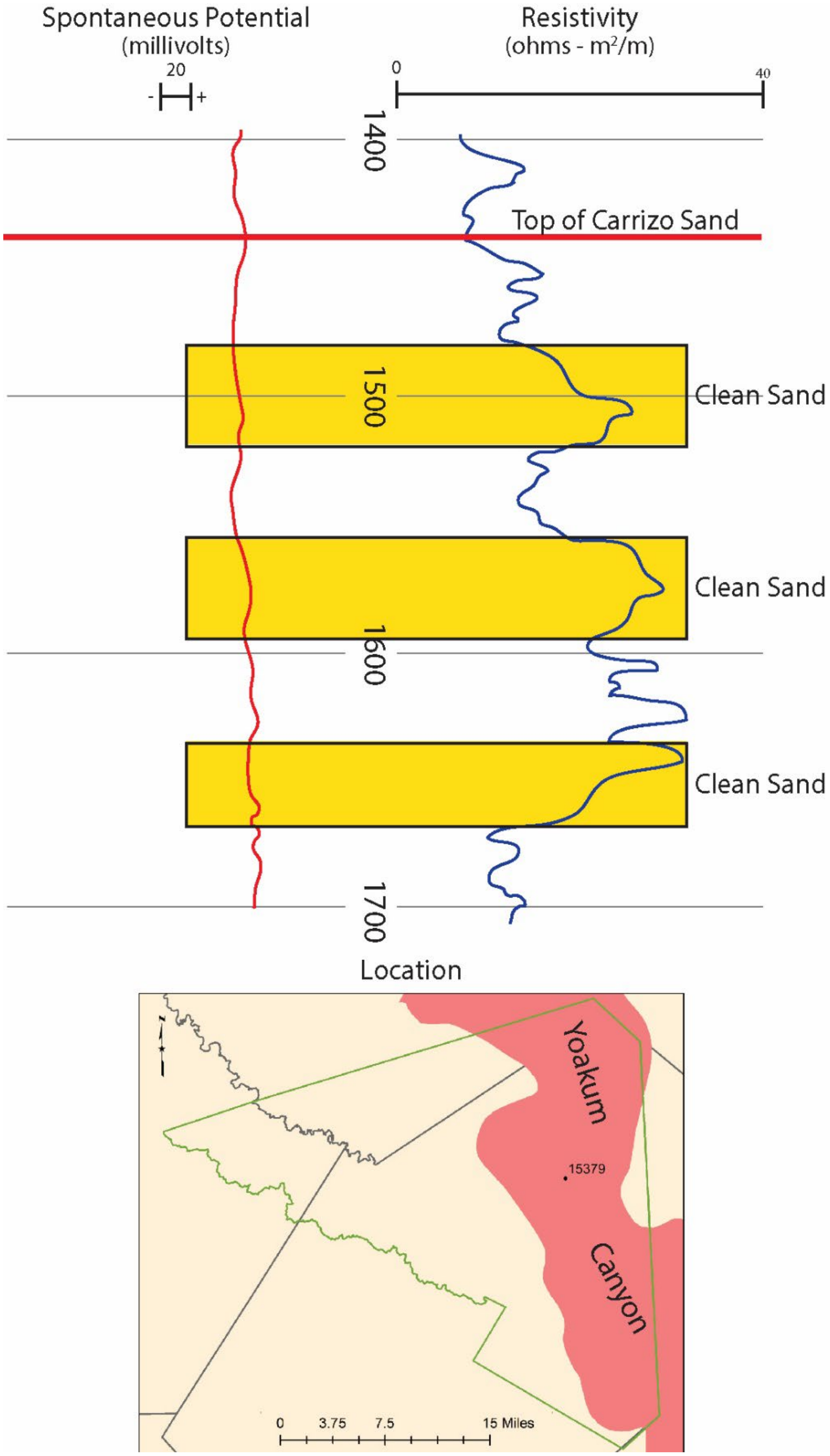


Figure 5-18. **Lithology of the sandstone units in the Carrizo Sand above the Yoakum Canyon interpreted from a geophysical well log in Gonzalez County, Texas (BRACS ID 15379). Spontaneous potential and deep resistivity values shown. Typical high-resistivity massive sandstone units are highlighted.**

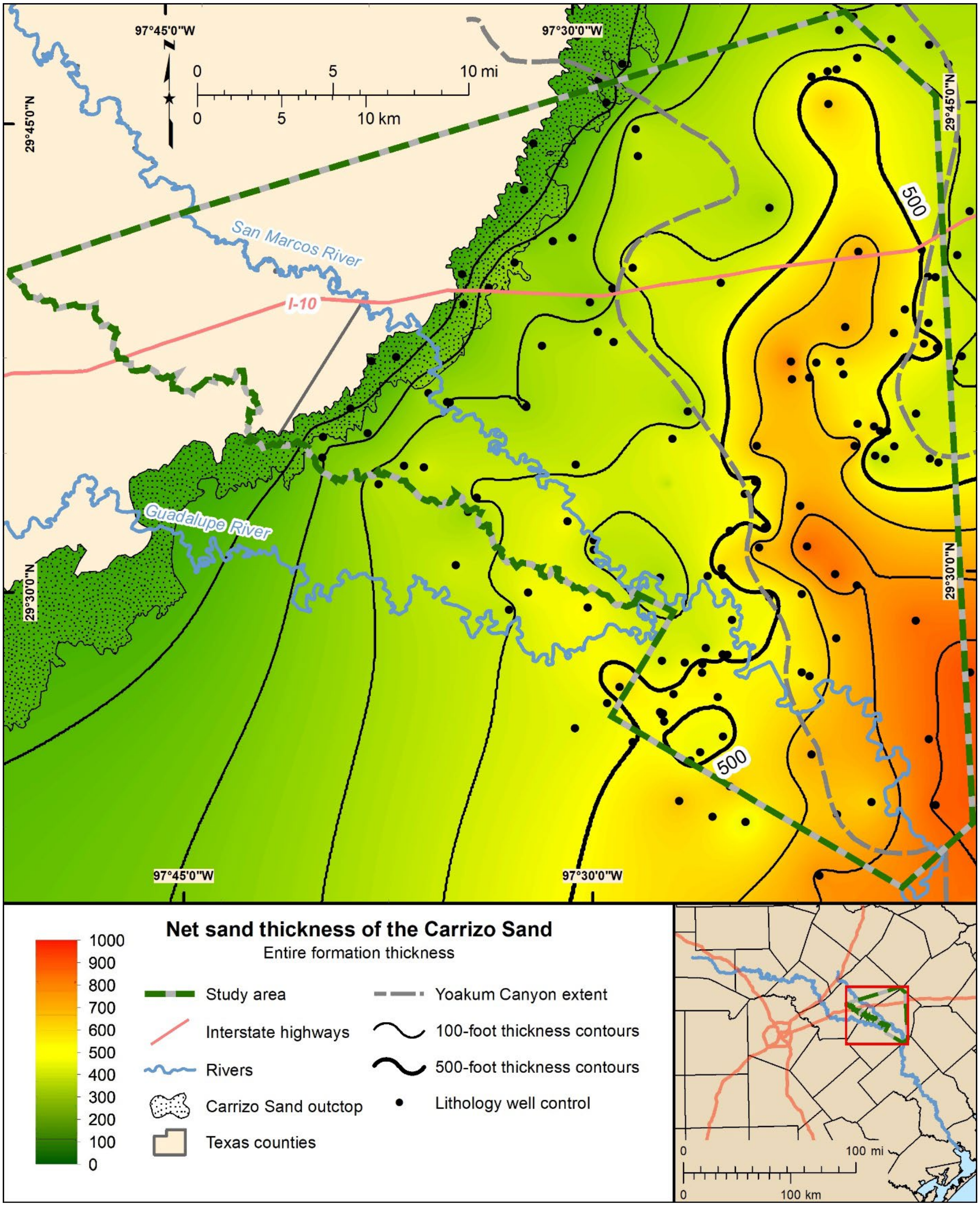


Figure 5-19. Net Sand thickness (feet) of the entire Carrizo Sand within the study area prepared using 148 wells for control (black dots). Extent of the underlying Yoakum Canyon is outlined.

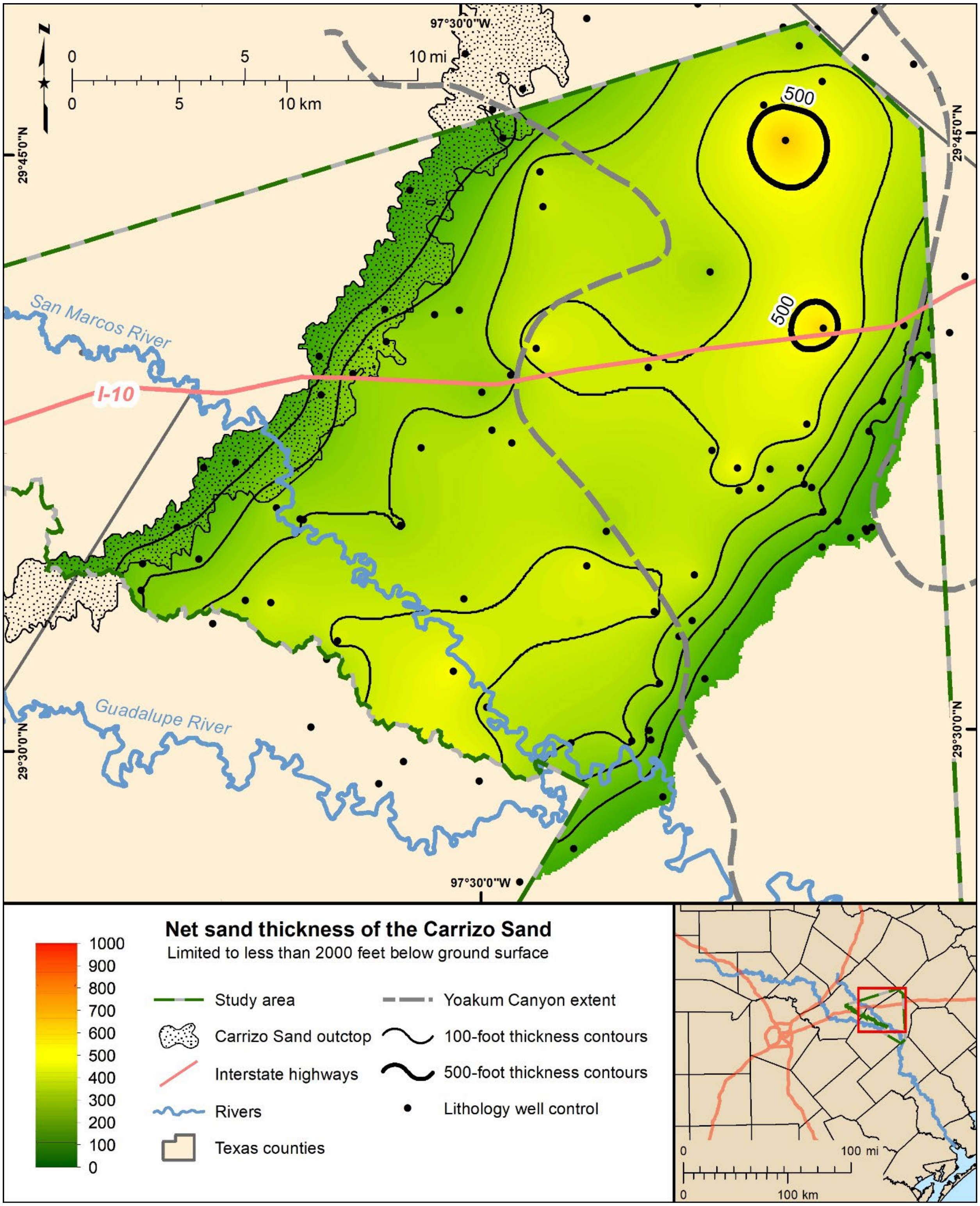


Figure 5-20. **Net Sand thickness (feet) of the Carrizo Sand limited to 2,000 feet below ground surface prepared using 100 wells for control (black dots). Extent of the underlying Yoakum Canyon is outlined.**

5.3 **Salinity class results**

One of the hydrogeological characteristics important to ASR is water quality of the native groundwater in the aquifer chosen as a storage zone. The salinity of the native groundwater has to be considered when assessing possible chemical interaction with source water, designing the well construction, planning operations, and applying to TCEQ for approval. Mapping of salinity classes was based on measured water quality samples from wells and calculated TDS concentrations from geophysical well logs as described in Section 4. We started with the salinity class polygons and calculations produced in Meyer and others (2020). However, this study was limited to 2,000 feet below ground surface (bgs) or shallower for both the Wilcox Group and Carrizo Sand. This resulted in simplified salinity classes for both formations but especially for the Wilcox Group. Limiting the study area to the 2,000-foot depth limit for both formations also cut out the down-dip salinity classes, which are more saline and too deep for the interest of this report.

5.3.1 Wilcox Group

There were 50 Wilcox Group wells with 90 measured water quality samples in the entire study area. Wells can have multiple samples, so there are more samples than wells. These 90 water quality samples were grouped into the following three salinity classes: 37 fresh samples, 51 slightly saline samples, and 2 moderately saline samples. Measured water quality samples represent the collective groundwater for the entire screened interval of the well. Therefore, multiple salinity classes cannot be assigned to a single well that only had measured water quality and no geophysical well logs.

For the Wilcox Group, we examined 168 wells for TDS and performed 389 calculations. Because the Wilcox Group can be up to 1,528 feet thick in this study, one well could have multiple stacked salinity class well intervals and we may have done multiple TDS calculations to define one salinity class well interval. A total of 227 salinity class intervals were assigned totaling: 12 fresh, 82 slightly saline, 72 moderately saline, 57 very saline, and 4 brine intervals. Mapping the general Wilcox Group salinity classes based on the measured water quality samples and salinity class well intervals resulted in six types of polygons: 1) fresh and slightly saline; 2) fresh, slightly, and moderately saline; 3) slightly saline; 4) slightly and moderately saline; 5) moderately saline; and 6) moderately and very saline (Figure 5-21).

The Wilcox Group reaches depths of over 8,000 feet in the study area with a maximum thickness of almost 3,000 feet. In the Wilcox Group, groundwater salinity generally increases with depth, and with so much of the Wilcox Group below the 2,000-foot limit, many deeper and saltier salinity classes were excluded. It is freshest near the outcrop, increasing from fresh and slightly saline in the western-most part of the study area to moderately and slightly saline at the 2,000-foot depth limit. There is additional complexity in the groundwater salinity in the north central portion of the study area where the "fresh, slightly, and moderately" salinity class was drawn. This greater complexity in salinity class distribution is probably due to faulting (see Section 3.3) and the more hydraulically isolated nature of sands in the Wilcox Group. Discontinuous sands, isolated by faults or layers of clay, limit groundwater recharge and mixing.

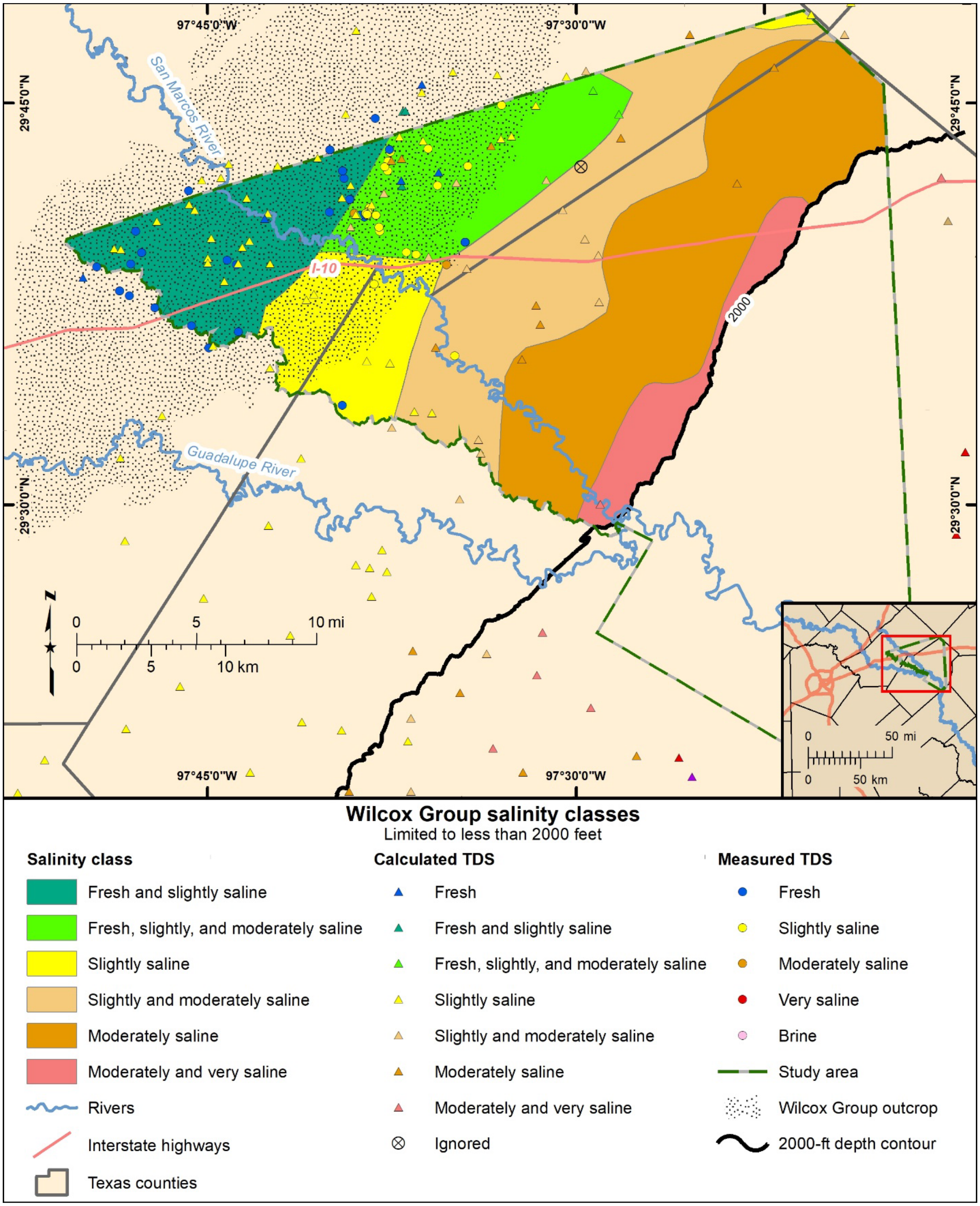


Figure 5-21. Wilcox Group salinity classes. The map is limited to an area where the top of the Wilcox Group is less than 2,000 feet below the ground surface.

