Geologic Characterization of and Data Collection in the Corpus Christi Aquifer Storage and Recovery Conservation District and Surrounding Counties

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John E. Meyer, P.G.

Texas Water Development Board

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John. E. Meyer, P.G. No. 2026

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John E. Meyer
Geology
No. 2026

John E. Meyer

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“Sunrise on the Texas Coast”

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1. Executive summary

The Corpus Christi Aquifer Storage and Recovery Conservation District (District) was created to manage and protect the District's groundwater resources, including those injected into the ground for storage and later use (CCASRCD, 2008). At the request of the District, Texas Water Development Board (TWDB) and District staffs met to discuss the scope of the study. Study scope includes geologic characterization of the District, collection of geophysical and water well information in Nueces and San Patricio counties, data compilation in a relational database, and a written report. Project deliverables include a report, database, database data dictionary, geographic information system (GIS) files, and digital geophysical well logs. The study scope is similar to the five-year plan activities (3.1.3, 3.2, and 3.3) proposed by HDR (2009).

The database was designed and the information collected to provide flexibility in the types of analyses that can be performed to identify test well sites if the District implements an aquifer storage and recovery system. The database is designed to allow additional well information, such as test well data, to be appended by District staff or their representatives.

The report describes the methodology of data collection and analysis and examples of maps that can be created with the database information.

There are numerous sand units in the various geological formations that constitute the Gulf Coast Aquifer which underlies the District. These sands vary in thickness from a few feet to tens of feet. The sands are generally not laterally continuous, at least between the wells from which data were collected for this study. Many of these sands could be likely candidates for aquifer storage and recovery; however, an extensive test well drilling program will be needed to provide the critical site-specific data that are necessary for well field design and modeling.

Potential contaminants within the study area include elevated radioactivity, hydrocarbons, and arsenic within the Gulf Coast Aquifer. The presence of these contaminants will need to be evaluated during future test well drilling.

Limited water quality data for aquifers in the District precluded a detailed evaluation of the potential reservoir sands. Extrapolation of water quality data from outside of the District, especially from deeper formations, was not reliable, because of the relatively rapid change in the concentration of total dissolved solids even within short distances. Geophysical well log analysis techniques combined with water quality data from water wells were used to interpret total dissolved solids content. These techniques have limited success in the study area and should be used only as generalizations. The geophysical well log analysis indicates that the base of brackish water (> 10,000 milligrams per liter, total dissolved solids) is approximately 1,000 feet below ground surface in much of the western third of the District. This depth becomes shallower and reaches approximately 500 feet or less in the vicinity of the Nueces and Corpus Christi bays in the east.

2. Introduction

The Corpus Christi Aquifer Storage and Recovery Conservation District (District) was created by the 79th Texas Legislature, 2005, to manage and protect the District's groundwater resources, including water injected into the ground for storage and later use (CCASRCD, 2008). As part of a five-year plan for the District, HDR, Inc. (2009) proposed that the District conduct a well inventory, and characterize and determine aquifer conditions to identify potential operational issues and gain confidence in developing a successful aquifer storage and recovery program. To accomplish these goals, the District requested technical assistance from the Texas Water Development Board (TWDB). Texas Water Code Chapter 11.053 authorizes TWDB to participate in aquifer storage and recovery pilot projects, and undertake studies of aquifers in the state to determine the occurrence, quantity, quality, and availability of other aquifers in which water can be stored and subsequently retrieved for beneficial use.

TWDB's Innovative Water Technologies Division conducted the study. The study provided an opportunity to map and characterize the geology of the Gulf Coast Aquifer in Nueces and San Patricio counties using techniques developed for the Brackish Resources Aquifer Characterization System program. It also provided an opportunity to evaluate the use of geophysical well log techniques to characterize groundwater in the Gulf Coast Aquifer. The BRACS Database (named after the Brackish Resources Aquifer Characterization System program) was selected to store the information developed for the study.

The tasks for the study included:

- Developing a geophysical and water well database for the District and surrounding Nueces and San Patricio counties. Records include water, oil, and gas wells and Class II injection wells. Records in this database primarily focus on wells that contain information on water chemistry, aquifer properties, and lithology that can be used to characterize the Gulf Coast Aquifer for potential aquifer storage and recovery systems.
- Analyzing geophysical well logs in conjunction with lithologies recorded on water well logs to determine the distribution of sand and clay layers in the Gulf Coast Aquifer within and immediately adjacent to the District.
- Analyzing geophysical well logs in conjunction with groundwater quality data available in the TWDB Groundwater Database to characterize the groundwater within and immediately adjacent to the District.

The deliverables included:

- A technical report detailing the data sources, study methodology, and results characterizing the Gulf Coast Aquifer for potential aquifer storage and recovery systems.
- A Microsoft® Access® 2007 database containing well records for the District and the surrounding counties (Nueces and San Patricio counties).
- A database dictionary for the Microsoft® Access® BRACS Database.
- Geographic information system (GIS) files showing location of wells and aquifer data.
- Copies of digital geophysical well logs from Nueces and San Patricio counties.

This report documents the methodologies used to collect the information and characterize the geology and the aquifer in the study area. The information will serve as a resource to future geologists and engineers pursuing the application of aquifer storage and recovery in the District.

3. Study area

The study area is located in Nueces and San Patricio counties and covers an area of approximately 1,563 square miles of which approximately 518 square miles lies within the District and 1,045 square miles outside the District (Figure 1). Useful water well control within the District is extremely limited because of the paucity of water wells in the area resulting from the elevated levels of dissolved minerals in the underlying aquifers.

Because of this, the study area was extended beyond the boundaries of the District to obtain sufficient well control to extrapolate parameters such as groundwater chemistry, aquifer properties, and sand distribution into areas within the District. The geologic structure of the study area was correlated with the hydrostratigraphy of the Gulf Coast Aquifer developed by Young and others (2010) for 30 counties along the central and southern Gulf Coast.