5.3.2 Carrizo Sand

For the Carrizo Sand in the entire study area, there were 20 wells with 80 measured water quality samples. These samples were grouped into the following salinity classes: 7 fresh samples, 72 slightly saline samples, and 1 moderately saline sample. Measured water quality samples represent the collective groundwater for the entire screened interval of the well. Therefore, multiple salinity classes cannot be assigned to a single well that only had measured water quality and no geophysical well logs.

For the Carrizo Sand, we examined 123 wells for TDS and performed 220 calculations. Since the Carrizo Sand can be up to 907 feet thick in this study, one well could have multiple stacked salinity class well intervals and we may have done multiple TDS calculations to define one salinity class well interval. A total of 164 salinity class intervals were assigned, totaling: 63 fresh, 56 slightly saline, 35 moderately saline, 8 very saline, and 2 brine intervals. Mapping the general Carrizo Sand salinity classes based on the measured water quality samples and salinity class well intervals resulted in five types of polygons: 1) fresh, 2) fresh and slightly saline, 3) slightly saline, 4) slightly and moderately saline, and 5) moderately saline (Figure 5-22).

The Carrizo Sand salinity class mapping was not affected by the 2000-foot depth limit as much as the Wilcox Group for several reasons. The Carrizo Sand is a thinner formation with a maximum thickness of 1,173 feet in the study area. It also has more transmissive sands intervals via thicker, massive sands, some of which are over 500 feet thick, so there is less stacked variability in salinity and more gradual lateral transitions in water chemistry. The largest salinity class in the Carrizo Sand is fresh. In general, salinity increases with depth, changing from the fresh salinity class to mixed fresh and slightly saline at the 2,000-foot depth limit, but there are a few notable exceptions. Near the outcrop, there are two areas of mixed fresh and slightly saline classes that extend in a roughly downdip direction. These lobes of mixed salinity were drawn to capture two areas with slightly saline measurements and calculations within the large area of predominantly freshwater measurements and calculations. In the southern part of the study area, near the Guadalupe River, there is a lobe of moderately saline and mixed slightly and moderately saline water. These areas with moderately saline water extended updip into the slightly saline area that is also in the southern corner of the study area. While it is difficult to determine the cause for salinity class transitions in the aquifer, there are some correlations with regional geologic features.

The much greater depth that fresh water can be found from the Carrizo Sand outcrop when compared to the Wilcox Group outcrop may be due to the lithology and net sand distribution in the eastern part of the study area within the Yoakum Canyon (see Section 5.2.2). Individual sand intervals over the Yoakum Canyon are generally thinner and more interbedded with clay layers than areas of the Carrizo Sand that do not overlay the Yoakum Canyon. Additionally, the overall thickness and accumulated sand in the Carrizo Sand geologic formation are thicker over the canyon than outside of it. This geometry and volume of sand, along with faults, could be influencing the hydraulic pathways for transmitting fresh water recharged in the outcrop downdip into the aquifer.

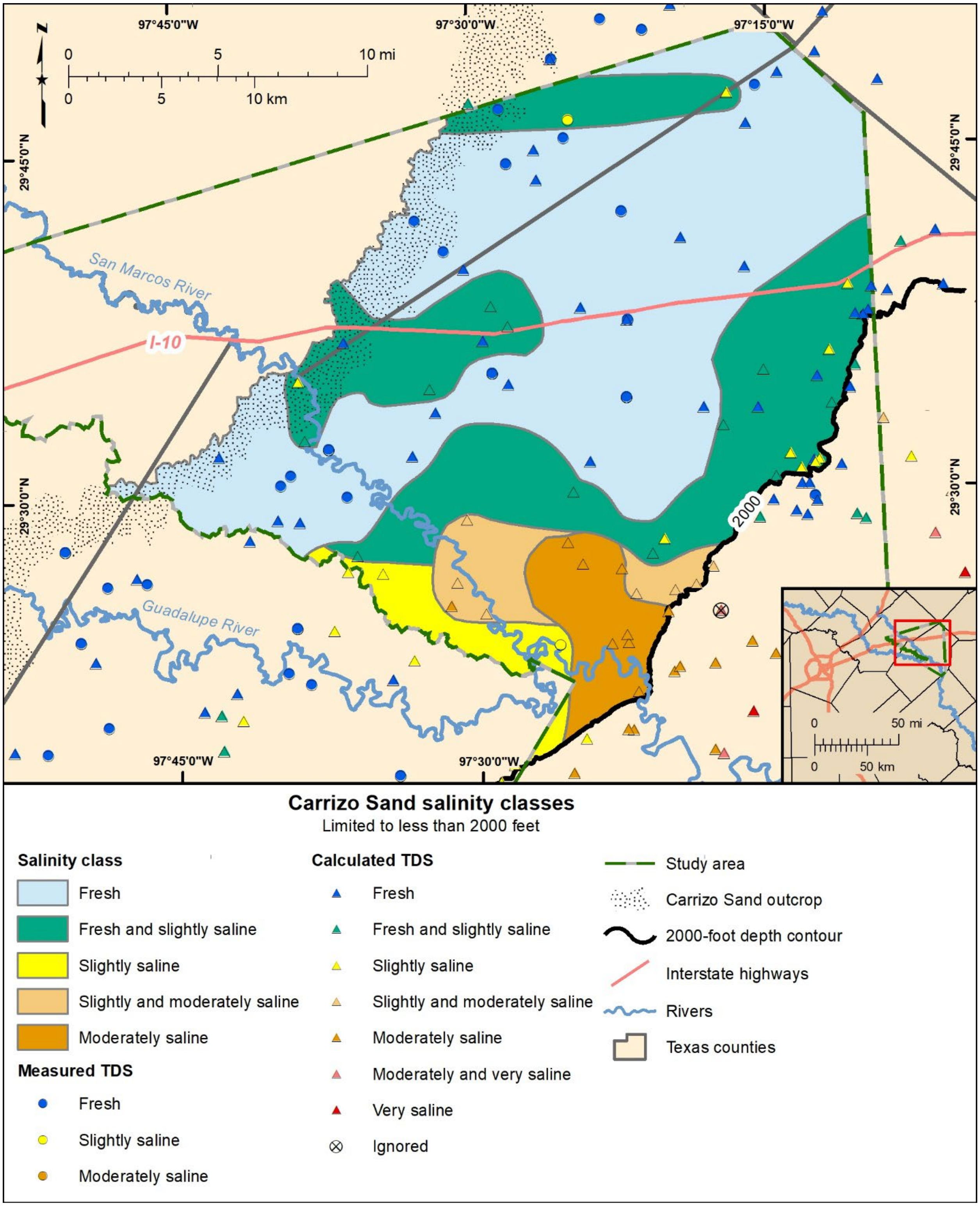


Figure 5-22. **Carrizo Sand salinity classes. The map is limited to an area where the top of the Carrizo Sand is less than 2,000 feet below the ground surface.**

6. Discussion

Aquifer characterization is an integral part of planning and developing an ASR system, as all properties of the aquifer affect the potential efficiency of the injection, storage, recovery, system design, material selections, and operations. ASR projects have been developed in numerous aquifers with highly variable physical and geochemical characteristics, and although most conditions can be accounted for during the planning and engineering process, these factors may affect the choice of site location and potential success of the project (Smith and others, 2017). Success of an ASR project is also dependent on other variables including, but not limited to

- proximity to existing water supply, water demand, and infrastructure;
- compatibility with existing water supply, water demand, and infrastructure; and
- the water quality of the injected and recovered water.

6.1 Statewide ASR Suitability Survey

The Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects (referred to as the Statewide ASR Suitability Survey in this report) met the first portion of HB 721 legislative mandates (Shaw and others, 2020). The Statewide ASR Suitability Survey mapped Texas with 50,000 by 50,000-foot grid cells. For each grid cell, the survey screened three primary criteria for determining suitability for ASR or AR as identified in HB 721:

1. Hydrogeological characteristics (such as storage potential, transmissivity, infiltration, storativity, recoverability, and water quality)
2. Frequency, volume, and distance to excess water that may be available for storage
3. Current and projected future water supply needs identified in the state water plan

Each of these three criteria were screened independently and screening scores were normalized to a score of 0–1. In grid cells where two or more aquifers were present, such as the Sparta Aquifer stacked on top of the Queen City Aquifer, the aquifer with the highest scoring hydrogeological characteristics was used for the screening. Due to the complex nature of many ASR and AR projects, values for excess water and water needs screening scores were considered for a distance of up to two grid cells from any given aquifer score, and a weight was applied to give stronger consideration to closer grid cells. Because all three criteria are considered critical for the successful completion of an ASR or AR project, only grid cells that contained scores for all three screenings were given a final ASR or AR rating. This final suitability rating placed regions into one of three general categories of relative suitability: less, moderately, or most suitable. Additional details on the methodology used for rating ASR or AR suitability across the state is found in Shaw and others (2020).

6.1.1 Hydrogeological ratings

House Bill 721 specified consideration of several hydrogeological characteristics for potential ASR and AR projects: storage potential, transmissivity, infiltration characteristics, storativity, recoverability, and water quality. Infiltration characteristics was only applicable to the final suitability rating for AR. The remaining five specified characteristics were captured by three categories used to create the final suitability for ASR rating: recharge, storage, and recoverability (Shaw and others, 2020). Eleven unique parameters were mapped and scored for these three categories: storage zone depth, horizontal hydraulic conductivity, available drawup, dominant lithology, thickness, storativity, age, confinement, water quality, drift velocity, and available drawdown (Shaw and others, 2020). The parameters used, their descriptions, and the category they were assigned to in the ASR hydrogeological screening are summarized in Table 6-1. The hydrogeological screening parameter values and normalized scores are summarized in Table 6-2. Additional information on the methodologies used in determining the values and normalized scores for the hydrogeological screening can be found in Shaw and others (2020).

Table 6-1. Parameters used for the hydrogeological screening for aquifer storage and recovery projects in confined aquifers from the Statewide Suitability Survey. Categories indicate which stage of an ASR project is most affected by the individual parameter (Modified from Shaw and others, 2020).

Parameter	Category	Description
Storage zone depth	Recharge	Depth to top of aquifer unit
Horizontal hydraulic conductivity	Recharge, recoverability	Ability of sediment to transmit fluid. Estimated using Darcy's Law
Drawup available	Recharge	Distance between hydraulic head and ground surface
Dominant lithology	Recharge, recoverability	Dominant water bearing lithology and presence of secondary porosity
Aquifer thickness	Storage, recharge	Total thickness of unit
Aquifer storativity	Storage	Confined aquifer: Total thickness of unit
Sediment age	Storage	Qualitative assessment of sediment induration
Confinement	Recoverability	Presence of non-permeable unit above and below aquifer
Groundwater quality	Recoverability	Total dissolved solids
Drift velocity	Recoverability	Estimated rate of drift of recharged water
Drawdown available	Recoverability	Height of hydraulic head

Table 6-2. Hydrogeological screening parameter values for the Carrizo-Wilcox Aquifer from the Statewide Suitability Survey within the study area. Units are given for each value.

Parameter	Value	Normalized score
Storage zone depth	270.1–4207.6 feet	0.1–1.0
Horizontal hydraulic conductivity	6.1–32.1 feet/day	0.5–1.0
Drawup available	-70.7–93.6 feet	0.1–0.2
Dominant lithology	Sand	1.0
Aquifer thickness	270.1–877.4 feet	0.5–1.0
Aquifer storativity	0.001–0.03 S	0.8-1.0
Sediment age	57 million years	0.99
Confinement	confined in subsurface unconfined in outcrop	1.0 where confined 0.0 where unconfined
Groundwater quality	321.1–1484.5 mg/L	0.8-0.9
Drift velocity	3.80–97.1 feet/year	0.75–1.0
Drawdown available	73.7–4278.3 feet	0.2–1.0

Notes: Normalized scores range from 0 to 1 based on individual parameters. Additional information on the methodologies used to determine values and normalized scores is found in Shaw and others (2020).

For the hydrogeological characteristics screening, the majority of the study area was scored as most suitable for ASR (Figure 6-1). The screening indicates that the highest scoring aquifer in most of the study area is Carrizo-Wilcox Aquifer, which scores very high across most parameters and is generally very suitable for ASR where present. The normalized hydrogeological screening scores for the Carrizo-Wilcox Aquifer range from 0.59–0.83 (moderately to most suitable). This result was expected due to the well-documented porosity and permeability characteristics of the Carrizo Sand (see 5.2 Lithology). Only two grid cells scored moderately suitable, and these were in the northwesternmost portion of the study area and within the Wilcox Group outcrop area, where the aquifer is thinnest and unconfined.

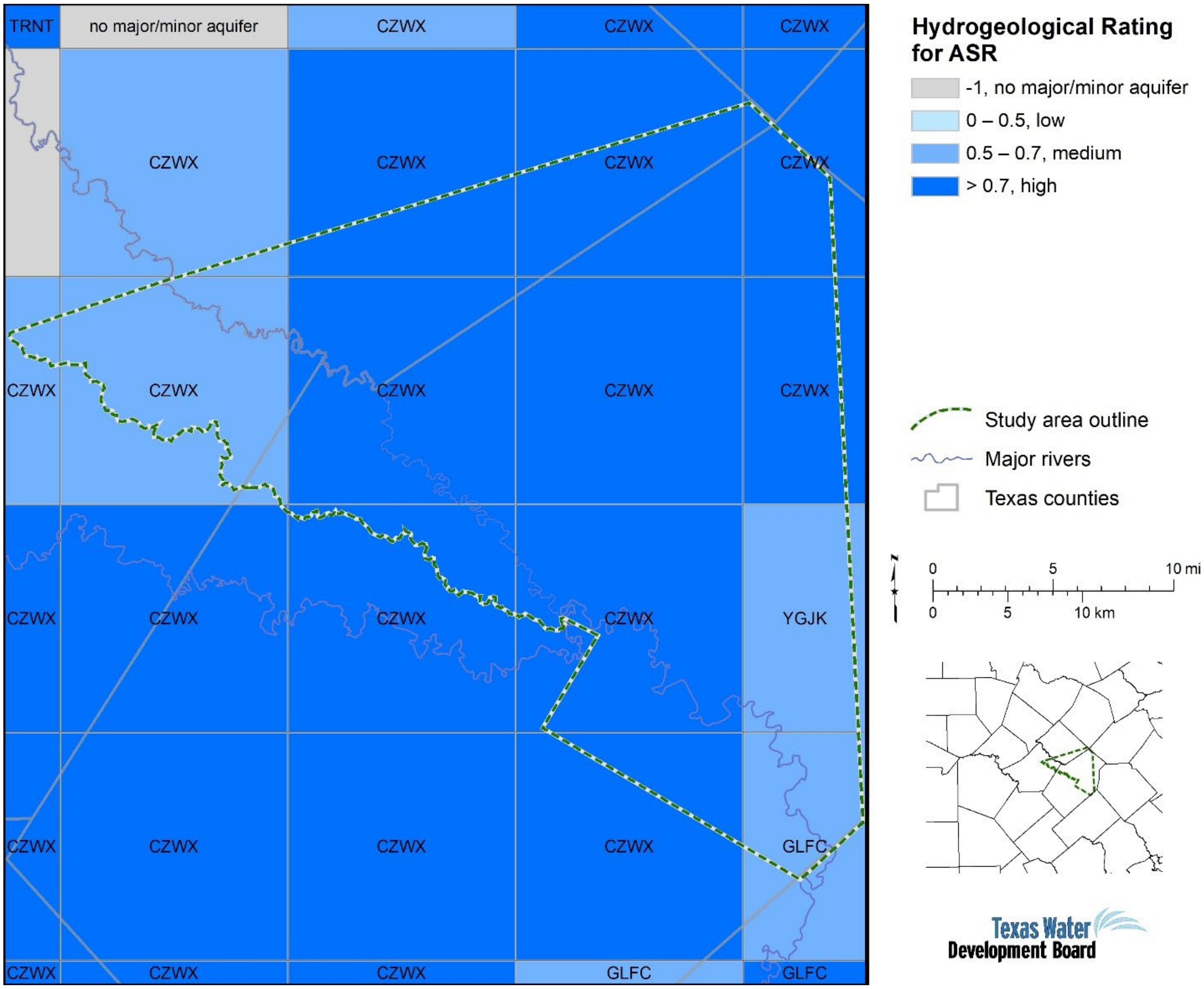


Figure 6-1. **Hydrogeological parameter screening results for ASR from the statewide survey for the study area. Grid cells are labeled with the highest scoring aquifer in that location: the Carrizo-Wilcox Aquifer (CZWX), Yegua-Jackson Aquifer (YGJK), Trinity Aquifer (TRNT), and Gulf Coast Aquifer System (GLFC) (Shaw and others, 2020).**

There are two grid cells in the southeast corner of the study area that are just outside the TWDB boundary for the Carrizo-Wilcox Aquifer (Figure 6-2). Since the hydrogeological screening of the Statewide ASR Suitability Survey was limited to the TWDB boundaries of the major and minor aquifers, the overlying Yegua-Jackson or Gulf Coast aquifers were identified as most suitable aquifers for ASR in these two grid cells. Although the Gulf Coast Aquifer system is present in the southeastern corner of the study area, it is deeper than the 2,000-foot depth limit. Additionally, the Queen City and Sparta aquifers are present in the northern portion of the study area. However, they are commonly found in outcrop and therefore unconfined and have lower hydrogeological screening scores when compared to the Carrizo-Wilcox Aquifer. If the GBRA were compelled to install an ASR well field in the southeastern portion of the study area, where the Carrizo-Wilcox Aquifer is greater than 2,000 feet deep, then an aquifer characterization of the Yegua-Jackson Aquifer, and possibly the Queen City and Sparta aquifers, is suggested.

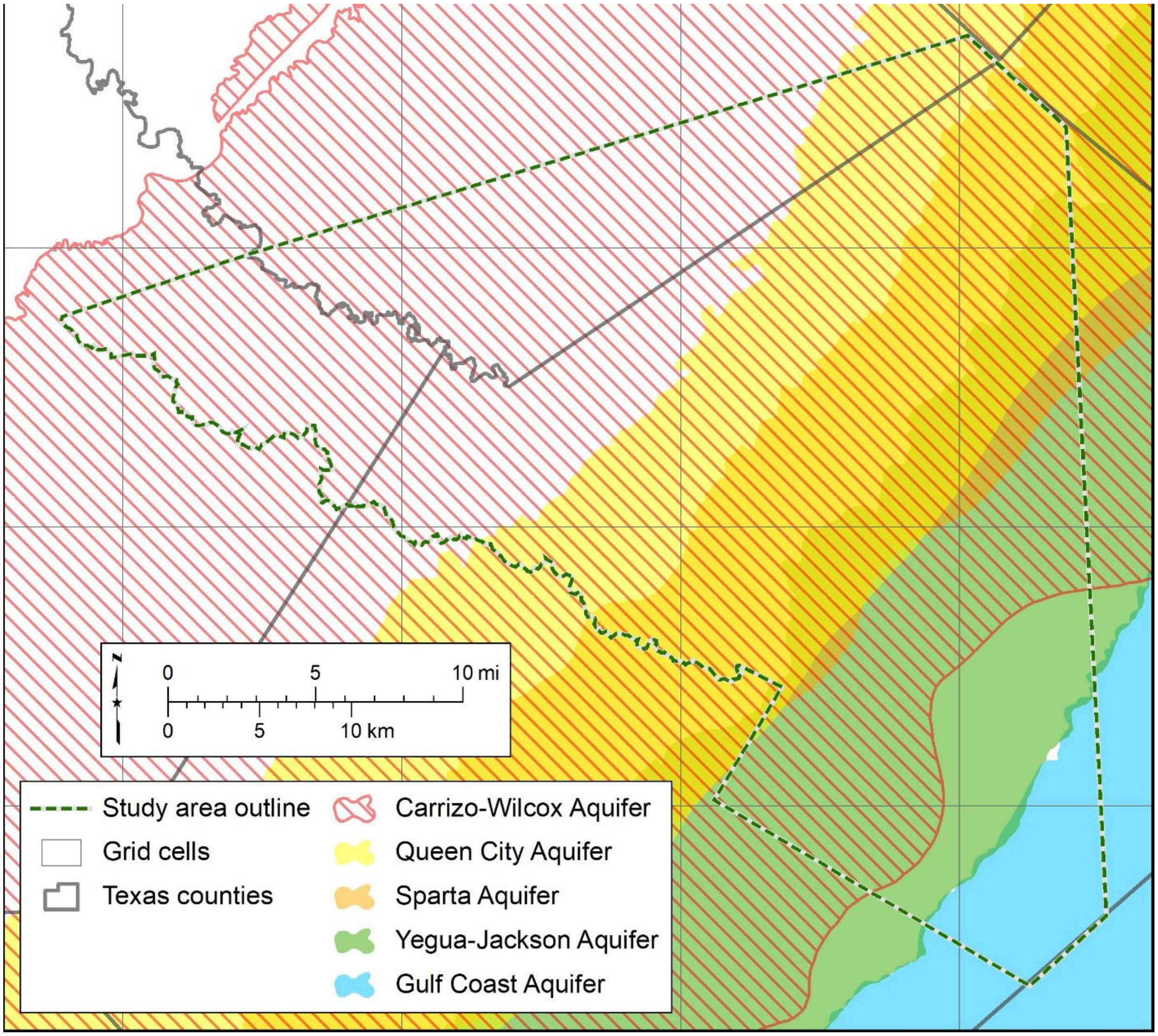


Figure 6-2. Extent of TWDB major and minor aquifer boundaries in the study area.

6.1.2 Excess water ratings

Potential excess water across the aquifer characterization study area comes from several sources, and screening scores range from most to less suitable (0.94–0.27) (Figure 6-3). Excess water screening scores are generally dominated by surface water from the San Marcos or Guadalupe rivers. Most of this surface water is from unappropriated flows from these rivers as no unused appropriated flows or surface reservoirs were identified in the study area in 2020. The GBRA was in the process of acquiring a new surface water permit for the Guadalupe River at this time, so this “unused appropriated flow” wasn’t identified by the Statewide ASR Suitability Survey. No excess groundwater was found to be available within the study area outside of Caldwell County. A small amount of reclaimed water was identified from the cities of Gonzales and Luling.

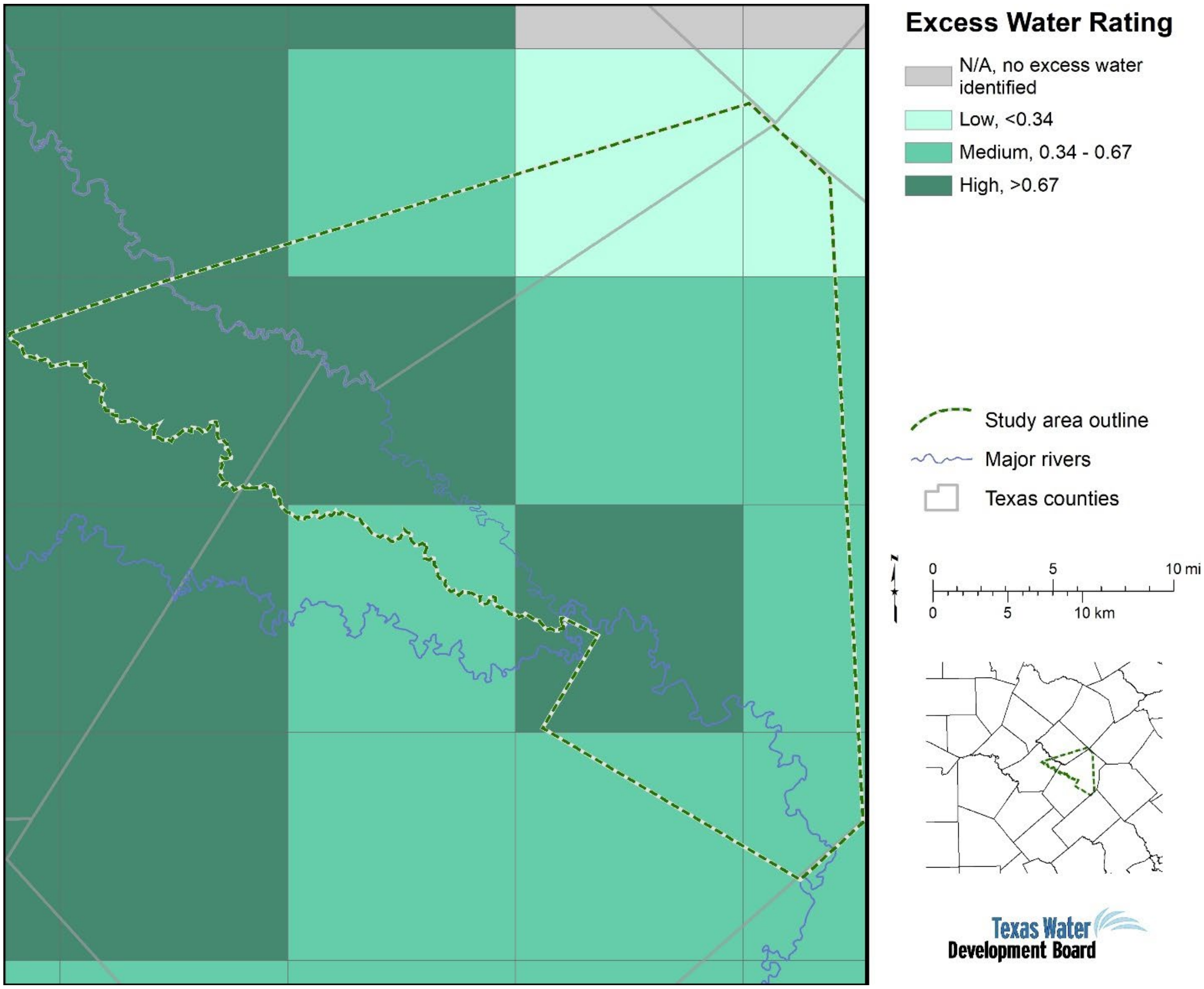


Figure 6-3. **Excess water ratings from the statewide ASR and AR survey for the study area (Shaw and others, 2020).**

6.1.3 Water supply need ratings

The water supply needs screening in the aquifer characterization study area has scores ranging from 0 to 0.92 (Figure 6-4). Current and projected needs from the state water plan were used by this screening and show a pronounced decrease in score from west to east. Most grid cells over the study area indicate the presence of a water user group, but 8 of the 15 grid cells have a volume of need less than the cutoff set to be counted as suitable for an ASR project (Shaw and others, 2020). There are large municipal and manufacturing water needs to the west of the study area in Caldwell and Guadalupe counties. Since the Statewide ASR Suitability Survey utilized need scores from up to two grid cells away, the final suitability for ASR ratings generally decreases from northwest to southeast as the study area gets further away from the larger water needs of the heavily populated I-35 corridor.

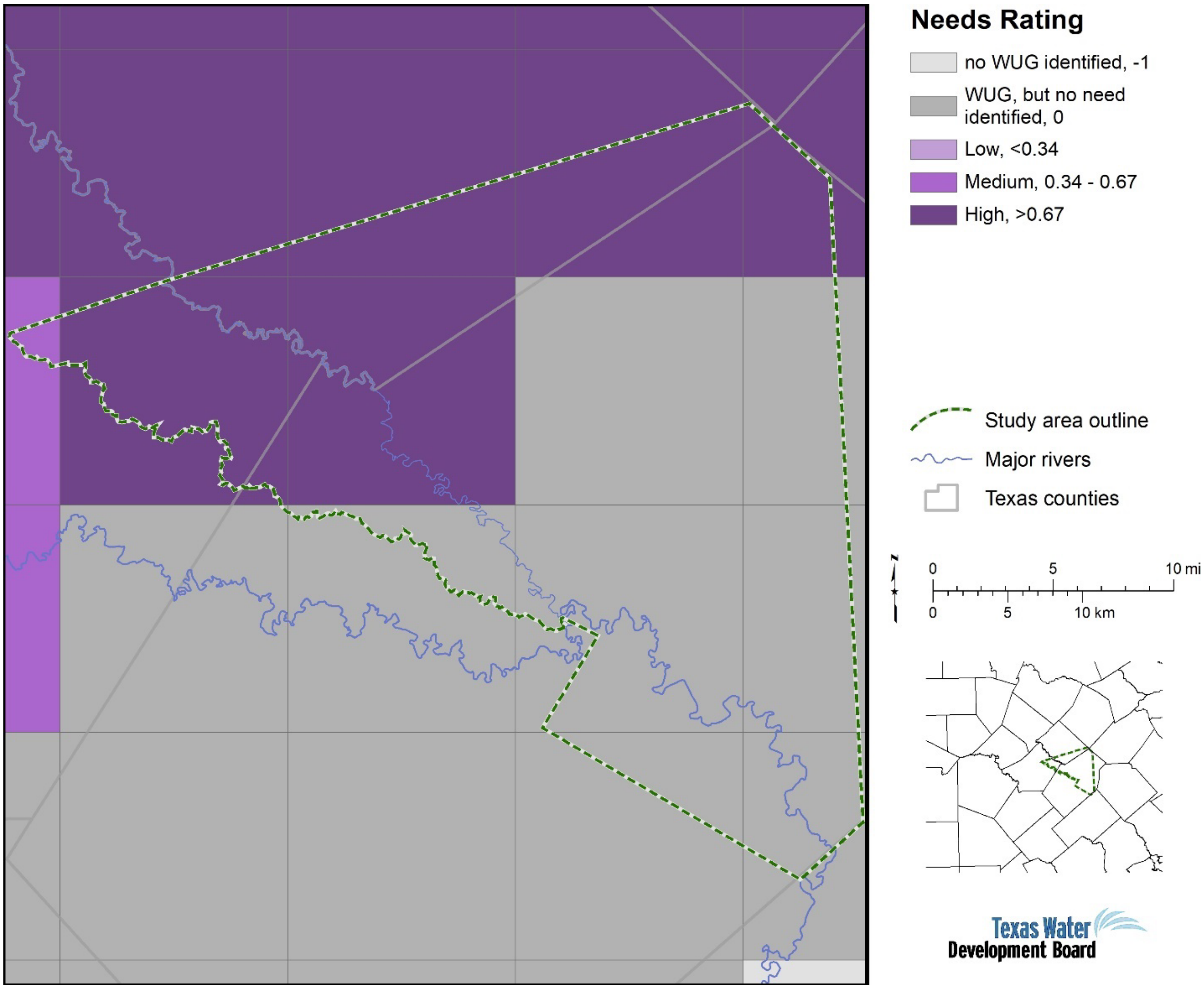


Figure 6-4. **Water supply need ratings from the statewide ASR and AR survey for the study area (Shaw and others, 2020). A score of 0 indicates that a Water User Group is present, but need was not scored in that location.**

6.1.4 Final ASR ratings

All 15 grid cells that overlap with the study area contained ratings from all three of the previously described screenings and therefore received normalized final suitability for ASR ratings. These ratings range from 0.83 to 0.59 (most to less suitable) and generally decrease from northwest to southeast across the entire study area (Figure 6-5). This general trend is driven by several factors across the three individual criteria screenings. The hydrogeological parameter screening indicated generally high scores across the entire study area, so factors other than the aquifer are causing this observed trend. Access to potential excess water is likely one factor in this trend because more excess water is available northwest of the study area. The primary cause of the observed trend, however, is likely the distance from and direction to the populated I-35 corridor, as seen in the water needs screening. The GBRA is planning to develop a distribution network necessary to transport treated water to these populated areas and using a river diversion along the Guadalupe River as a source of excess water.