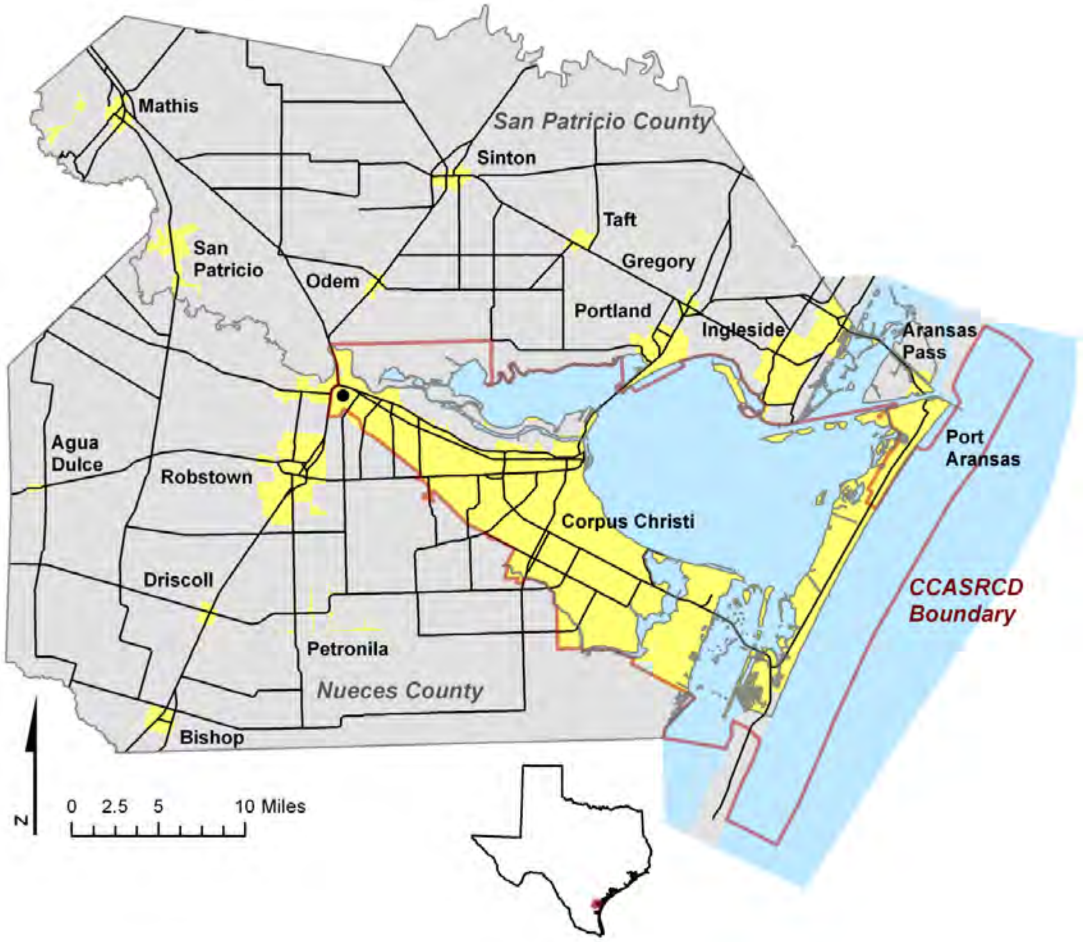


Figure 1. Study area in southeast Texas. The boundary is based on Nueces and San Patricio counties, adjacent bays, and the Gulf of Mexico. The District boundary is shown in red. The O.N. Stevens Water Treatment Plant is shown with a black dot in the western part of the District.

4. Hydrogeologic setting

The study area is located on the Gulf Coast Aquifer, a regional aquifer that extends from the Texas-Republic of Mexico border in the south to Louisiana and beyond in the north. Sediments of the Gulf Coast Aquifer are Cenozoic in age and were deposited in fluvial-deltaic or shallow marine depositional environments influenced by basin subsidence, sediment compaction and movement, and sea-level fluctuations. These cyclic sedimentary sequences consist of discontinuous sand, silt, clay, and gravel deposits influenced by syn- and post-depositional growth faults and, in parts of the Gulf Coast, by movement of salt domes.

While a detailed description of the hydrostratigraphy of the study area is beyond the scope of this report, excellent information on the subject (for example, Young and others, 2006 and 2010) is presented in reports that are available on the TWDB website.

For our study, we used the stratigraphic picks defined by Young and others (2010) for the Gulf Coast Aquifer. The hydrostratigraphy forms the basis for subdividing the lithology, water quality, and hydraulic properties information into consistent formations/aquifers for comparison purposes. The relationship between the geologic formations, their age, and individual aquifers that comprise the Gulf Coast Aquifer is shown in Table 1.

The regional dip of the Gulf Coast Aquifer was estimated along a 45-mile-long, northwest-southeast line that bisects the study area. The regional dip is approximately 21 feet per mile at the base of the Chicot Aquifer, 51 feet per mile at the base of the Evangeline Aquifer, and 70 feet per mile at the base of the Jasper Aquifer. The increase in dip with depth of the aquifer across the study area is the result of the increasing thickness of formations coastward, with each hydrogeologic unit gaining approximately 1,000 feet of sediment within the 45-mile section.

5. Previous investigations

County-wide hydrological studies by TWDB (and predecessor agencies) and the U.S. Geological Survey began in the 1930s for Nueces and San Patricio counties (Baker, 1979; Broadhurst and others, 1950; Johnson, 1939; Lynch, 1934; Shafer, 1968). Mace and others (2006) compiled a number of articles on the aquifers of the Gulf Coast of Texas.

The hydrostratigraphy of the Gulf Coast Aquifer was evaluated by Young and others (2010). The datasets developed in this study form the basis for the stratigraphic segregation of the sand and clay units that were mapped in greater detail in our study. It is likely that future Gulf Coast Aquifer Groundwater Availability Model(s) may be based on the hydrostratigraphy mapped during this study. Therefore, information collected for or generated during the study needed to be formatted for seamless integration into future studies.