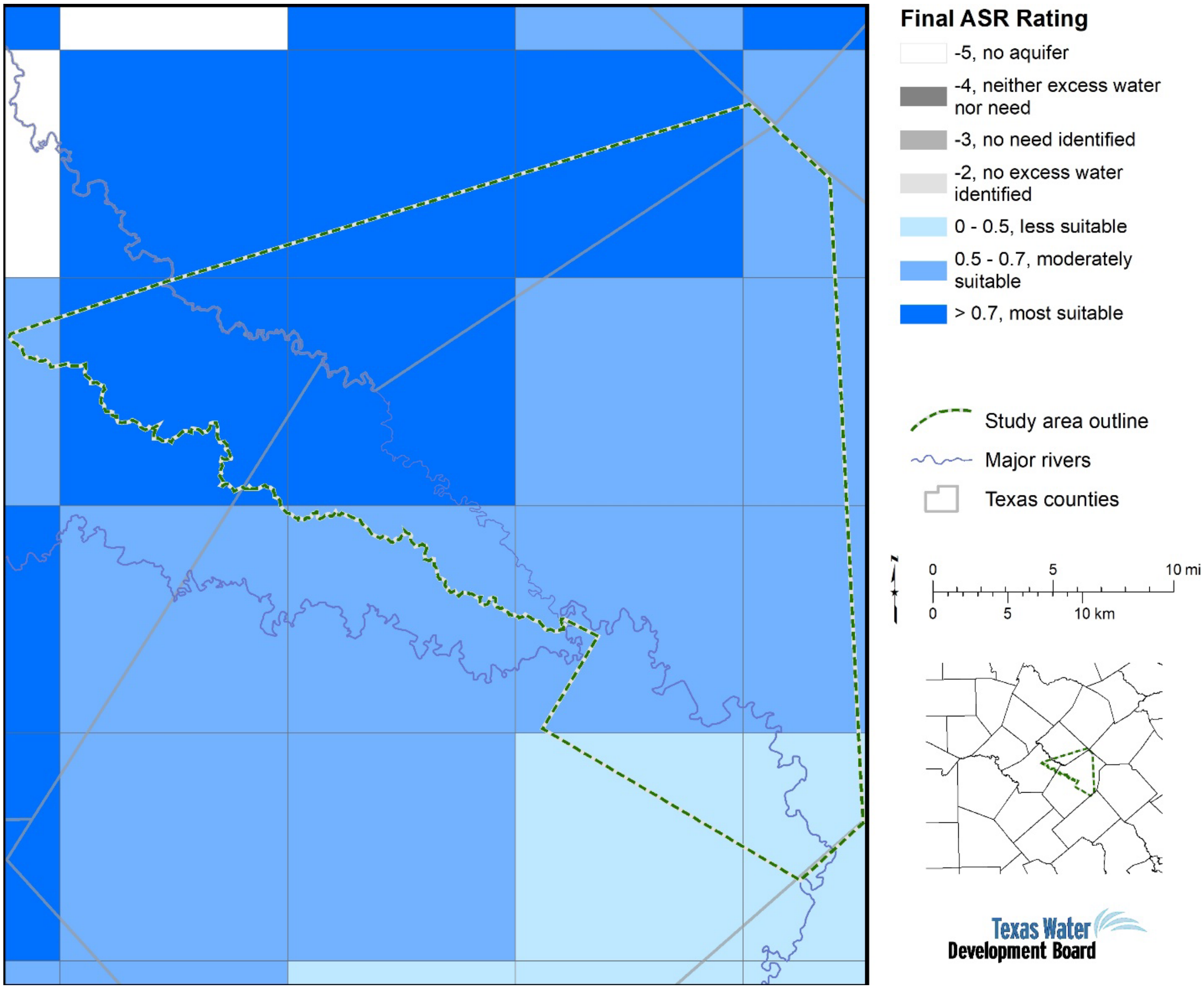


Figure 6-5. **Final suitability ratings for aquifer storage and recovery from the statewide survey for the study area (Shaw and others, 2020).**

Looking at the aquifer characterization study area in the context of the Statewide ASR Suitability Survey illustrates many of the survey's strengths but also shows some of the weaknesses of a large, statewide survey. The Statewide ASR Suitability Survey provides an excellent initial look at the hydrogeological characteristics within the study area as well as some potential sources of excess water and water supply needs. However, the GBRA Mid-Basin Water Supply Project contains several interconnected pieces of infrastructure, including distribution improvements to service the needs of the growing population along the I-35 corridor, which occur at a distance and level of detail greater than the Statewide ASR Suitability Survey was designed to capture. This shows that, while the Statewide ASR Suitability Survey is a powerful tool for examining the potential viability of an ASR or AR project, it does not replace the need for site-specific studies and must be examined with the current extent and infrastructure of the existing utilities in mind.

6.2 Site selection considerations from stratigraphy and lithology

Evaluation of the hydrogeologic characteristics for an ASR project is necessary for the selection of a suitable site location and will inform future planning of infrastructure and treatment requirements for the project (Pyne 2005). We examined both the Carrizo Sand and Wilcox

Group down to a depth of 2,000 feet bgs. This depth limit was provided by the GBRA based primarily on economic considerations for drilling. Additionally, wells deeper than 2,500 feet would likely require staged pump systems and smaller diameter screens leading to additional well design and construction considerations beyond drilling (Pyne, 2005; Shaw and others, 2020).

Stratigraphic results from this aquifer characterization show that both the Wilcox Group and Carrizo Sand are present within the study area and dip below a depth of 2,000 feet in the southeastern portion of the study area (Figures 5-3 and 5-10). When considering well construction costs in the study area, the shallower portion of the Carrizo-Wilcox Aquifer in the northwestern region should be less expensive to develop ASR wells than the deeper portions of the aquifer. In terms of lithology, clean sandstones have the best porosity, permeability, and conductivity, making them preferred targets for injection wells. In addition, ASR projects benefit from having confining units above and below the injection zones, which is important for maintaining control of the injected water and reducing drift of the bubble (Shaw and others, 2020). The northwestern half of the study area also contains a significant amount of thick, clean sands within both the Wilcox Group and Carrizo Sand layers.

The Wilcox Group consists of interbedded clean sands and clay. These sand bodies are commonly less than 100 feet thick and are separated by relatively impermeable clay bodies. These sand bodies can be challenging to correlate across large distances but could provide confined locations for ASR. The exception to this is the Yoakum Canyon, which is dominated by clay and covers a significant portion of the confined Wilcox Group within the study area. Due to the large amount of clay and the large portion of the confined study area dominated by the Yoakum Canyon, the Wilcox Group does not appear to be the best target for ASR in the study area.

Throughout most of Texas, the Carrizo Sand is dominated by thick, massive sands with high porosity. The entire Carrizo Sand is thickest overlaying the Yoakum Canyon and contains the greatest accumulation of net sands; however, these sands are more vertically isolated and contain significantly more clay. Overall, the Carrizo Sand in the study area has a lower portion of clay to sand than the Wilcox Group. Although differences in lithology should be considered when choosing a location for an ASR well field and well construction and operations design, the Carrizo Sand appears to be the more suitable location for an ASR project in the study area. This conclusion is supported by pump test data from three new production wells of the Carrizo Groundwater Supply Project, which show that the aquifer is very productive, and therefore permeable, within the study area. All of these wells were located above the Yoakum Canyon and pump tested between approximately 1,900 and 3,000 gallons per minute. The three wells with pump test data produced no sand over the 36-hour tests and had specific capacities between 27.6 and 41.4 gallons per minute per foot of drawdown. Specific capacity calculations are affected by both the hydrogeological characteristics of the aquifer and by well design specifics such as screen interval and pump size. However, specific capacity can be used to make initial observations on the well’s performance, such as the maximum pumping rate, and estimate the transmissivity of the aquifer.

Based solely on hydrogeological characteristics, the middle third of the study area is likely the most desirable area to place an ASR wellfield within the Carrizo Sand. This area is defined by containing a confined portion of the Carrizo Sand containing at least 300 feet of nets sands within 2,000 feet of the surface (Figure 6-6). These characteristics are considered good targets for an ASR project within the Carrizo Sand based on analysis and operations of the San Antonio Water System, which is discussed in Section 6.4. More than 250 square miles of the Carrizo Sand fit these criteria and are almost entirely upstream of the GBRA's Guadalupe River diversion rights.

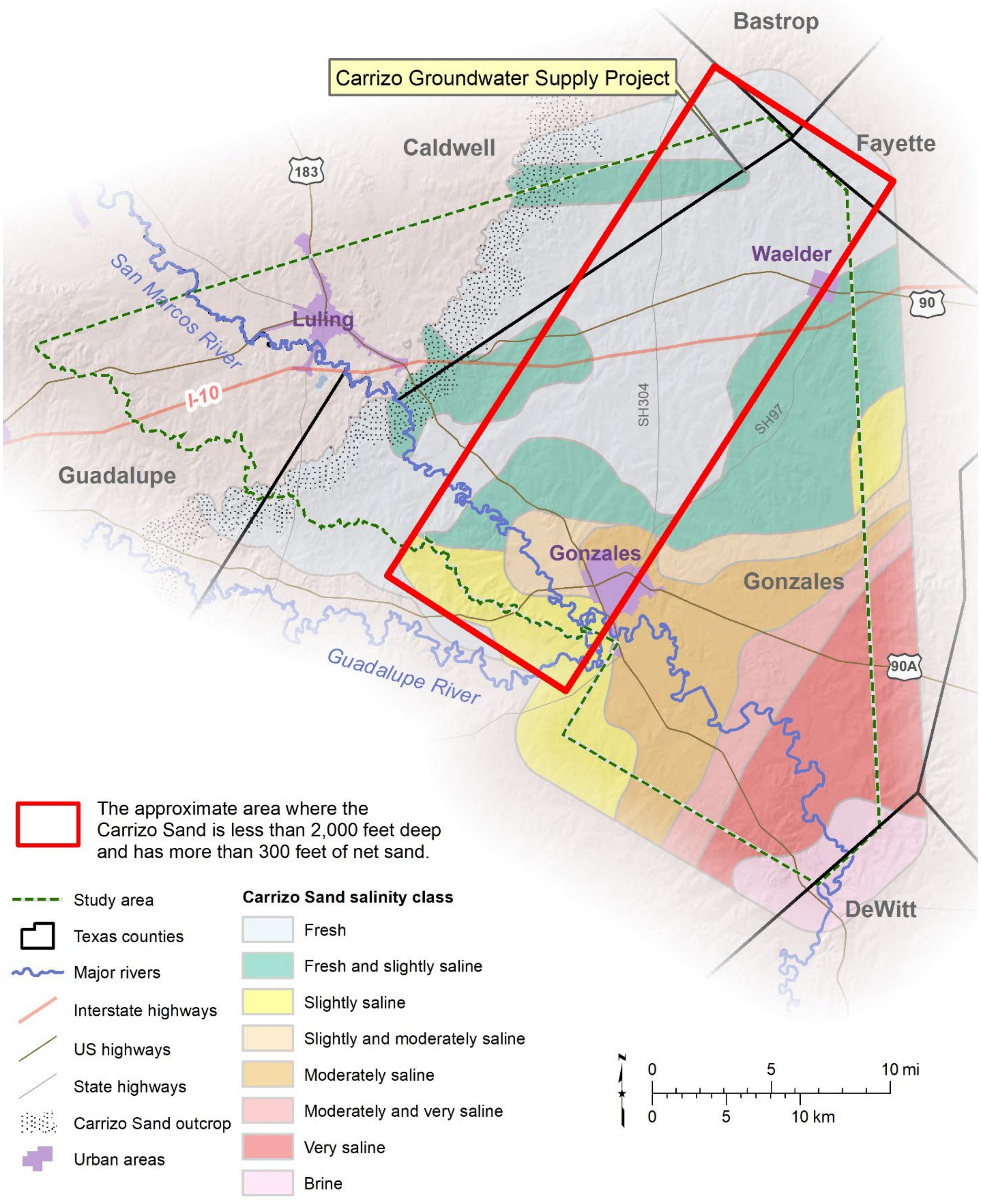


Figure 6-6. **Study area location map with Carrizo Aquifer production well field highlighted. Red rectangle indicates the approximate area of the confined portion of the Carrizo Sand that contains at least 300 feet of net sands within 2,000 feet of the surface.**

6.3 Well construction considerations from salinity mapping and geochemistry

While successful ASR projects have been implemented in a variety of groundwater salinity conditions, refined salinity mapping for the groundwater in the potential project area facilitates better decision making on well field location, well construction design, water treatment, piloting design, and project costs. Understanding the hydrogeological characteristics of an aquifer is critical to designing a well for optimal performance. The characteristics of both raw and treated water may affect the operations and efficiency of a well; therefore, geochemical data on both the native groundwater and the treated injected water should be considered when designing an ASR project (Pyne, 2005).

This aquifer characterization identified significant groundwater salinity changes throughout both the Wilcox Group and the Carrizo Sand in the study area. In general, the Wilcox group is more saline and increases in salinity with distance from the outcrop. Many existing wells contained multiple stacked salinity classes and there was lateral variability with neighboring wells having different water quality. Well design and operations in the more saline and complex areas of the Wilcox Group would need to consider establishing a transition or buffer zone between the native groundwater and injected surface water to protect the water quality of the injected water. The vertical stacking of salinity classes highlights the need to consider scenarios where poorer quality groundwater may be drawn into the desired injection and recovery zones. This may need to be addressed by well design and operations. Selecting to screen sand intervals with substantial clay units isolating them from surrounding sands with poorer water quality may also reduce undesired degradation of the injected water for the ASR project.

Groundwater in the Carrizo Sand is generally fresher than the groundwater in the Wilcox Group in the study area. Looking at the area where the Carrizo Sand is shallower than 2,000 feet deep, most of the groundwater is fresh with an important exception around the City of Gonzales where there is a 46-square-mile lobe of slightly to moderately saline groundwater in the Carrizo Sand (Figure 6-6). Placing an ASR well field here, rather than in the fresh portions of the Carrizo Sand, would add well design and operation complexities to preserve the water quality of the injected and recovered surface water. These complexities could include using more of the surface water to establish a large buffer or transition zone between the host groundwater and treated surface water, managing injection and recovery cycles to maintain this transition zone, and constructing the well infrastructure to withstand a more corrosive environment. These saline groundwater complexities would also affect the project if the GBRA wanted to consider the portion of the Carrizo Sand that is deeper than 2,000 feet bgs but adjacent to its river diversion rights downstream from the City of Gonzales, since this portion of the aquifer is moderately saline to greater than 35,000 milligrams per liter (mg/L) of TDS.

One of the primary considerations affecting well construction is whether the native groundwater is corrosive or incrusting. Measured water quality values can be used to calculate the water's Langelier Saturation Index, which is an estimation of the saturation of calcium carbonate within the sample (Mehmert, 2007). The Langelier Saturation Index is calculated using a sample's pH, alkalinity, calcium concentration, total dissolved solids, and water temperature (Mehmert, 2007). If the Langelier Saturation Index is negative, the water will be corrosive to the casing and screen. If the index is positive, then the water will tend to deposit calcium carbonate on the casing and screen (i.e., encrusting). Additional factors may also contribute to the corrosiveness of the water and are listed below (Mehmert, 2007).

- The primary geochemical characteristics of water that indicate corrosive water conditions include
  - pH that creates a negative Langelier Saturation Index (commonly less than 6.5),
  - hydrogen sulfide concentration greater than 1 mg/L,
  - TDS greater than 1,000 mg/L,
  - free carbon dioxide concentration greater than 50 mg/L, and
  - chloride concentration greater than 200 mg/L.
- The primary geochemical characteristics of water that indicate incrusting water conditions include
  - pH that creates a positive Langelier Saturation Index (commonly greater than 7.5),
  - carbonate hardness greater than 300 mg/L,
  - total iron concentration greater than 0.5 mg/L, and
  - total manganese concentration greater than 0.2 mg/L.

Detailed geochemical data collected as part of Carrizo Groundwater Supply Project (Phase I) of the GBRA Mid-Basin Water Supply Project show that the native groundwater within the Carrizo Sand in the study area has a low TDS, high iron content, and high manganese concentration (Table 6-3). However, the low pH and carbonate hardness overall create corrosive conditions (Table 6-4). Corrosive groundwater can cause well casings and screens to deteriorate, so material selection will be critical (Spencer and others, 2013). Additionally, these wells were completed in the portion of the Carrizo Sand mapped as fresh in Section 5.3, and it is likely that areas mapped as more saline will be increasingly corrosive to the casing and screen materials.

Table 6-3. Water quality data from three wells of the Carrizo Groundwater Supply Project.

Parameter	Well #1	Well #2	Well #3
pH	6.25	6.28	6.12
Carbonate hardness (mg/L)	92.7	86.4	95.3
Iron (mg/L)	10.9	8.7	4.11
Manganese (mg/L)	0.348	0.233	0.329
Hydrogen sulfide (mg/L)	<0.05	<0.05	<0.05
Total dissolved solids (mg/L)	202	182	274
Carbon dioxide (mg/L)	>10	>10	>10
Chloride (mg/L)	50.0	51.0	51.2

Table 6-4. Calculated Langelier Saturation Index for the first three wells of the Carrizo Groundwater Supply Project.

Well	Langelier Index
GBRA Well #1	-2.30
GBRA Well #2	-2.31
GBRA Well #3	-2.55

There are several materials commonly used for well casing and screens that are approved by the TCEQ (Spencer and others, 2013). These materials include plastic, low carbon steel, stainless steel, high-steel low-alloy steel (HSLA), fiberglass, and several various alloys used for specialized conditions (Mehmert, 2007; Spencer and others, 2013). Plastic casing is very corrosion resistant and is commonly used in shallow vadose wells (Spencer and others, 2013). Plastic casing, however, has a relatively low strength and is therefore not suitable for deeper wells or the stresses associated with ASR injection and storage (Pyne, 2005; Spencer and others, 2013). Carbon steel is low cost and the most commonly used casing material in Texas, however, it is highly susceptible to corrosion and can only be used in wells with groundwater that has a positive Langelier Saturation Index (Mehmert, 2007; Spencer and others, 2013). This makes it unsuitable for an ASR well in the study area. HSLA does not have a specific composition but can be formulated to be moderately corrosion resistant (Spencer and others, 2013). HSLA can be high cost and is not a common material; therefore, it is only generally used in specialized projects. Stainless steel is commonly used in water wells where corrosion resistance is needed and there are several types readily available (Spencer and others 2013). The GBRA Carrizo Groundwater Supply Project wells were cased in stainless steel, which is both strong and resistant to salinity up to moderately saline (Mehmert, 2007; Spencer and others, 2013). Fiberglass casing is relatively new and is very corrosion resistant and is generally lower cost than stainless steel. However, fiberglass casing is not nearly as strong as carbon or stainless steel, requires special handling and permitting, and is not commonly available (Spencer and others, 2013). Other alloys such as Hastelloy C can be formatted to be both strong and have corrosion resistance in high salinity to brine conditions (Mehmert, 2007). These alloys are often very high cost and are generally only considered if the project requires resistance to such conditions (Mehmert, 2007).

7. Comparable existing ASR facility

The San Antonio Water System's (SAWS) H_2Oaks ASR Facility (referred to hereafter as the SAWS ASR Project) is located approximately 30 miles south of San Antonio and was developed to capture Edwards Aquifer water during wet periods and store it in the Carrizo Sand to meet peaks in demand (Morris and others, 2010; Miller and others, 2020). The SAWS ASR project does not use surface water as an injectate but instead transfers water from the more transmissive karstic Edwards Aquifer to the shallower Carrizo-Wilcox Aquifer, since it has better hydrogeologic properties for water storage and recovery (Miller and others, 2020).

The Carrizo Sand was selected by SAWS for several reasons but most notably its confinement and low regional demand (Morris and others, 2010). The Carrizo Sand is vertically hydraulically isolated between the Wilcox Group shale layers below and the thick marine shales of the Reklaw Formation above. This isolation means that there is little to no transfer of water from the Carrizo Sand through the Reklaw Formation to overlying surface water. The Carrizo Sand was also not heavily utilized in the region. This is similar to the study area, where most water wells were completed in the shallower Queen City and Sparta aquifers. This relatively low demand on the Carrizo Sand portion of the Carrizo-Wilcox Aquifer means that the water is under constant confinement pressure, and this helps maintain a stable bubble of injected water with minimal formation water mixing (Morris and others, 2010). This storage bubble can, however, be affected by hydrogeologic gradients, and SAWS reports an average drift in the stored water bubble of approximately 5 feet per year.

On February 11, 2021, TWDB staff and the GBRA met with SAWS representatives to discuss what was learned during the development and operations of their ASR wellfield. SAWS gave an overview of the project and discussed the importance of the planning process as ASR regulation and permitting has changed significantly since the planning phases of the SAWS ASR project in 1996 (see Section 6.5). To address potential operation impacts on surrounding owners, SAWS developed a well mitigation program for Carrizo Sand wells in the vicinity of the ASR project. Additionally, SAWS shared the following insights:

- Take the time and resources to provide outreach to educate and engage the public, stakeholders, and political leadership.
- Work closely with both contracted engineers and drilling experts to design the wellfield with both the current goals and anticipated growth in mind.
- Use the Competitive Sealed Proposal method to procure the best drilling firm (based on price and qualifications).
- Document the groundwater conditions before, during, and after the project. Implement comprehensive and accurate sampling on regular intervals, including
    - water quality from wells near the planned wellfield to select the proper materials for the well casing and pump column prior to drilling the ASR wells;
    - water quality from each ASR well during storage and recovery operations for use in future water chemistry modeling; and
    - water level information from the supervisory control and data acquisition (SCADA) system used to operate the well field.
- Construct recovery wells downgradient from injection, because the hydraulic gradients in the Carrizo Sand can affect recovery. Water sampling records can be a benefit when planning for this challenge.
- Implement practices to mitigate collapse in the Carrizo Sand, such as
    - using two-piece construction method for the ASR wells;
    - immediately placing the gravel pack after landing the screen section of the casing; and
    - ensuring no voids (bridges) in the gravel pack occur by carefully monitoring the installation.
- Utilize hydrologic models and update them periodically as new information is gathered to increase the efficiency of the well field operations.
- Pipe loop test the ASR well water and distribution system water for detrimental impacts, such as color and descaling, when the ASR water is introduced to the distribution system.

Although the SAWS ASR project shares several similarities with the GBRA ASR project, it is important to note that there are several major differences. The SAWS ASR project is much larger in scale, is designed to meet the needs of the San Antonio metropolitan area, and drilled 29 ASR wells from 2002 to 2005. The GBRA ASR project is planned to begin smaller and expand with increasing demand over time. This longer development will allow the GBRA to test and make adjustments to wellfield design based on direct observations of the hydrogeological properties of the aquifer, something that was not possible in the development timeframe of the SAWS ASR project.

A second major difference between the SAWS ASR wellfield and the proposed GBRA ASR project is that the aquifer characterization study area for this investigation is north of the San Marcos Arch, whereas SAWS' facility is south of this regional structure. Many studies have documented significant differences in the stratigraphy and lithology of the Carrizo Sand on either side of the San Marcos Arch (e.g., Payne, 1975; Ambrose and others, 2020; Meyer and others, 2020). The Carrizo Sand north of the San Marcos Arch is generally thinner, averaging only 100–200 feet, but thickens greatly to several hundred feet toward the study area. These sands were deposited by the Rockdale Delta System and therefore may contain more discontinuous sands that were deposited with some fluvial influence. However, during this period, the most active portion of the Carrizo Sand was south of the San Marcos Arch and deposited cleaner, massive shoreface sands where the SAWS ASR Project is located (Dutton and others, 2003). Although the depositional environments were different, this study shows that several criteria that were prominent in site selection for the SAWS ASR Project are present within the aquifer characterization study area, including

- enough net sand for approximately 100 to 250 feet of well screen;
- confinement above and below the Carrizo Sand; and
- good to moderate water quality.

Pump test data from three new production wells in the Carrizo Sand of the GBRA's Carrizo Groundwater Supply Project show that the aquifer is very productive within the study area. All of these wells were located above the Yoakum Canyon and pump tested between approximately 1,900 and 3,000 gallons per minute. The three wells with pump test data produced no sand over the 36-hour tests and had specific capacities between 27.6 and 41.4 gallons per minute per foot of drawdown. This is slightly lower than what was seen at the SAWS ASR wellfield, which ranged between 45 and 60 gallons per minute per foot of drawdown at initial testing (Morris and others, 2010). Specific capacity calculations are affected by both the hydrogeological characteristics of the aquifer and by well design specifics such as screen interval and pump size. However, specific capacity can be used to make initial observations on the well's performance such as the maximum pumping rate and estimate the transmissivity of the aquifer.

The third major difference between the SAWS and GBRA ASR projects is the source of the injected water. As mentioned above, the SAWS ASR project is an aquifer-to-aquifer system. The groundwater pumped from the Edwards Aquifer is of high quality and treated to drinking water standards prior to injection. Only disinfection is needed to prepare recovered water for distribution (Morris and others 2010). SAWS has not had issues with the injected water plugging well screens (Morris and others 2010) or any issues with contaminant metal mobilization. The GBRA ASR project plans on storing surface water treated to potable water standards. When compared to groundwater, surface water typically requires a higher degree of treatment to reach potable water standards, assure no degradation of native groundwater, and limit plugging of well screens. Currently, the GBRA is contributing Carrizo Sand well cuttings to the Texas Bureau of Economic Geology to get initial geochemical data that will be useful to investigate geochemical compatibility for its project (Perkins and Fakhreddine, 2021).

While there are several similarities between the GBRA ASR and SAWS ASR projects, the above differences again show the importance of site-specific investigations for the planning of ASR systems. The GBRA ASR project is smaller in scale but has several additional challenges that were not part of the SAWS ASR planning process. However, as ASR continues to be explored as a water management strategy in Texas, the lessons learned from previous projects can provide a framework for how to plan a new project and spot potential challenges in advance.

8. ASR regulations and permitting

All ASR injection and recovery wells in Texas must be authorized by the Texas Commission on Environmental Quality (TCEQ) Underground Injection Control (UIC) program. Regulatory requirements for Class V injection wells are in the 30 Texas Administrative Code § 331. Subchapter H provides the standards for all Class V wells and Subchapter K has additional requirements for ASR projects. For example, all ASR injection and recovery wells associated with a single ASR project must be located within a continuous perimeter boundary of one parcel of land or within two or more parcels of land under common ownership or lease. Also, applicants for an ASR injection well authorization are also required to contact the Texas Railroad Commission Groundwater Advisory Unit if the target storage aquifer has native groundwater with TDS greater than 3,000 milligrams per liter (moderately saline water). Since the GBRA's proposed ASR project will be for public water supply, an additional approval will be required for the recovered water being used as public water supply. Public water system plans need to be submitted to the TCEQ Water Supply Division/Plan and Technical Review Section for approval before construction begins.

On December 16, 2020, TWDB staff and GBRA met with TCEQ UIC program representatives to discuss the authorization process for a Class V ASR well. The TCEQ provided a general overview of the statutes and the authorization process. Due to the complexity of the process, it was recommended that applicants have pre-authorization meetings with the TCEQ as they develop the project. Such pre-authorization meetings will allow the GBRA to develop their project in conjunction with state statutes and streamline the later authorization process.

The TCEQ also explained the difference between applying for authorization for a pilot test as opposed to an operational facility. There are several options including: filing a full Class V authorization prior to the study, applying for the project in two phases, or potentially applying for an experimental well authorization. Early pre-authorization meetings with the TCEQ will help an applicant determine the best approach for the project.

The TCEQ UIC Class V ASR authorization application process does not require application or operation fees. The UIC Permits Section provides a form and instructions for ASR well permits and authorizations that documents the required information for completing the application, www.tceq.texas.gov/permitting/radmat/uic_permits/UIC_Guidance_Class_5.html (TCEQ, 2018). The application must have a notarized signature page and include

- information to post notice, such as for groundwater conservation districts the project is within;
- the project area and any contracts with landowners;
- identification of artificial penetrations (wells) in the area of review;

- well construction and closure details;
- injection well operation details;
- the regional geology, hydrogeology, and geochemistry;
- site-specific geology;
- the source and characteristics of the water to be injected;
- the planned horizontal and vertical extents, residence time, and effects of the injected water in and on the native groundwater of the aquifer;
- operation plans (including cycle testing, injection pressures, and maintenance); and
- and demonstration of recoverability.

A web-based model has been developed by the University of Texas at Austin. It is provided to the public by the TCEQ to complete the demonstration of recovery analysis, the last item in the list above, and is accessed on the TCEQ website at https://txasr.tceq.texas.gov/. This model requires the users to enter an estimate of hydraulic conductivity, hydraulic gradient, porosity, aquifer thickness, injection volume, injection time, storage time, extraction volume, and extraction time to receive the modeled recoverability. However, for more complex projects involving multiple injection wells and/or nearby extraction wells, a more complete model is recommended (Alcalde and Werth, 2019).

The TCEQ is required to notify groundwater conservation districts and certain other special purpose districts of proposed ASR projects within their jurisdictional boundaries. Once an authorization is reviewed for completeness and granted, it may or may not have an expiration or renewal date. The TCEQ will need specific data reports for initial well construction and operation (i.e., cycle testing), well closure reports, and possibly other site-specific reporting elements. ASR authorizations will also require reporting on key UIC operational parameters, which can include

- monthly injection volumes, recovery volumes, and average injection pressures;
- annual injected and recovered water quality analyses; and
- other data such as monitoring well water levels and water quality.

The TCEQ also provided examples of issues other utilities have come across in the process of authorizing and developing ASR projects, such as clogging (well screen and/or formation) and arsenic mobilization. Treating and conditioning water prior to injection and thoughtful well operations can alleviate some of these issues, as can developing and maintaining a buffer (mixing) zone between the stored water bubble and the native groundwater. The TCEQ has contracted with the University of Texas at Austin Bureau of Economic Geology and Center for Water and the Environment to develop guidelines to minimize the potential for arsenic mobilization. These guidelines should be available on the TCEQ website in 2022.

9. Conclusions

The capture and storage of water when it is available is a critical challenge faced by many water utilities across Texas (Malcolm Pirnie, 2011). The 2022 State Water Plan projects increasing need across the state, particularly in areas with growing populations, and meeting this increasing demand will require the use of supplementary methods (TWDB 2021d). Aquifer storage and recovery is a flexible and commonly cost-effective method that is gaining increased interest across Texas (Malcolm Pirnie, 2011; Morris and others 2010). In general, ASR systems are half the capital cost of other water storage options such as surface reservoirs or storage tanks (Morris and others, 2010).

The GBRA needed an aquifer characterization to facilitate site selection, which is the next step in its plan for implementing the ASR portion of the Mid-Basin Water Supply Project. This aquifer characterization study provides data and maps on the depth, extent, lithology, and salinity of the Wilcox Group and Carrizo Sand needed for the hydrogeological portion of the site selection process. It shows that there are considerable differences between the characteristics of sands across the study area and that there is considerable complexity in the salinity classes. Understanding the geography of these hydrogeological characteristics will inform future planning and engineering decisions for developing the ASR project for the GBRA. This report also provides some of the regional geologic information that is needed for the TCEQ ASR project authorization application. In addition to the aquifer characterization, the site selection process will also need to

- engage potential customers, landowners, political leaders, and/or government agencies;
- review project goals;
- evaluate existing and planned infrastructure;
- estimate project costs;
- consider environmental impacts; and
- assess economic viability.

Public data from 662 wells were utilized for this aquifer characterization. Analyses were a combination of new interpretations and updates on a number of wells previously used in TWDB studies, such as Meyer and others (2020). This additional data allowed us to refine the stratigraphic and lithologic interpretations within the study area and reevaluate the salinity class mapping to create a more accurate and detailed salinity class map for the study area.

Our stratigraphic mapping identified that the approximately northwestern half of the study area has either Wilcox Group or Carrizo Sands less than 2,000 feet deep. When considering well construction costs in the study area, this shallower portion of the Carrizo-Wilcox Aquifer should be less expensive to develop ASR wells than the deeper portions of the aquifer. In terms of lithology, clean sandstones have the best porosity, permeability, and conductivity, making them targets for injection wells. In addition, ASR projects benefit from having confining units above and below the injection zones, which is important for maintaining control of the injectate and reducing drift of the bubble (Shaw and others, 2020). The northwestern half of study area also contains a significant amount of thick, clean sands within both the Wilcox Group and Carrizo Sand layers. The Wilcox Group, in general, contains isolated sand units with thick interbedded clays. The shale-filled Yoakum Canyon is a significant feature in the Wilcox Group and contains few sand units. The Carrizo Sand is dominated by thick, massive sands with high porosity. The entire Carrizo Sand is thickest overlaying the Yoakum Canyon and contains the greatest accumulation of net sands. The sands in this area are more vertically isolated and contain significantly more clay. These differences in lithology should be considered when choosing a location for an ASR field and well construction and operations design. There are over 200 square miles of the confined portion of the Wilcox Group that is greater than 300 feet of net sands and less than 2,000 feet deep. More than 250 square miles of the Carrizo Sand fit those criteria.

While successful ASR projects have been implemented in a variety of groundwater salinity conditions, refined salinity class mapping for the groundwater in the potential project area facilitates better decision making on well field location, well construction design, water treatment, piloting design, and project costs. Both the Wilcox Group and the Carrizo Sand show significant groundwater salinity changes throughout the northwestern half of the study area. In general, the Wilcox Group is more saline and increases in salinity with distance from the outcrop. Many existing wells had multiple stacked salinity classes and there was lateral variability with neighboring wells having different water quality. Well design and operations in the more saline and complex areas of the Wilcox Group would need to consider establishing a transition or buffer zone between the native groundwater and injected surface water to protect the water quality of the recovered water. The vertical stacking of salinity classes highlights the need to consider scenarios where poorer quality groundwater may be drawn into the desired injection and recovery zones and may need to be addressed by well design and operations. Groundwater in the Carrizo Sand is generally fresher than the groundwater in the Wilcox Group in the study area, with at least one freshwater well and several freshwater calculations south of State Highway 97. Looking at the area where the Carrizo Sand is shallower than 2,000 feet deep, most of the groundwater is fresh with an important exception around the City of Gonzales where a 46-square-mile lobe of slightly to moderately saline groundwater is in the Carrizo Sand. Placing an ASR well field here, rather than in the fresh portions of the Carrizo Sand, would add well design and operation complexities to preserve the water quality of the injected and recovered surface water.

The information contained within this report is not intended to replace the need for further investigation but rather to inform and provide a source of data for further engineering and infrastructure studies. Collection of well-field scale data on water quality and hydrogeology is recommended to evaluate a final site location for an ASR field and associated system.