Surface geologic mapping conducted by The University of Texas at Austin at a scale of 1:250,000 (BEG, 1975a and 1975b) was subsequently processed into a statewide digital geologic map in a geodatabase format.

Development of groundwater models of the Gulf Coast Aquifer in Texas began in 1965 and continues to this day. Chowdhury and Mace (2006) summarize Gulf Coast Aquifer models. As described in Young and others (2006), other entities have also developed groundwater models within areas of the Gulf Coast Aquifer to meet their own specific needs. Several groundwater studies have been developed for water purveyors in the study area (HDR, 2009; Malcolm Pirnie, Inc., 2001; Turner Collie and Braden, 2004). Daniel B. Stephens and Associates prepared a 635-well database (provided to us by the District) using water well records from the Texas Commission on Environmental Quality. This dataset was incorporated into the study area database, even though the amount of information available was limited.

Table 1. **Stratigraphic column showing relationship between geologic age, formation, and aquifer. The Gulf Coast Aquifer comprises the Chicot, Evangeline, and Jasper aquifers. Modified from Young and others (2010).**

Age (millions of years before present)	Geologic formation	Hydrogeologic unit	
Pleistocene (1.8-present)	Beaumont	Chicot Aquifer	Coast Aquifer
	Lissie		
Pliocene (5.6-1.8)	Willis		
Miocene (23.8-5.6)	Upper Goliad	Evangeline Aquifer	
	Lower Goliad		
	Upper Lagarto		
	Middle Lagarto	Burkeville Confining Unit	
	Lower Lagarto	Jasper Aquifer	Gulf
	Oakville		
Oligocene	(upper) Catahoula		
	(lower) Catahoula	Catahoula Confining Unit	

6. Data collection and analysis

One of the primary objectives of the study was to gather available well data from existing water well reports, geophysical well logs, water chemistry samples, and aquifer tests. This information augmented existing well information contained in the TWDB Groundwater Database. No single agency has complete information on all water wells or oil and gas wells in Texas. Therefore, we had to evaluate a number of existing collections that contain publicly available paper and digital information. Because many of the datasets and analysis features did not fit into the structure of the existing TWDB Groundwater Database, the information was loaded into the BRACS Database. Each well that was added to the BRACS Database shows the source of the information and all applicable well identification numbers.

Another equally important objective was to make the information and datasets gathered for the study readily available to the public. Thus, all of the information collected is non-confidential. The information includes raw data, such as water well reports and digital geophysical well logs; processed data, such as lithology, simplified lithologic descriptions, stratigraphic picks, and water chemistry; and interpreted results in the form of GIS datasets.

With these goals in mind, we added information from 3,048 wells located in Nueces and San Patricio counties to the BRACS Database; only 694 of these wells are located within the geographical boundaries of the District (Figure 2). This represents only a fraction of all the wells installed in the study area because information from many other wells was either unavailable, incomplete, limited in scope, of poor quality, confidential, or does not meet study requirements. Information not collected for this study may still be available from public and private sources should it be required for future studies.

The geophysical well logs, stratigraphic picks, and interpreted lithology from the Young and others (2010) study were appended to the BRACS Database.

From the Groundwater Advisory Unit of the Railroad Commission of Texas, we obtained and appended to the Brackish Resources Aquifer Characterization System geophysical well log collection and the BRACS Database one specific collection of digital geophysical well logs that was originally assembled to support the Malcolm Pirnie, Inc. (2001) project in San Patricio County. The quality of many of the digital files in this collection and the original paper logs is extremely poor. During the course of our study, we replaced some of these files with better quality images. The latitude and longitude coordinates for these wells were not available, and although many were located by TWDB staff, more than 1,200 wells still lack location coordinates. Any future work in San Patricio County using this collection will require substantial effort to establish the locations of the images and find replacements for poor quality images.

We did not verify the location of every well that was obtained from other agency datasets unless there appeared to be a problem, such as a mismatch in the geology. When locations had to be verified or digital locations were not available, the Original Texas Land Survey GIS data from the Railroad Commission of Texas were used as a base map. The legal descriptions of locations noted on the log header were used to plot the wells in GIS to determine the latitude and longitude coordinates. Users of our study data should be aware that well locations may need to be verified.