10. References

Adams, S.S., and Smith, R.B., 1980, Geology and recognition criteria for sandstone uranium deposits in mixed fluvial-shallow marine sedimentary sequences, south Texas: Contract report by Samuel S. Adams and Associates and R.B. Smith and Associates prepared for the U.S. Department of Energy, 162 p.

Alcalde, R.E. and Werth, C.J., 2019, A modeling approach to assess the feasibility of water injection, storage, and recovery: ASR recoverability guidance project: presentation at the University of Austin Trade Fair, Austin, Texas.

Ambrose, W.A., Flaig, P., Zhang, J., Olariu, M.I., Denison, C., Demchuck, T., and O'Keefe, J., 2020, The Midway to Carrizo succession in the southeastern Texas Gulf Coast: Evolution of a tidally-influenced coastline: Gulf Coast Association of Geological Societies Journal, vol. 9, p. 41-75.

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Petroleum Technology, v. 5, p. 54-62.

Bebout, D. G., Weise, B. R., Gregory, A. R., and Edwards, M. B., 1982, Wilcox sandstone reservoirs in the deep subsurface along the Texas Gulf Coast: Their potential for production of geopressured geothermal energy: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 117, 125 p.

Black & Veatch, Daniel B. Stephens & Associates, Inc., SWCA Environmental Consultants, and Ximenes & Associates, Inc., 2020, 2021 South Central Texas Regional Water Plan – Region L, Volume 2, 868 p.

Blondes, M.S., Gans, K.D., Rowan, E.L., Thordsen, J.J., Reidy, M.E., Engle, M.A., Kharaka, Y.K., and Thomas, B., 2016, U.S. Geological Survey national produced waters geochemical database v2.2 (Provisional): U.S. Geological Survey, 28 p. and database files.

Breton, C., 2013, Digital GIS version of the tectonic map of Texas by Ewing (1991): The University of Texas at Austin, Bureau of Economic Geology, compact disk.

Brown, L.F., Jr., and Loucks, R.G., 2009, Chronostratigraphy of Cenozoic depositional sequences and systems tracts: A Wheeler chart of the northwest margin of the Gulf of Mexico Basin: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations 273, 28 p. and one plate.

Chuber, S., and Begeman, R. L., 1982, Productive lower Wilcox stratigraphic traps from an entrenched valley in Kinkier Field, Lavaca County, Texas: Gulf Coast Association of Geological Societies Transactions, vol. 32, p. 255-262.

Demchuk, T.D., Denison, C.N., and O'Keefe, J., 2019, An integrated reevaluation of Wilcox/Carrizo stratigraphy, Bastrop County, Texas: Refined chronostratigraphy and revised paleoenvironments, in Denne, R.A and Kahn, A. (eds.) Geologic Problem Solving with Microfossils IV: SEPM Special Publication No. 111, p. 172-185.

Dickey R.L. and Yancey T.E., 2010, Palynological age control of sediments bracketing the Paleocene–Eocene boundary, Bastrop, Texas: Transactions of the Gulf Coast Association of Geological Societies, vol. 60, p. 717–724.

Dingus, W.A., 1987, Morphology, paleogeographic setting, and origin of the Middle Wilcox Yoakum Canyon, Texas Coastal Plain: The University of Texas at Austin, M.A. thesis, 77 p.

Dutton, A.R., Harden, B., Nicot, J.P., and O'Rourke, D., 2003, Groundwater availability model for the central part of the Carrizo-Wilcox Aquifer in Texas: Texas Water Development Board Contracted Report, No. 2001-483-378.

Estepp, J.D., 1998, Evaluation of ground-water quality using geophysical logs: Texas Natural Resource Conservation Commission, unpublished report, 516 p.

Ewing, T.E., 1991, The tectonic framework of Texas: The University of Texas at Austin, Bureau of Economic Geology report to accompany the Tectonic Map of Texas, 36 p. and one plate.

Fisher, R.S., 1982, Diagenetic history of Eocene Wilcox Sandstones and associated formation waters, south-central Texas: Ph.D. dissertation, The University of Texas at Austin, 185 p.

Freese and Nichols, HDR Engineering, K Friese & Associates, SWCA Environmental Consultants, CH2M Hill, 2017, Mid-Basin Water Supply Project Study Final Draft Engineering Feasibility Report: contract report to the Guadalupe-Blanco River Authority and the Texas Water Development Board, 87 p.

Fisher, W.L. and McGowen, J.H., 1967, Depositional Systems in the Wilcox Group of Texas and their relationship to the occurrence of oil and gas: Transactions of the Gulf Coast Association of Geological Societies, vol. 18, p. 105-125.

Galloway, W.E., 1989. Genetic Stratigraphic Sequences in Basin Analysis II: Application to Northwest Gulf of Mexico Cenozoic Basin. AAPG Bulletin, vol 73, no.2, p. 143-154.

Galloway, W.E., Dingus, W.A., and Paige, R.E., 1991. Seismic and depositional facies of Paleocene-Eocene Wilcox Group submarine canyon fills, northwest Gulf Coast, USA, in Weimer, P. and Link, M.H. (eds.), Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems), p. 247–271.

Galloway, W.E., Ganey-Curry, P.E., Li, X., and Buffler, R.T., 2000, Cenozoic depositional history of the Gulf of Mexico basin: American Association of Petroleum Geologists Bulletin, v. 84, p. 1743-1774.

George, P.G., Mace, R.E., and Petrossian, R., 2011, Aquifers of Texas: Texas Water Development Board Report 380, 172 p.

LBG-Guyton Associates, 2007, Preliminary evaluation of groundwater resources in the Wilcox Aquifer, Gonzales and eastern Wilson counties: LBG-Guyton Associates, contract report to the San Antonio Water System, 42 p.

Olariu, M.I. and Ambrose, W.A., 2016, Process regime variability across growth faults in the Paleogene Lower Wilcox Guadalupe Delta, South Texas Gulf Coast: Sedimentary Geology, vol. 341, pp.27–49.

Mehmert, M., 2007, Chapter 9: Production Water Well Design: in Sterrett, R.J. (ed.), Groundwater and Wells, Johnson Screens, New Brighton, MN, p. 353–438.

Meyer, J.E., 2020, Brackish Resources Aquifer Characterization System Database data dictionary: Texas Water Development Board Open-File Report 12-02, Fifth Edition, 260 p.

Meyer, J.E., Croskrey, A.D., Suydam, A.K., and van Oort, N., 2020, Brackish Groundwater in aquifers of the upper coastal plains, central Texas: Texas Water Development Board Report 385, 278 p.

Miller, K., Milman, A., Burson, M., Tracy, J., and Kiparsky, M., 2020, Groundwater Recharge for Drought and Endangered Species Protection: The H$_2$Oaks Aquifer to Aquifer Transfer for Storage and Recovery, San Antonio, Texas: Case Studies in the Environment, Special Collection: Institutional Dimensions of Groundwater Recharge, p. 1-10.

Morris, T., Macias, R., and Pyne R.D.G., 2010, Design, installation, and operation challenges of large-scale aquifer storage and recovery wells in San Antonio, South Texas, in Chang, N.B. (ed), Effects of urbanization on groundwater: an engineering case-based approach for sustainable development: American Society of Civil Engineers (ASCE), p. 1-26.

Novalis, S., 1999, Access 2000 VBA Handbook: Sybex, Inc., 845 p.

Parkhurst, D.L and Appelo, C.A.J., 2013, Description of input and examples for PHREEQC Version 3—A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations: U.S Geological Survey Techniques and Methods 6-A43, 497 p.

Payne, J.N, 1975, Geohydrologic significance of the lithofacies of the Carrizo Sand of Arkansas, Louisiana, and Texas and the Meridian Sand of Mississippi: U.S. Geological Survey Professional Paper 569-D. 11 p.

Perkins, R.B., Guadalupe-Blanco River Authority: Seguin, Texas, personal communication, October 2020.

Perkins, R.B. and Fakhreddine, S., Guadalupe-Blanco River Authority: Seguin, Texas and Texas Bureau of Economic Geology: Austin, Texas, personal communication, August 2021.

Pirnie, 2011, An assessment of aquifer storage and recovery in Texas: Texas Water Development Board Contract Report 0904830940, 117 p.

Pyne, R.D.G., 2005, Aquifer Storage and Recovery: A Guide to Groundwater Recharge Through Wells: ASR Systems LLC, ASR Systems Press, Gainesville, FL.

Railroad Commission of Texas, 2020a, Groundwater Advisory Unit Q-log geophysical well log collection.

Railroad Commission of Texas, 2020b, Wellbore Database: Railroad Commission of Texas.

Ryder, P.D., 1996, Ground water atlas of the United States, segment 4 Oklahoma and Texas: U.S. Geological Survey Hydrologic Investigations Atlas 730-E, 30 p.

SCTRWPG (South Central Texas Regional Water Planning Group), 2016, 2016 South Central Texas Regional Water Plan, administration by San Antonio River Authority, technical assistance by HDR Engineering, Inc., and Ximenes & Associates, Inc., Volume 2, 586 p.

Shafer, G.H., 1966, Ground-water resources of Guadalupe County, Texas: Texas Water Development Board Report 19, 93 p.

Shaw, K.S., Stein, Z.A., Deeds, N.E., George, P.G., Milczarek, M., and Yang, Q., 2020, Statewide survey of aquifer suitability for aquifer storage and recovery projects or aquifer recharge projects: contract report by HDR Engineering with support by the Bureau of Economic Geology at the University of Texas at Austin, Collier Consulting, Cooper Consulting, GeoSystems Analysis Inc., INTERA Inc., and Floodace, prepared for the Texas Water Development Board, 234 p.

Smith, W.B., Miller, G.R., and Sheng, Z., 2017, Assessing aquifer storage and recovery feasibility in the Gulf Coastal Plains of Texas: Journal of Hydrology, vol. 14, p. 92-108.

Spencer, K.J., Harden, B., Leal, J., and Sanchez, S., 2013, Guidance Manual: Fiberglass Casing Use in Texas Water Supply Wells: contract report by R.W. Harden and Associates, prepared for the Texas Water Development Board, 117 p.

TCEQ (Texas Commission on Environmental Quality), 2018, UIC Class V ASR Injection Well Application, TCEQ-20772 (Revised June 18, 2018), 15 p.

Torres-Verdín, C., 2017, Integrated geological-petrophysical interpretation of well logs: Department of Petroleum and Geosystems Engineering, The University of Texas at Austin, unpublished class notes, variously paginated.

TWDB (Texas Water Development Board), 2007a, Water for Texas 2007, Volume II: Texas Water Development Board Report GP-8-1, 392 p.

TWDB (Texas Water Development Board), 2007b, The Geologic Atlas of Texas: U.S. Geological Survey, contract geodatabase to the Texas Water Development Board, Version 3, one geodatabase.

TWDB (Texas Water Development Board), 2017, Water for Texas, 2017 State Water Plan: Texas Water Development Board, 150 p.

TWDB (Texas Water Development Board), 2020, Statewide Survey of Aquifer Suitability for Aquifer Storage and Recovery Projects or Aquifer Recharge Projects [Abridged]: Texas Water Development Board Special Legislative Report to the 87th Texas Legislature, 126 p.

TWDB (Texas Water Development Board), 2021a, Brackish Resources Aquifer Characterization System Database (BRACS DB): Texas Water Development Board.

TWDB (Texas Water Development Board), 2021b, Groundwater Database (GWDB): Texas Water Development Board.

TWDB (Texas Water Development Board), 2021c, Submitted Driller's Report Database (SDR): Texas Water Development Board.

TWDB (Texas Water Development Board), 2021d, Water for Texas, 2022 State Water Plan: Texas Water Development Board, 203 p.

Warwick, P.D., 2017, Geologic assessment of undiscovered conventional oil and gas resources in the lower Paleogene Midway and Wilcox Groups, and the Carrizo Sand of the Claiborne Group, of the northern Gulf Coast region: U.S. Geological Survey Open-File Report 2017–1111, 67 p.

Webb, M.L., 2015. Aquifer Storage and Recovery in Texas: 2015, Texas Water Development Board Technical Note 15-04, 42 p.

Winkler, C. D., 1982, Cenozoic shelf margins, Northwestern Gulf Coast: Gulf Coast Association of Geological Societies Transactions, vol. 32, p.427-448.

Winslow, A.G., and Kister, L.R., 1956, Saline-water resources of Texas: U.S. Geological Survey Water-Supply Paper 1365, 105 p.

11. Appendix A – Detailed methodology

The goal of this study is to provide a detailed characterization of the Carrizo-Wilcox Aquifer to the GBRA to aid in the site selection process for the GBRA ASR project. The work completed for this aquifer characterization study builds off *Brackish Groundwater in Aquifers of the Upper Coastal Plains, Central Texas* (UCPA), a regional study covering the entirety or parts of 14 counties (Atascosa, Bastrop, Bexar, Caldwell, Dewitt, Fayette, Gonzales, Guadalupe, Karnes, Lavaca, Lee, Live Oak, Williamson, and Wilson) that included a hydrogeological analysis of the geological formations containing the Carrizo-Wilcox, Queen City, Sparta, and Yegua-Jackson aquifers (Meyer and others, 2020). Hereto "UCPA study" will be used to refer to that study in general, including database records and GIS data and "TWDB Report 385" will be used to refer to the published final report from the UCPA study.

This study utilizes additional well control that was available from the BRACS Database and the Railroad Commission of Texas records that were not included in the regional UCPA study. Additional analyses were also performed on a number of wells used in the UCPA, including additional lithologic and salinity analyses. Information on a total of 1,215 wells were available within the study area, which included 666 water wells, 516 oil or gas wells, and 33 "other" type wells.

All well control, analytical methods, interpretations, and results used in this aquifer characterization are summarized in this report and provided in Geographic Information System (GIS) files, and the Brackish Resources Aquifer Characterization System Database (TWDB, 2021a). The effort to provide clear documentation and source data aids in the replicability of this work and enables stakeholders to use the data as needed. This section is subdivided below into the main tasks performed for this study in the approximate order they were performed. Some tasks were done in parallel over the course of the study and data were revisited when necessary for quality control and assurance. The main differences between that UCPA study and this report are 1) the increase in the scale, density, and correlation of well control and 2) an update to the salinity class calculated total dissolved solids from geophysical well logs methodology.

11.1 Stratigraphy methodology

The study area lies completely within the UCPA study boundaries so the geophysical well logs, driller's reports, and stratigraphic elevations for the Wilcox Group and Carrizo Sand from UCPA study were used as a framework and initial guide. We expanded the analysis by adding additional stratigraphic picks within the study area and refining the existing stratigraphy by utilizing depth calibrated logs in IHS Kingdom® software.

The general stratigraphic mapping process used is outlined below:

1. Look in the BRACS Database for geophysical well logs without picks for the top or bottom of the Wilcox Group or Carrizo Sand in the study area.
2. Depth-calibrate all geophysical logs in the study area with curves that overlap with the Carrizo-Wilcox Aquifer.
3. Set up an IHS Kingdom® project.
4. Import relevant BRACS Database data and depth calibrated logs into the Kingdom® project.

5. Review previous picks from UCPA study.
6. Interpret additional stratigraphic depths for the study.
7. Export the stratigraphic depths data back to the BRACS Database.
8. Create stratigraphic elevation point shapefiles for the Carrizo Sand and Wilcox Group tops and bottoms.
9. Build additional data needed for surface interpolation such as outcrop extents, digital elevation model (DEM) for the ground surface, outcrop elevation points, and guide points to aid the interpolation where well control was sparse.
10. Interpolate the data inputs points to build raster surfaces (TIFs)
11. Review the raster surfaces and run through the process again until quality control is complete.

For details on the methodology and descriptions of the geophysical well log signatures, see TWDB Report 385 sections 7.1.2 and 7.2.2 (Meyer and others, 2020).

11.2 **Aquifer determination**

To determine which wells in the study area were completed within the Carrizo Sand or the Wilcox Group, an aquifer determination table for each formation was created in the BRACS Database. These tables were used to assign the correct aquifer to every well in the study area. This aquifer assignment creates a framework for the analysis of lithology and water quality data. This process uses the top and bottom depths for the Carrizo Sand and the Wilcox Group from the stratigraphy rasters created in Section 11.1.

The aquifer determination tables contain all well control (from BRACS and Groundwater databases) in the study area and were populated with well construction information such as screen intervals or total depth. The tables were also populated with the top and bottom depths of the Wilcox Group or Carrizo Sand from the stratigraphic analysis (see Section 11.1). Using queries within the database, each well's screen interval is compared with the top and bottom depths of the formation to assign the correct formation to the well. If well screen information was missing, the total depth of the well was used to determine whether it was completed within the formations of interest. If a well was partially completed within a formation or not within the formation at all, an identifier was assigned to indicate those situations. Wells that were identified as partially completed in the formation of interest were manually reviewed and reassigned as needed based on professional judgement.

11.3 **Lithology methodology**

Lithology within the study area was interpreted using geophysical well logs and drillers' logs from the publicly available BRACS and Groundwater databases. Depth calibrated logs used for stratigraphic analysis (see Section 11.1) were used for lithologic interpretation and a total of 234 logs were interpreted. Additionally, 94 wells from UCPA study were included in this analysis. Most of these wells include spontaneous potential (SP) and dual-induction resistivity logs. Additional information was researched from the Texas Department of Licensing and Regulation State Driller Reports Database.