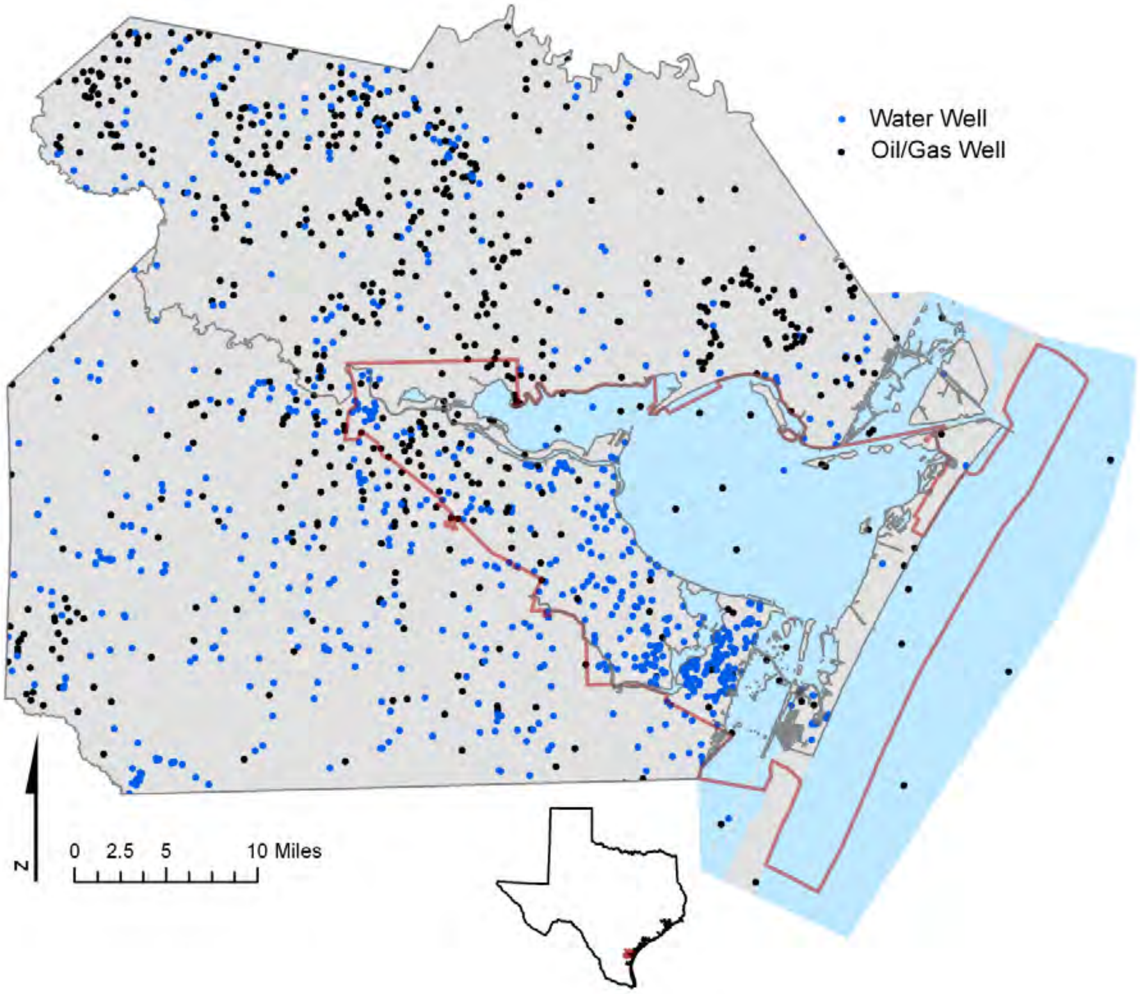


Figure 2. **Distribution of wells used in the study (total 1,645). There are approximately 1,017 water wells and approximately 628 wells drilled for oil and gas production. Many of the water wells drilled in the District (boundary in red) are used for environmental monitoring.**

The following sources of well data were utilized in this study:

- Bureau of Economic Geology Geophysical Log Facility;
- Texas Commission on Environmental Quality water well image files and public drinking water files;
- Texas Department of Licensing and Regulation digital water well reports;
- Railroad Commission of Texas paper and digital geophysical well logs;
- Texas Water Development Board Groundwater Database and paper well reports, paper geophysical log collection, groundwater availability model studies, and written reports;
- U.S. Geological Survey written reports; and
- consultant reports provided to water providers in the study area.

Each well in the BRACS Database contains a source reference for the information.