Lithologic analysis of geophysical wells was done using IHS Kingdom® software, which allowed geophysical wells to be examined at multiple scales across the study area. Lithology was described using a four-tier nomenclature system, also used in UCPA study. Lithologic interpretations are based on the relative amounts of sand and clay present within the section. These four tiers are defined as sand (100 percent sand), sand with clay (65 percent sand), clay with sand (35 percent sand), and clay (0 percent sand). A composite log consisting of interpreted lithologic intervals for each geophysical well log was created using these lithologic endpoints and then exported as a text file to be appended into the BRACS Database. Visual Basic for Applications® code was used to evaluate the record and a gap analysis routine with a three-foot tolerance was used to ensure the top/bottom of a lithologic intervals corresponded to the top/bottom of adjacent units.

Information from driller's reports were obtained from scanned PDFs in the Submitted Driller's Report Database (TWDB, 2019c). Due to differences between the records of companies and drillers, a process developed by the TWDB was used to simplify these descriptions into a consistent terminology that matched the four-tier system used in the geophysical well log interpretation. Further information on this method is found in TWDB Report 385 Section 6.4 (Meyer and others, 2020).

Points used in the net sands analysis were created from the geology table and well location table in the BRACS Database. The net sands point shapefile included the following information for each lithologic unit: top and bottom depths, thickness, lithologic description, simplified lithologic description, and the source of information. Only wells that completely or near completely (within 5 feet) penetrated the formation target area were used in the calculations and development of the net sand maps. This analysis was performed, and a total net sand map and percent net sand map were produced for the Wilcox Group to a depth of 2,000 feet bgs, the Carrizo Sand to a depth of 2,000 feet bgs, and the total thickness of the Carrizo Sand.

The 2,000-foot bgs limit in the analysis was accomplished in the BRACS Database by using a series of queries. A table of individual lithologic records for each well was produced for each formation. These tables contained the depth of the top and bottom of the formation, the top and bottom of each lithologic unit, and the location of the well. Wells where the entire target formation was greater than 2,000 feet bgs were removed from the table. Once these deeper wells were removed, individual lithologic units within a geologic formation were queried. All lithologic units with a top depth greater than 2,000 feet bgs were removed. Finally, the remaining lithologic units were queried and any bottom depth greater than 2,000 feet bgs was updated to 2,000 feet (Figure 11-1). Additional wells were added manually after this process that initially excluded for not representing the entire geologic formation but were then determined to penetrate the formation to the desired depth.

Each data point was compared to geological formation top and bottom depths to determine a net sand and sand percent value using sequential queries compiled in Visual Basic for Applications®. Net sand maps of geological formations present at the ground surface (within the outcrop) generally reflect a lower value of net sand.

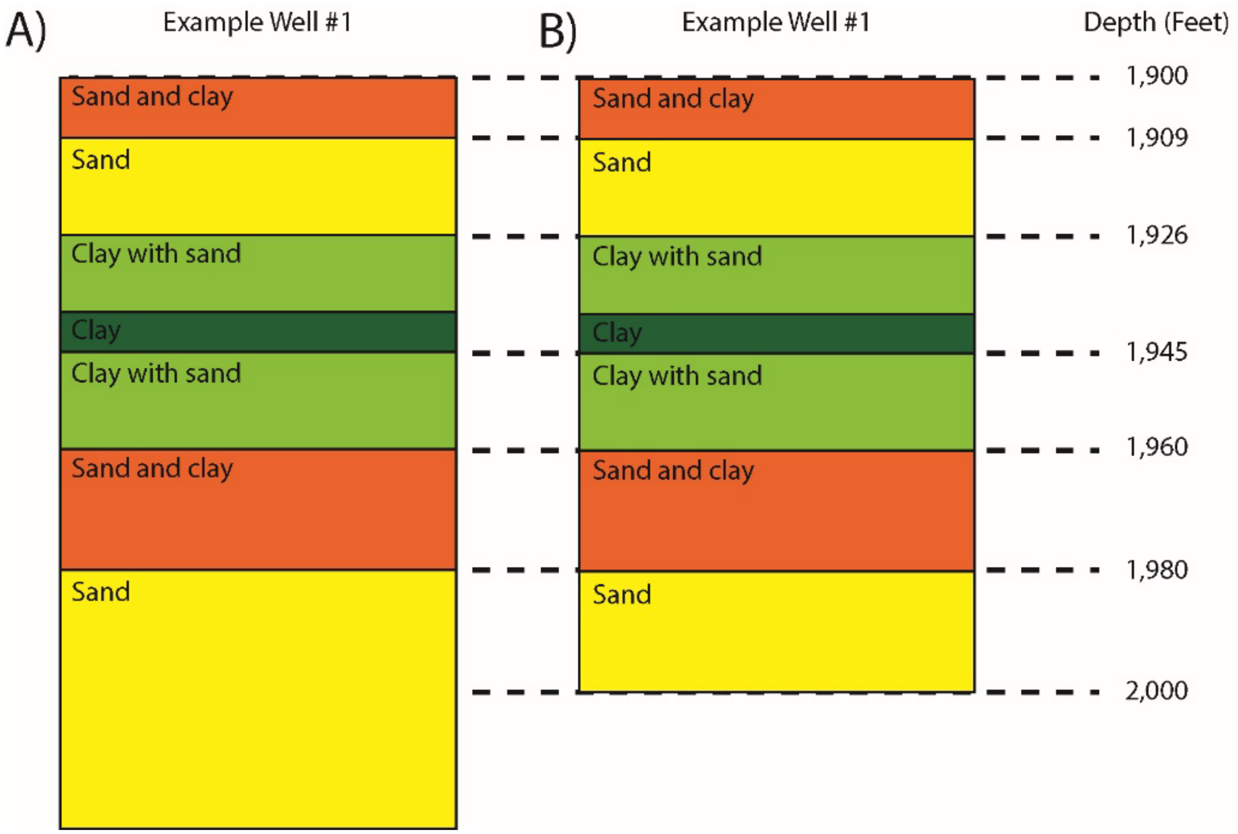


Figure 11-1. Illustration showing the final step of the process to depth limit lithologic intervals in the TWDB Brackish Aquifer Characterization System Database. Image A shows original lithologic picks. Image B shows the picks after the base of the composite log is limited to 2,000 feet in depth.

11.4 Salinity classes

This study built off previous salinity class well control and mapping completed for the UCPA study and incorporated additional well control. There were two data sources for salinity class well control used: measured water quality and TDS calculated from geophysical well logs.

11.4.1 Measured water quality

Measured water quality data were queried from records in the BRACS Database. Recent data were collected from the GBRA (including its recently drilled Carrizo Wells #1 and #2), the Groundwater Database (TWDB, 2021b), version 2.2 of the United States Geological Survey Produced Water Database (Blondes and others, 2016), Gonzales County Underground Water Conservation District, and TWDB Report 19 (Shafer, 1966).

Measured water quality data in the study area were queried for wells with completion and/or screen interval(s) in the Carrizo Sand or the Wilcox Group, as determined in the aquifer determination step described in Section 11.2. Measurements from the aquifer were separated into these two geologic units to remove formation-related variables (such as lithology and pore space geometry) that may influence later calculations. This process identified 95 water samples from wells completed in the Carrizo Sand and 88 water samples from wells completed in the Wilcox Group. These data were combined into a master water quality table.

To verify the accuracy of reported major constituent values, the charge balance was calculated between the major anions and cations (in milliequivalents per liter) using the following formulas:

$$\text{Total cation milliequivalents per liter} = ((Ca^{2+} * 0.0499) + (Mg^{2+} * 0.08229) + (Na^{+} * 0.0435) + (K^{+} * 0.02557) + (Sr^{2+} * 0.0228))$$

$$\text{Total anion milliequivalents per liter} = ((CO_3^{2-} * 0.03333) + (HCO_3^{-} * 0.01639) + (SO_4 * 0.02082) + (Cl^{-} * 0.02821) + (F^{-} * 0.05264) + (NO_3^{-} * 0.01613))$$

Where:

Ca^{2+} = Calcium
Mg^{2+} = Magnesium
K^{+} = Potassium
Na^{+} = Sodium
Sr^{2+} = Strontium
SiO_2 = Silicate
HCO_3^{-} = Bicarbonate
CO_3^{2-} = Carbonate
Cl^{-} = Chlorine
SO_4^{2-} = Sulfate
F^{-} = Fluoride
NO_3^{-} = Nitrate

The total cation milliequivalents per liter was compared to the total anion milliequivalents per liter, which should be equal in an ionically balanced sample. Any samples with an absolute percent difference in charge balance greater than five percent were considered unbalanced. Only samples with a balanced ionic charge were included in this analysis.

For consistency between measurements, empirically measured TDS values were recalculated from the sum of the major measured water quality constituents for all records, even if TDS was available from the lab report or database record. This recalculation was done to remove any variations in lab reporting techniques from samples that were analyzed over a span of almost 100 years (1930s to the 2020s). In addition, TDS was calculated for records of measured water quality samples that were missing TDS but had reported quantities of the major ions. The equation used for calculating TDS (in milligrams per liter) was

$$\text{TDS milligrams per liter} = Ca^{2+} + Mg^{2+} + K^{+} + Na^{+} + Sr^{2+} + SiO_2 + HCO_3^{-} + CO_3^{2} + Cl^{-} + SO_4^{2-} + F^{-} + NO_3^{-}$$

Finally, samples that were reviewed for anomalies and, if considered erroneous, were excluded from the study’s final measured water quality dataset. An example of excluded measurements included samples with an unusual concentration of an ion or ions relative to other samples with similar TDS in the same formation. These ion concentrations were considered unlikely if they differed by at least one order of magnitude from other records with similar TDS concentrations.

These calculations allowed us to develop a relationship between TDS and specific conductance for the Carrizo-Wilcox Aquifer in the study area that would be used in later calculations of salinity from geophysical well logs (see Section 11.4.3)

11.4.2 Total dissolved solids (TDS) vs specific conductance

Measured water quality samples are sparse and not available for the entire study area. This is especially true downdip of the outcrop where the Carrizo-Wilcox aquifer is deeper, and it is more expensive to drill wells. We calculated concentrations of TDS from geophysical well logs to improve the spatial distribution of TDS data in the study area. Estimation of TDS from resistivity measurements in geophysical logs first requires calculation of the relationship between TDS and specific conductance (SC). Specific conductance can be either measured in the lab or calculated, is the inverse of resistivity, and is a measure of the concentration of dissolved ions in water. To eliminate uncertainty in specific conductance values from different labs, PHREEQC version 3 was used to calculate the SC for all the measured water quality samples (Parkhurst and Appelo, 2013). Calculating the specific conductance also ensured consistency when comparing samples to each other.

Since the query for measured water quality data in the study area did not result in samples with a TDS greater than 3,025 mg/L in the Carrizo Sand and 3,741 mg/L in the Wilcox Group, a more expansive and inclusive search for high TDS water quality measurements was conducted. Higher TDS measured water quality measurements were needed to provide a correlation for the higher range of salinity calculations we would be making from the geophysical well logs. We searched the USGS Produced Water Database outside of the study area and filtered the samples based on the following criteria

1. no wells outside of Texas or updip of the Carrizo-Wilcox Aquifer outcrop;
2. formation names of ‘Carrizo’, ‘Wilcox’, or a known alias (Warwick, 2017);
3. had a specific conductance measurement or a resistivity measurement and temperature convertible to specific conductance; and
4. had a charge balance less than or equal to 5 percent.

Searching Texas wells downdip of the aquifer outcrop with the qualifying formation names yielded over 700 potential wells with higher TDS measurements in the Carrizo-Wilcox Aquifer. However, after applying the additional criteria, a resistivity or specific conductance measurement and appropriate charge balance, only 1 measured water quality remained for the Carrizo Sand and over 500 for the Wilcox Group. An additional criterion of being within 27 miles of the study area resulted in 20 measurements for the Wilcox Group (Table 11-1). The high salinity measured water quality samples pulled from the United States Geological Survey Produced Water Database from outside of the study area for the Carrizo-Wilcox Aquifer. ID_USGS is the unique identifier from the database.). The single Carrizo Sand well is located 135 miles northeast of the study area on the border of Houston and Walker counties and the 20 Wilcox Group wells are located less than 27 miles southeast of the study area near the borders of DeWitt, Victoria, and Lavaca counties (Figure 11-2).

Table 11-1. **The high salinity measured water quality samples pulled from the United States Geological Survey (USGS) Produced Water Database from outside of the study area for the Carrizo-Wilcox Aquifer. ID_USGS is the unique identifier from the database.**

ID_USGS	Formation	County	Total dissolved solids (milligrams per liter)	Date sampled
55136	Carrizo	Houston	7,438	1975-07-16
54897	Wilcox	Victoria	16,389	1953-05-08
54124	Wilcox	Victoria	26,735	1954-05-06
46220	Wilcox	Victoria	40,295	1959-08-19
54111	Wilcox	Victoria	40,295	1959-08-19
54123	Wilcox	Victoria	63,143	1963-01-30
54117	Wilcox	Victoria	72,120	1971-08-08
54112	Wilcox	Victoria	73,857	1969-08-28
54113	Wilcox	Victoria	74,108	1971-08-08
54109	Wilcox	Victoria	74,748	1979-04-04
54110	Wilcox	Victoria	74,816	1954-07-21
54115	Wilcox	Victoria	74,816	1969-09-19
54107	Wilcox	Victoria	78,700	1969-09-19
54105	Wilcox	Victoria	79,619	1971-08-08
54118	Wilcox	Victoria	80,451	1979-04-04
54116	Wilcox	Victoria	82,118	1980-01-14
54120	Wilcox	Victoria	84,021	1971-08-08
54121	Wilcox	Victoria	84,610	1972-02-05
54106	Wilcox	Victoria	87,831	1979-04-04
58290	Wilcox	De Witt	88,414	1960-01-23
54119	Wilcox	Victoria	101,693	1953-11-11

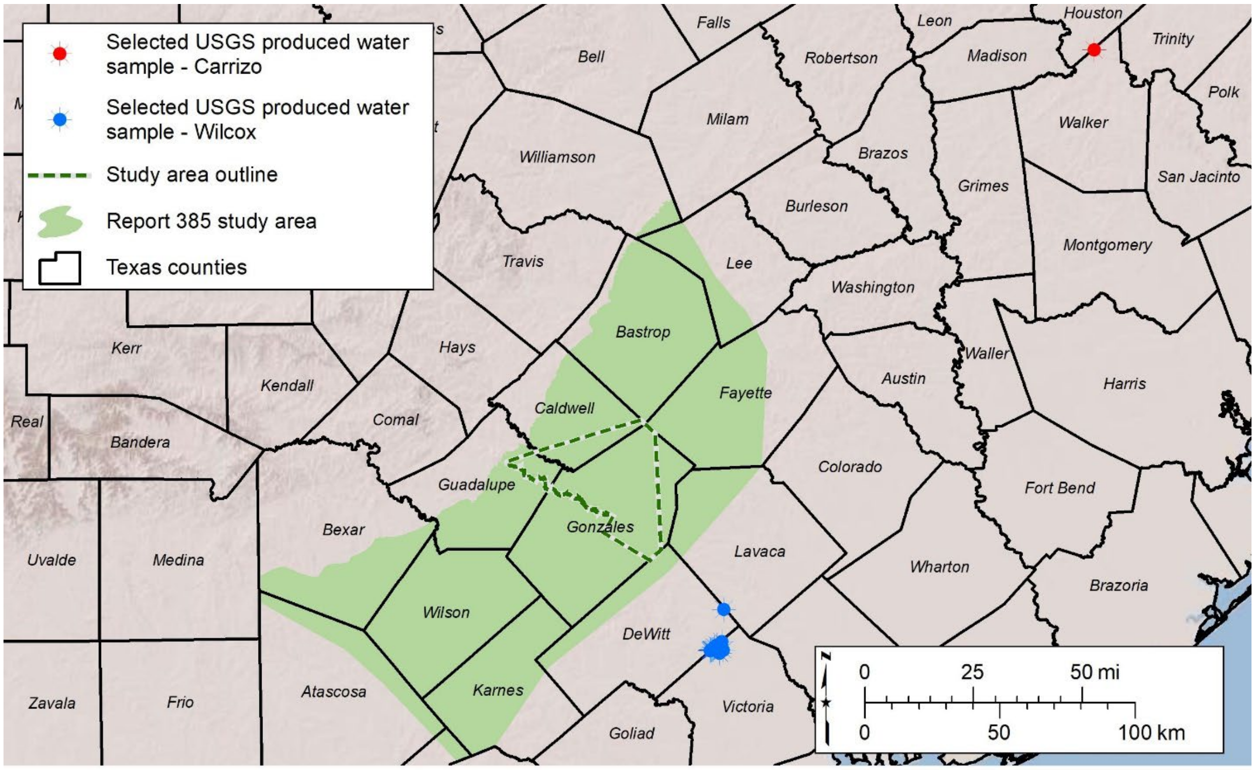


Figure 11-2. **United States Geological Survey produced water samples selected for representing high salinity groundwater in the Carrizo-Wilcox Aquifer for the GBRA ASR study.**

Even after incorporating the USGS produced water measurements from outside of the study area, the Carrizo Sand measured water quality samples had a TDS concentration of less than 7,438 milligrams per liter. To develop the relationship of TDS vs SC up to approximately 35,000 milligrams per liter (the limit between brackish water and brine), measured water quality data were supplemented with hypothetical ion concentrations. These hypothetical concentrations assumed sodium chloride (NaCl) dominated water at higher salinities, with increasing concentrations of sodium and chloride and constant or decreasing concentrations of all other ions. For the Wilcox Group, measured water quality samples were found for TDS concentrations up to 101,693 milligrams per liter so no hypothetical concentrations were used. The relationship was determined by plotting TDS concentrations calculated from measured water quality data versus calculated conductance and finding an equation or equations that best fit the data.