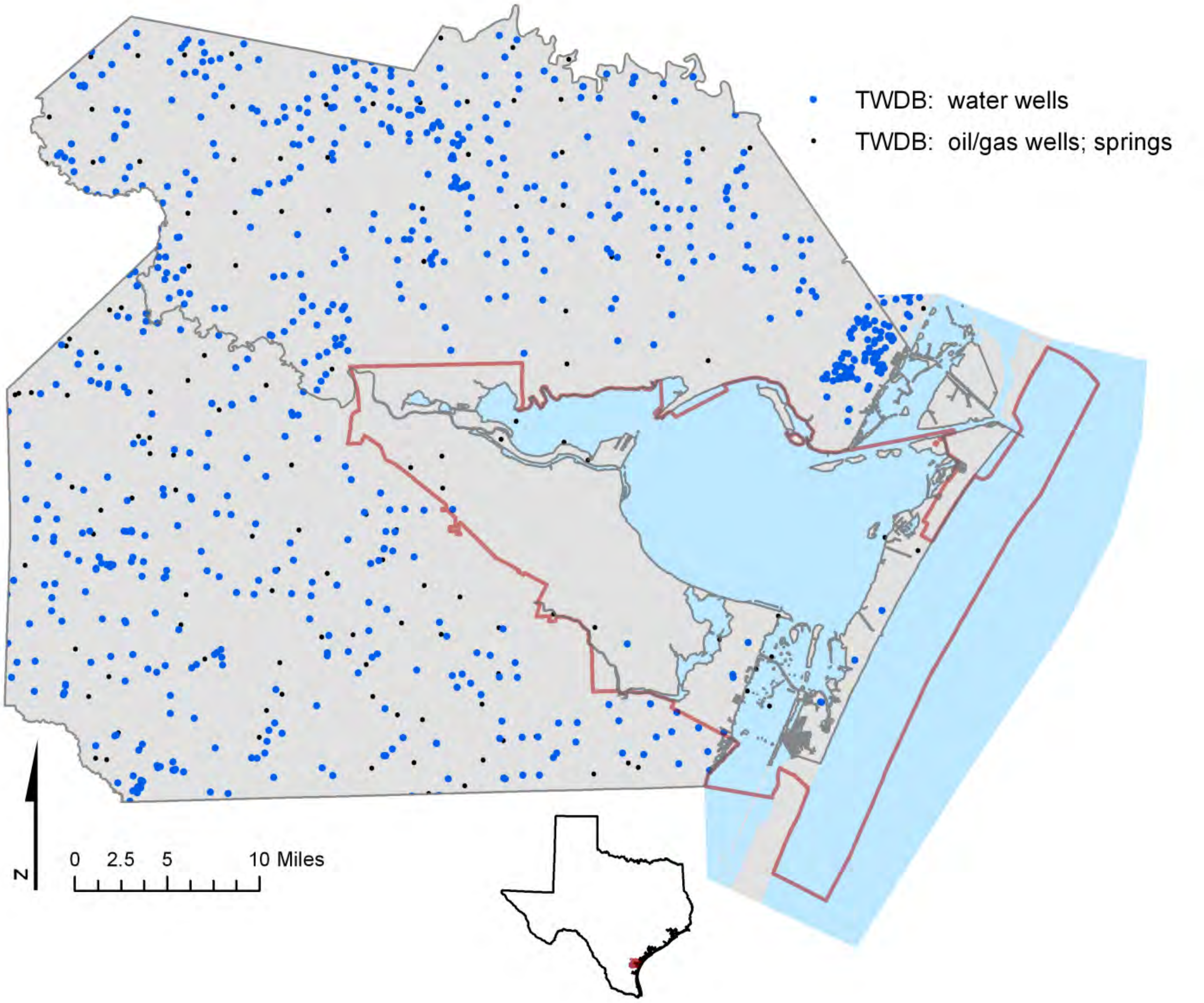


Figure 3. **Well locations (from the TWDB Groundwater Database) in the study area. There are 702 water supply wells, 2 springs, and 147 oil and gas production wells. District boundary is shown in red.**

We decided to include some of the wells contained in the TWDB Groundwater Database (Figure 3) and the Texas Department of Licensing and Regulation Water Well Database (Figure 4) into the BRACS Database. These wells contain information essential to understanding the geology of the region. Because the TWDB Groundwater and the Texas Department of Licensing and Regulation Water Well databases are updated on a daily basis, users should be aware that in the future there may be information available in these databases in addition to that present in the BRACS Database.

Based on information from the Railroad Commission of Texas Oil and Gas Well Database, the study area contains approximately 17,263 oil and gas wells and 166 Class II injection wells (Figure 5). Two publicly available collections of geophysical well logs that could supplement the study dataset include those at the Groundwater Advisory Unit of the Railroad Commission of Texas and the Geophysical Log Facility at the Bureau of Economic Geology. A fair amount of work will be required to identify and add data from these collections to the study database.

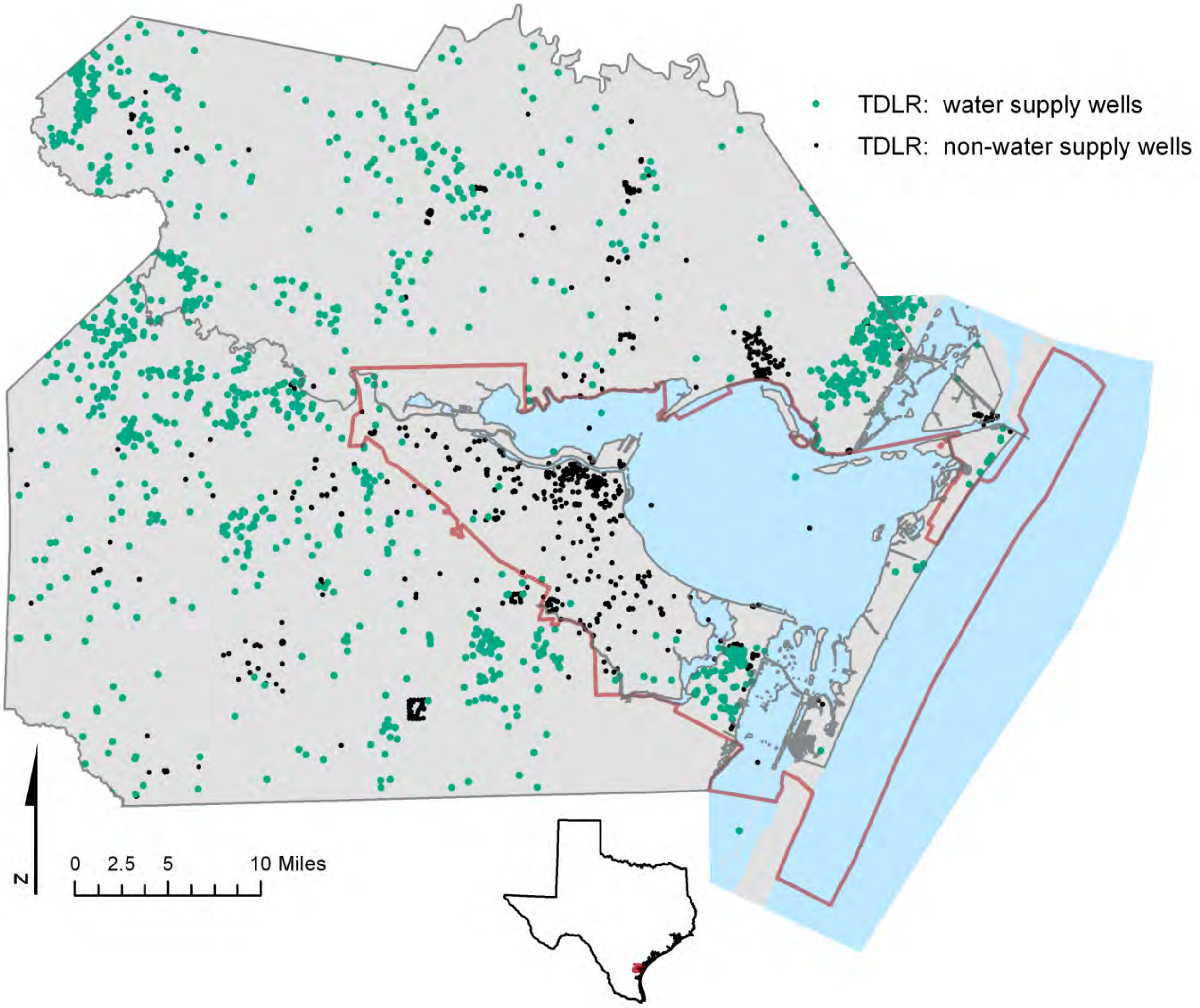


Figure 4. **Water well locations in the Texas Department of Licensing and Regulation digital well database. There are 1,263 water supply wells and 2,606 wells drilled for other purposes, including environmental soil boring, monitoring, and geothermal heat loop. District boundary is shown in red.**

Each well can have one or more unique identification names or numbers assigned by an entity. A table in the BRACS Database tracks these values and allows us to find additional data in other agency datasets or reports.

7. Aquifer determination

We employed a technique to consistently assign the correct aquifer(s) to wells drilled in the study area so that information from these wells, specifically hydraulic properties, lithology, and water quality, could be meaningfully compared and extrapolated across the study area. The hydrostratigraphic framework of the Gulf Coast Aquifer by Young and others (2010) was used to meet this objective. Each well in the study area was assigned stratigraphic top and bottom depths and elevations based on the GIS surfaces created for the nine geological formations within the

Gulf Coast Aquifer. Well screen information was compared with formation top and bottom depths to determine the aquifer(s) used by the water well. If well screen information was not available, the total depth of the well or borehole was used and all aquifers selected from the total depth to surface data. The aquifer determination technique also facilitated the assignment of sand layers to specific geologic formations, allowing the tabulation and mapping of net sand and sand percent information.

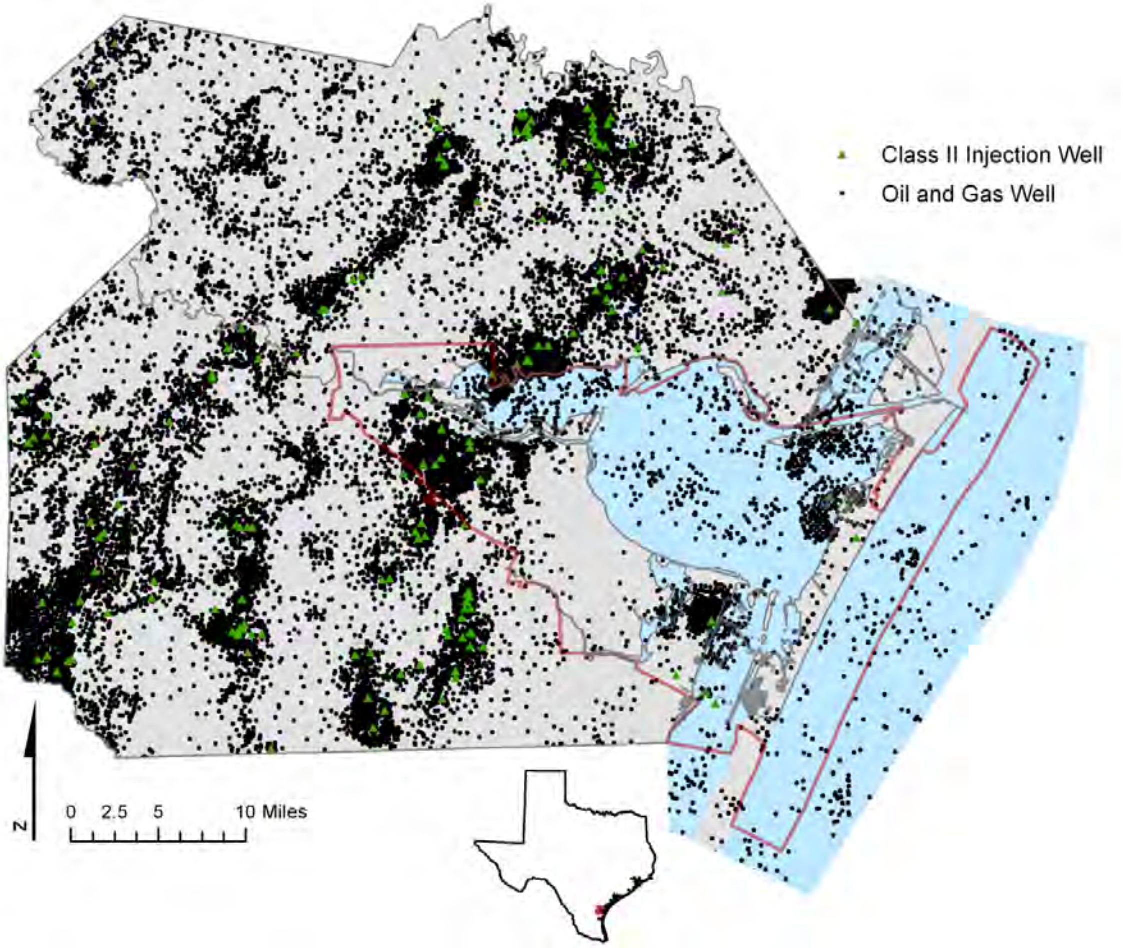


Figure 5. **Oil and gas activity in the study area. There are approximately 17,263 oil and gas wells in the study area. Class II injection wells in Texas are used for secondary recovery and to dispose produced salt water. There are approximately 166 Class II wells in the study area. Source: Railroad Commission of Texas. District boundary is shown in red.**

Water wells in the TWDB Groundwater Database have aquifer codes assigned to them. Over the 25 years that the database has been in existence, different staff using a variety of information has been assigning aquifer codes in the database. The complex stratigraphic nomenclature, changes in stratigraphic interpretation by different authors, and discontinuity of lithologic units within the Gulf Coast formations have led to inconsistencies in the application of aquifer codes. Because wells appended to the BRACS Database from sources other than the TWDB Groundwater Database do not have aquifers assigned to them, this technique assigns that attribute.

8. Hydraulic properties

The hydraulic properties of an aquifer refer to characteristics that allow water to flow through the aquifer. Hydraulic properties include transmissivity, hydraulic conductivity, specific yield, specific capacity, drawdown, pumping rate (well yield), and storativity. Lithology, cementation, fracturing, structural framework, and juxtaposition of adjacent formations all influence the flow of water within and between aquifers.

We compiled hydraulic properties for 242 wells completed in the Gulf Coast Aquifer (Table 2). A total of 254 analyses were performed and the information appended to the BRACS Database table tblBRACS_AquiferTestInformation. Values from wells consist of: transmissivity (18); hydraulic conductivity (10); specific capacity (50); and well yield (251). Because information on hydraulic properties from wells completed in the study area is limited (Figure 6), hydraulic properties had to be extrapolated into the District from other parts of the study area. Any future work to determine potential aquifer storage and recovery sites should include test well-drilling to gather site-specific hydraulic property information, as identified in the five-year plan developed by HDR (2009).