For the Carrizo Sand, the relationship between TDS and SC was best approximated by four equations. The relationship up to approximately 1,900 micromhos per centimeter (mmhos/cm) SC is approximated best by a polynomial equation. From 1,900 to 3,260 micromhos per centimeter and 3,260 to 10,270 micromhos per centimeter were best approximated by two linear functions. Beyond 10,270 micromhos per centimeter the TDS were linearly extrapolated to approximately 35,000 mg/L or a specific conductance of 53,000 mmhos/cm. The equations are summarized in Table 11-2.

Table 11-2. Total dissolved solids vs specific conductance equations for the Carrizo Sand.

SC (mmhos/cm)	TDS (mg/L)	Equation
0 to 1,900	0 to 2,450	$TDS = (0.00007 \cdot SC^2) + (0.5138 \cdot SC) + 54.707$
1,900 to 3,260	1,300 to 2,450	$TDS = 0.7603 \cdot SC$
3,260 to 10,270	2,450 to 7,438	$TDS = (0.6898 \cdot SC) + 320.69$
> 10,270	> 7,438	$TDS = (0.6508 \cdot SC) + 471.59$

Notes: TDS = total dissolved solids, SC = specific conductance, mmhos/cm = micromhos per centimeter, and mg/L = milligrams per liter.

The TDS/SC intervals in the Carrizo Sand were chosen because the chemical characteristics of the measured water samples change from the low TDS interval to the higher TDS interval between TDS concentrations of 1,300 to 2,540 mg/L or SC values of 1,900 to 3,260 mmhos/cm. Within that interval, the measured water quality samples showed a sharp increase in concentrations of bicarbonate while other ions, including calcium, magnesium, and sulfate, dropped significantly. In addition, the concentrations of fluoride, sodium, and chloride begin to increase in that interval. The intermediate interval was chosen because data in the intermediate range is scarce. This resulted in uncertainty in the transition between the low and high intervals. This intermediate function served to average out the values at either end of the interval and provides equations that better fit the high and low intervals. The third, high TDS interval from 3,260 to 10,270 mmhos/cm SC and 2,540 to 7,438 mg/L TDS, was characterized by increasing concentrations of sodium and chloride as TDS increased, while other ions remain at the same concentration or did not change significantly. Beyond 7,438 mg/L TDS, ionic concentrations were extrapolated from the measured water quality data in the third TDS interval up to a TDS of 35,000 mg/L. The hypothetical extrapolated values were used in PHREEQC version 3 to calculate specific conductance values. The extrapolated TDS and calculated SC points were used to create the fourth equation to approximate high TDS values.

In the Wilcox Group, the TDS vs SC relationship was best approximated by two equations. At lower TDS concentrations, up to 26,735 mg/L or a SC of 43,280 mmhos/cm, the relationship was best approximated by a linear equation. At concentrations beyond those limits, the relationship is best approximated by a polynomial equation. The equations are summarized in Table 11-3.

Table 11-3. Total dissolved solids vs specific conductance equations for the Wilcox Group.

SC (mmhos/cm)	TDS (mg/L)	Equation
0 to 43,280	0 to 26,735	$TDS = (0.6164 \cdot SC) + 154.96$
> 43,280	> 26,735	$TDS = (0.000002 \cdot SC^2) + (0.4557 \cdot SC) + 3588.3$

Notes: TDS = total dissolved solids; SC = specific conductance, mmhos/cm = micromhos per centimeter, and mg/L = milligrams per liter.

In the first interval of TDS concentrations in the Wilcox Group, under 26,735 mg/L, the samples are dominated by bicarbonate. With increasing TDS concentrations, bicarbonate, sodium, and chloride increase while sulfate concentrations decrease. In the second interval, for TDS concentrations greater than 26,735 mg/L, bicarbonate sharply drops off and the water was dominated by sodium and chloride. Concentrations of sodium and chloride increase with increasing TDS while concentrations of bicarbonate and other ions did not change significantly. In addition, these samples had a lower average pH of seven compared to the first group with an average pH of eight. Because of greater availability of measured water quality data in the Wilcox

Group across a wider range of TDS concentrations, there was not a significant gap in the TDS range covering the change from bicarbonate-dominated water to the sodium chloride-dominant water. Because of this, two equations were sufficient to approximate the Wilcox TDS/SC relationship. The two equations have some overlap to average out the transition from the first group to the second group.

11.4.3 Total Dissolved Solids (TDS) calculations from geophysical well logs

Salinity was calculated from geophysical well logs because of the scarcity of measured water quality samples in parts of the study area. These sparse areas especially occurred in the deeper and higher salinity portions of the aquifers. Calculating TDS from geophysical well logs provided a wider spatial distribution of well control and a wider range of salinities when mapping salinity classes. TDS were calculated for the entire thickness of the Carrizo Sand throughout the study area and for the Wilcox Group down to a 2,500-foot depth below ground surface. TDS were calculated from conductivity of water, which was calculated from resistivity of water. The resistivity of water was derived from the resistivity of the formation, which is measured from an electric log. The same method was also used in the UCPA study.

To calculate TDS from geophysical well logs, the R_{WA} Minimum Method was used, which relates formation resistivity to the resistivity of the water (Estepp, 1998). The R_{WA} Minimum Method is based on Archie's equation (Archie, 1942):

$$R_o = R_w \cdot \frac{a}{\phi^m} \cdot \frac{1}{S_w{}^n}$$

Where:

R_o = resistivity of the formation in ohm-meters
R_w = resistivity of water in ohm-meters
a = Winsauer factor (dimensionless)
ϕ = porosity as a decimal
m = cementation exponent (dimensionless)
S_w = water saturation as a decimal
n = saturation exponent (dimensionless)

The equation can be simplified given the following assumptions. The groundwater in the Carrizo-Wilcox Aquifer is fresh to brackish and is assumed to be 100 percent water, which makes the water saturation value (S_w) equal to 1. The Winsauer factor (a) is often reported as 1 (Estepp, 1998; Torres-Verdín, 2017). These simplified factors allow the formula to be simplified and rearranged as

$$R_w = R_o \cdot \phi^m$$

With this simplified equation, only resistivity of the formation (R_o), porosity (ϕ), and the cementation exponent (m) are needed to calculate the resistivity of the water. The resistivity of the formation was determined by reading the curve from the deep investigation resistivity logging tool in a geophysical well log. These readings were done in 89 depth intervals in 56 resistivity logs for the Carrizo Sand in the entire study area. The UCPA study originally had 67 logs, for a total of 123 logs. For the Wilcox Group, readings were done in the 2,000-foot depth limited area, in 150 depth intervals in 67 logs. The UCPA study originally had 19 logs, which brings the total number of logs to 86 for the 2000-foot depth limited area. Readings were made from relatively clean (shale-free), thick sands (greater than 10 feet), that were representative of the entire formation and the salinity classes present. In well logs where multiple salinity classes are present, multiple readings were needed to ensure that those intervals of different salinity were included in the analysis.

Porosity logs were not available in the study area, so porosity was derived from equations that estimate porosity based on depth and formation from TWDB Report 385 Section 6.8 (Meyer and others, 2020). These equations were empirically derived from porosity measurements from geophysical well logs in the 14-county study area. These measurements included 36 measurements from the Carrizo Sand and 40 measurements from the Wilcox Group. The following equations relate porosity to depth:

Wilcox Group porosity: $y = -0.0019x + 39.839$

Carrizo Sand porosity: $y = -0.0015x + 38.465$

Where:

y = porosity

x = depth in feet below ground surface

The cementation exponent (*m*) could not be derived from geophysical well logs so a value of 1.75 was used for both the Carrizo Sand and the Wilcox Group based on best professional judgement of the known lithology of these formations. A value of 1.75 is in the range of slightly to moderately cemented sandstone (Torres-Verdín, 2017). After calculating resistivity of water, that value is converted into conductivity with two equations:

Convert resistivity of water (R_w) at formation temperature to 75 degrees Fahrenheit:

$$R_{w75} = R_w \cdot \frac{T_f}{75}$$

Where:

T_f = formation temperature in Fahrenheit

R_w = resistivity of water in ohm-meters

R_{w75} = resistivity of water at 75 degrees Fahrenheit in ohm-meters

Convert R_{w75} to conductivity of water at 75 degrees Fahrenheit:

$$C_w = \frac{10{,}000}{R_{w75}}$$

Where:

C_w = conductivity of water in micromhos per centimeter

R_{w75} = resistivity of water at 75 degrees Fahrenheit in ohm-meters

Finally, conductivity of water is converted to TDS using the equations in Table 11-2 and Table 11-3 derived from determining the relationship between TDS and SC All these equations were programmed into a Microsoft® Access® database form to expedite the calculations and limit errors that could be introduced in the process of entering data from geophysical log analysis and producing calculated TDS. In addition, existing TDS values calculated for the UCPA study (Meyer and others, 2020) were recalculated using the equations derived in Section 11.4.2 of this study. For the Carrizo Sand, 87 TDS values were recalculated and 156 were recalculated for the Wilcox Group. A salinity class was assigned to the formation based on the calculated TDS values. In cases where a formation had more than one salinity class, multiple intervals within the formation were assigned their corresponding salinity class. Cutoffs for the salinity classes are listed in Table 11-4.

Table 11-4. Groundwater salinity classification (Winslow and Kister, 1956).

Salinity class	Total dissolved solids concentration (mg/l)
Fresh	0 to 1,000
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	Greater than 35,000

To map the salinity classes, TDS calculated from measured water quality and from geophysical well logs were used. Additional TDS data from TWDB Report 385 sections 7.1.5 and 7.2.5 were also used outside of the study area to eliminate interpolation edge effects. The TDS values were exported from the database into GIS shapefiles for both the Carrizo Sand and Wilcox Group. In addition, two other GIS shapefiles based on queries of the salinity classes assignments were created for each formation. The first shapefile contained the salinity classes for each for formation and the second contained the number of salinity classes per well.

Contour lines of TDS were interpolated using the measured water quality and calculated TDS shapefiles to help delineation of salinity class boundaries. Salinity class polygons from UCPA study were clipped to the project study area to use as a starting point to map the salinity classes. These salinity class polygon boundaries were modified based on changes in the TDS calculations and data added as part of this sub-county scale study. Other reference datasets were also used to modify the salinity class polygons. These included interpolated contour lines, locations of structural faults from the Tectonic Map of Texas (Ewing, 1991), and the net sand distribution (Section 11.3). Some salinity class boundaries were slightly modified while others were removed or simplified. In areas with wells of different salinity classes near each other or multiple salinity classes in the same well, the polygon was assigned a mixed salinity class status. For example, if an area contains fresh wells and slightly saline wells, the polygon was designated “fresh and slightly saline”. Finally, the salinity class polygons for the Carrizo Sand and Wilcox Group were clipped to the 2,000-foot depth limited area.

12. Appendix B – GIS datasets

All Geographic Information System (GIS) datasets and each of the GIS files prepared for this study are available for download from the TWDB website. These files were created using ArcGIS® 10.2 and the Spatial Analyst® extension software by Environmental Systems Research Institute, Inc. (ESRI).

Point files are in the ArcGIS® shapefile format. Point files of well control used for general purposes are originally projected as a geographic projection North America with the North American Datum 1983 as the horizontal datum. Point files are re-projected to a TWDB Groundwater Availability Model projection and the North American Datum 1983 as the horizontal datum.

All surface files are in the ArcGIS® raster integer grid file format with a Groundwater Availability Model 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 and polyline files are in the ArcGIS® shapefile format with a Groundwater Availability Model projection and the North American Datum 1983 as the horizontal datum.

All well records are managed in the Microsoft® Access® BRACS Database. Well records are queried from the database and imported into ArcGIS® for spatial analysis. When new attributes are obtained for a well using ArcGIS® the information is imported into Microsoft® Access® and the well record is updated.

Every well record in each supporting database used for this study contains latitude and longitude coordinates in the format of decimal degrees with a North American Datum of 1983. These well records are imported into ArcGIS® and georeferenced in a geographic coordinate system North America with the North American Datum 1983 as the horizontal datum.

13. Appendix C – BRACS Database

All point-based well and geophysical well log information for this study are managed in the BRACS Database using Microsoft® Access® for Microsoft 365. When spatial analysis is required, copies of information are exported into ArcGIS®. Information developed in ArcGIS® is then imported back to the BRACS Database and the tables are updated accordingly. Although this approach may be cumbersome, it takes advantage of the strengths of each software. The study also relied on other software for specific tasks, including Microsoft® Excel® and IHS-Markit Kingdom®.

For the study, we assembled information from external agencies and updated these databases frequently. Each of these supporting databases are maintained in Microsoft® Access® and GIS files were developed for spatial analysis and well selection. Many of the database objects were built from scratch or were redesigned to meet project objectives. Data from external agencies or projects were available in many different data designs, so establishing a common design structure proved beneficial in leveraging information compiled by other groups.

The BRACS and supporting databases are fully relational. Data fields common to multiple datasets have been standardized in data type and name with lookup tables shared between all databases. Database object names use a self-documenting style that follows the Hungarian naming convention (Novalis, 1999). The volume of project information required us to develop comprehensive data entry and analysis procedures (coded as tools) that were embedded on forms used to display information. Visual Basic for Applications® is the programming language used in Microsoft® Access®, and most code was written at the Microsoft® ActiveX® Data Objects level with full code annotation. The code for geophysical well log resistivity analysis was specifically designed with a custom BRACS class object to support a rapid analysis of information with the benefit of only appending data when the user approves the results.

The BRACS Database is documented in the BRACS Database (TWDB, 2021a) and Data Dictionary (Meyer, 2020), which both are available from the TWDB website (www.twdb.texas.gov/groundwater/bracs/database.asp). We develop custom tables for each study and incorporate them into the BRACS Database and add a study appendix describing these tables to the data dictionary after each study is completed. The custom tables developed for this study contain the final data used by and produce in the methodology section and are listed in Table 13-1.

Table 13-1. Tables in the BRACS database containing data used in and produced by this study.

Table name	Table description
gBRACS_GBRA_ST	This table contains all the wells in the study area with corresponding spatial data and geological formation depths and elevation values.
tblAquiferDetermination_GBRA	This table contains information on which aquifer(s) may be used or penetrated by a well in the study area.
tblWell_Geology_NetSand_GBRA_CZ	This table contains one record per well with net sand and sand percent values for the Carrizo Sand, limited to a depth of 2,000 feet bgs.
tblWell_Geology_NetSand_GBRA_CZ_Temp	This table was created to support the processing of net sand and sand percent data for Carrizo Sand wells in the study area. This table will contain one or more records per well if the lithologic description for any record contains reference to sand or gravel.
tblWell_Geology_NetSand_GBRA_CZ_Well_Decisions	This table was created to capture a decision on whether to use or not use a net sand value during the preparation of the GIS raster dataset.
tblWell_Geology_NetSand_GBRA_CZ_2	This table contains one record per well with net sand and sand percent values for the Carrizo Sand.
tblWell_Geology_NetSand_GBRA_CZ_2_Temp	This table was created to support the processing of net sand and sand percent data for Carrizo Sand wells in the study area. This table will contain one or more records per well if the lithologic description for any record contains reference to sand or gravel.
tblWell_Geology_NetSand_GBRA_CZ_2_Well_Decisions	This table was created to capture a decision on whether to use or not use a net sand value during the preparation of the GIS raster dataset.
tblWell_Geology_NetSand_GBRA_WX	This table contains one record per well with net sand and sand percent values for the Wilcox Group, limited to a depth of 2,000 feet bgs.
tblWell_Geology_NetSand_GBRA_WX_Temp	This table was created to support the processing of net sand and sand percent data for Wilcox Group wells in the study area. This table will contain one or more records per well if the lithologic description for any record contains reference to sand or gravel.
tblWell_Geology_NetSand_GBRA_WX_Well_Decisions	This table was created to capture a decision on whether to use or not use a net sand value during the preparation of the GIS raster dataset.
gBracs_GBRA_MWQ	This table contains a copy of every water quality record in the study area organized with one record per well per date sampled with constituents in separate fields.
gBRACS_GBRA_WQ_RADIOCHEM	This table contains a copy of every water quality record in the study area organized with one record per well per date sampled with radiochemical constituents in separate fields.