The sources of aquifer test information include: TWDB aquifer test spreadsheet and the remarks table in the TWDB Groundwater Database; published reports (Broadhurst and others, 1950; Johnson, 1939; Lynch, 1934; Myers, 1969; Shafer, 1968); Texas Commission on Environmental Quality digital water well images; and Texas Department of Licensing and Regulation submitted driller log database. Additional information is available in the TWDB paper well reports.

Specific yield data for wells located within the study area were not available. Chowdhury and Mace (2006) used values of 0.01 to 0.005 to calibrate the central part of the Gulf Coast Aquifer model, which includes the study area. They reported that these values are quite low compared to values of 0.14 to 0.38 typically used for sedimentary materials in unconfined aquifers. The models did not calibrate correctly with the higher values, leading the authors to conclude that the aquifer units may be under semi-confined conditions. The model calibrated correctly after lower values for semi-confined conditions were used.

Young and others (2006) related hydraulic conductivity to screen length and lithology in a project area consisting of the Chicot and Evangeline aquifers in Colorado, Wharton, and Matagorda counties. They determined that hydraulic conductivity decreased with increasing screen length (that is, greater depth) and attributed this relationship to: an increasing chance of encountering lower permeability units with increasing depth; increased compaction of sediments with depth; and the likelihood of over-estimating hydraulic conductivity in wells with shorter well screens because of an increase in non-lateral flow to a well. They also developed an equation, not presented in the report, relating the percent of sand within the screened zone of the Chicot aquifer to predicting hydraulic conductivity.

Table 2. **Hydraulic properties of aquifers within the study area. The Chicot and Evangeline aquifers represent wells with screens that overlap both aquifers, wells with no screen data, or wells terminating in the Evangeline with the potential for contributions from the Chicot.**

Hydraulic property	Chicot Aquifer	Chicot and Evangeline aquifers	Evangeline Aquifer
Transmissivity			
Number of values	3	8	7
Low	3,030	3,700 gpd/ft	4,410 gpd/ft
High	3,930 gpd/ft	24,200 gpd/ft	20,600 gpd/ft
Average	3,560 gpd/ft	10,100 gpd/ft	7,875 gpd/ft
Hydraulic Conductivity			
Number of values	0	5	5
Low	–	1.8 ft/day	5.7 ft/day
High	–	20.9 ft/day	15.4 ft/day
Average	–	10.7 ft/day	8.9 ft/day
Storativity			
Number of values	3	4	5
Low	0.00071	0.00008	0.00008
High	0.0029	0.00029	0.00085
Average	0.002	0.00015	0.00024
Specific Capacity			
Number of values	23	16	11
Low	0.14 gpm/ft	1.1 gpm/ft	2.2 gpm/ft
High	14.3 gpm/ft	14 gpm/ft	16.9 gpm/ft
Average	1.85 gpm/ft	6.5 gpm/ft	6.1 gpm/ft
Well Yield			
Number of values	133	71	47
Low	2 gpm	10 gpm	15 gpm
High	1,500 gpm	1,800 gpm	3,000 gpm
Average	216 gpm	434 gpm	795 gpm

Notes: gpd/ft=gallons per day per foot; gpm/ft=gallons per minute per foot; gpm=gallons per minute
ft/day=feet per day; -=not available

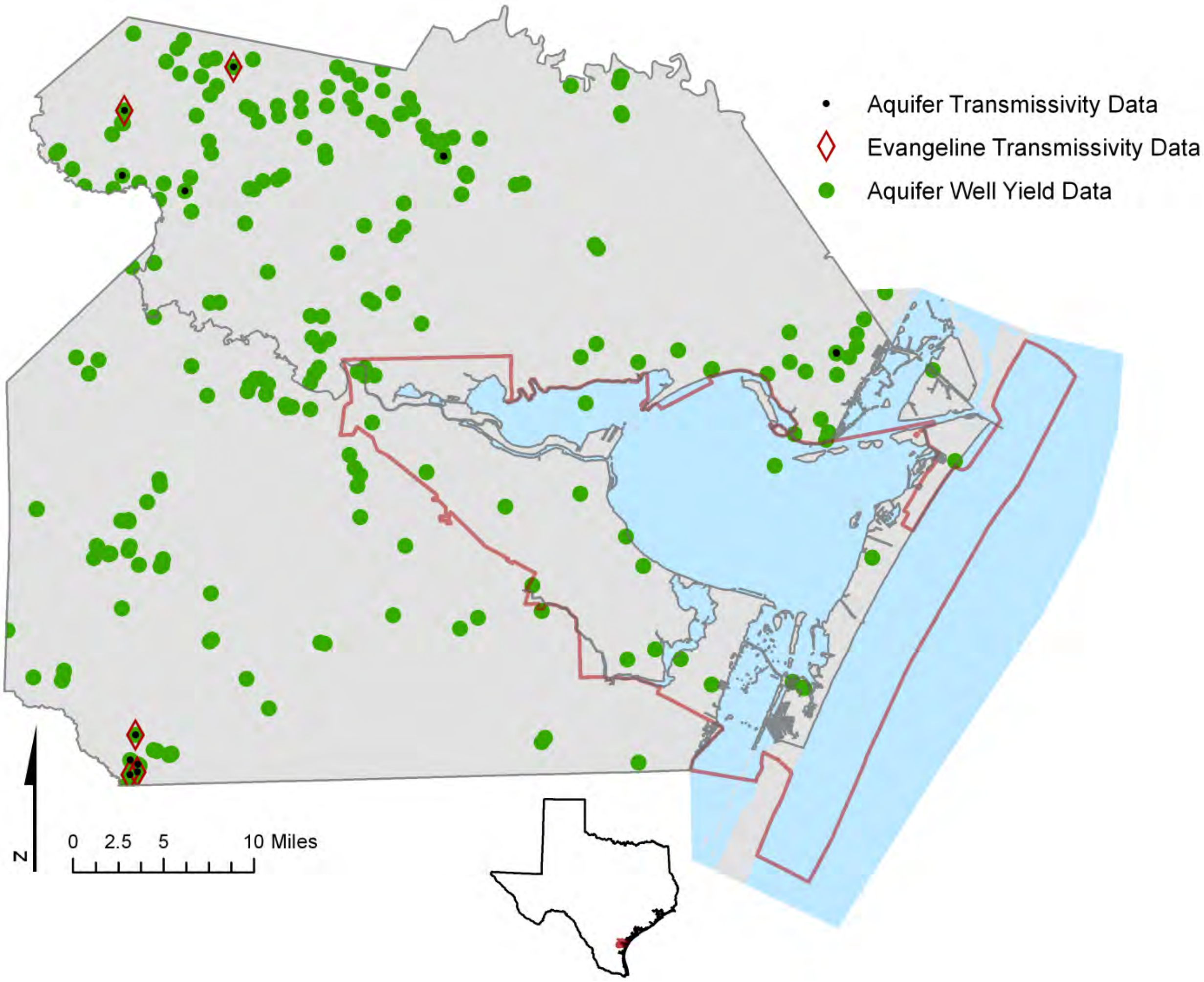


Figure 6. **Wells completed in the Gulf Coast Aquifer with some form of aquifer test information (total 242). These wells have a total of 254 test results. Well yield data are represented by green dots (gallons per minute). A subset of these wells has transmissivity data (black dots), and a further subset has transmissivity data within the Evangeline Aquifer (red diamond). Some well records have additional information such as hydraulic conductivity and specific capacity. District boundary is shown in red.**

9. Resistivity analysis of geophysical well logs

Geophysical well logs are produced from tools that are lowered into a well bore with a wireline and retrieved back to the ground surface at a specific rate. Combinations of different tools can be assembled in standard “packages” to measure specific formation, fluid, borehole, casing, and cement properties. Tools are selected based on a number of factors including cased or uncased bore holes, and the composition of the well bore (air or drilling muds). The tools have progressively improved since they were first applied to oil field investigations in the 1930s. The geophysical well logs collected for this study were produced between 1936 and 2010. Interpretation of logs that were produced over such a long time span and presumably with varying designs and accuracies presents challenges. Obviously, some of the older logs simply could not be used in all aspects of the study. The digital image quality of some logs also presented challenges. Oil field wells are generally logged after a section of surface casing is installed. With the exception of the gamma ray tool, the section of the wellbore containing surface casing cannot be logged. It thus limits the amount of information that can be collected from the ground surface to the top of the casing, which can be several hundred or thousand feet.

Geophysical well logs capable of recording shallow and deep resistivity within a formation were evaluated to determine whether these tools could provide an interpreted total dissolved solids concentration. Three methods to estimate total dissolved solids—detailed by Estepp (1998)—were evaluated in this study: Modified Alger-Harrison, Rwa Minimum, and Mean Ro. This task was not a comprehensive evaluation of each method; comprehensive evaluation is an ongoing research task at the TWDB. Each method attempts to approximate a highly complex geologic system, often with incomplete information, using log parameters and correction factors that were designed to address oilfield rather than groundwater environments. Despite these shortcomings, geophysical well logs are routinely used to derive an interpreted total dissolved solids value for groundwater. While the results obtained from these methods can be used to generalize total dissolved solids in the study area, they cannot provide an exact total dissolved solids value. Accurate total dissolved solids concentrations using these methods can be determined only with a properly designed test well drilling, logging, and formation sample and chemical analysis program that determines each variable used in the formulas. This, however, would defeat the purpose of using existing geophysical well logs available from oil and gas wells to estimate the concentration of total dissolved solids.

The formation resistivity is determined by reading a deep resistivity geophysical tool in a thick layer of shale-free sand that is not affected by hydrocarbons. The measured formation resistivity is the result of several parameters: resistivity of the formation minerals, resistivity of formation water and its composition, porosity, cementation of sediment grains, sediment grain size, and surface conductance on mineral grains (Alger, 1966). The objective is to determine formation water resistivity from formation resistivity. Obtaining some of these parameters is not possible with information from a geophysical well log. Lab experiments indicating parameter variance under different conditions have shown that this is complex (Alger, 1966). To solve the calculations, some of the parameters are estimated based on similar geologic conditions.

Two logging tools were utilized for deep resistivity measurement: the induction log and the 18-foot, 8-inch resistivity log. The formation invaded zone, potentially impacted by drilling mud filtrate, was evaluated using shallow resistivity tools such as the shallow focused log or 16-inch normal resistivity. Porosity logging tools were not available in the study area within the evaluated depth zones; a value of 35 percent porosity was used for the Rwa Minimum Total Dissolved Solids Method.

The Modified Alger-Harrison and the Rwa Minimum Total Dissolved Solids methods are two quantitative methods of interpreting total dissolved solids from geophysical well log resistivity (Estepp, 1998). These methods were applied to 11 wells in the study area at multiple depth intervals per well (Figure 7). The 11 selected wells each had a geophysical well log with the appropriate tool types and complete log header information. The wells were located close to water wells for which total dissolved solids concentration information was available. The log parameters were appended to the BRACS Database using a multi-table relational form with the calculations for total dissolved solids interpretation written in Visual Basic for Applications and assigned to form command buttons. Interpreted total dissolved solids is the value generated using geophysical log parameters, log correction factors, formation factors, and aquifer ct (linear relationship of total dissolved solids versus specific conductance) as input parameters. In our study, the log parameters were obtained from the geophysical well log, the ct was determined from nearby water wells in the Gulf Coast Aquifer, and the formation factors were inferred (not measured) from Gulf Coast lithology.

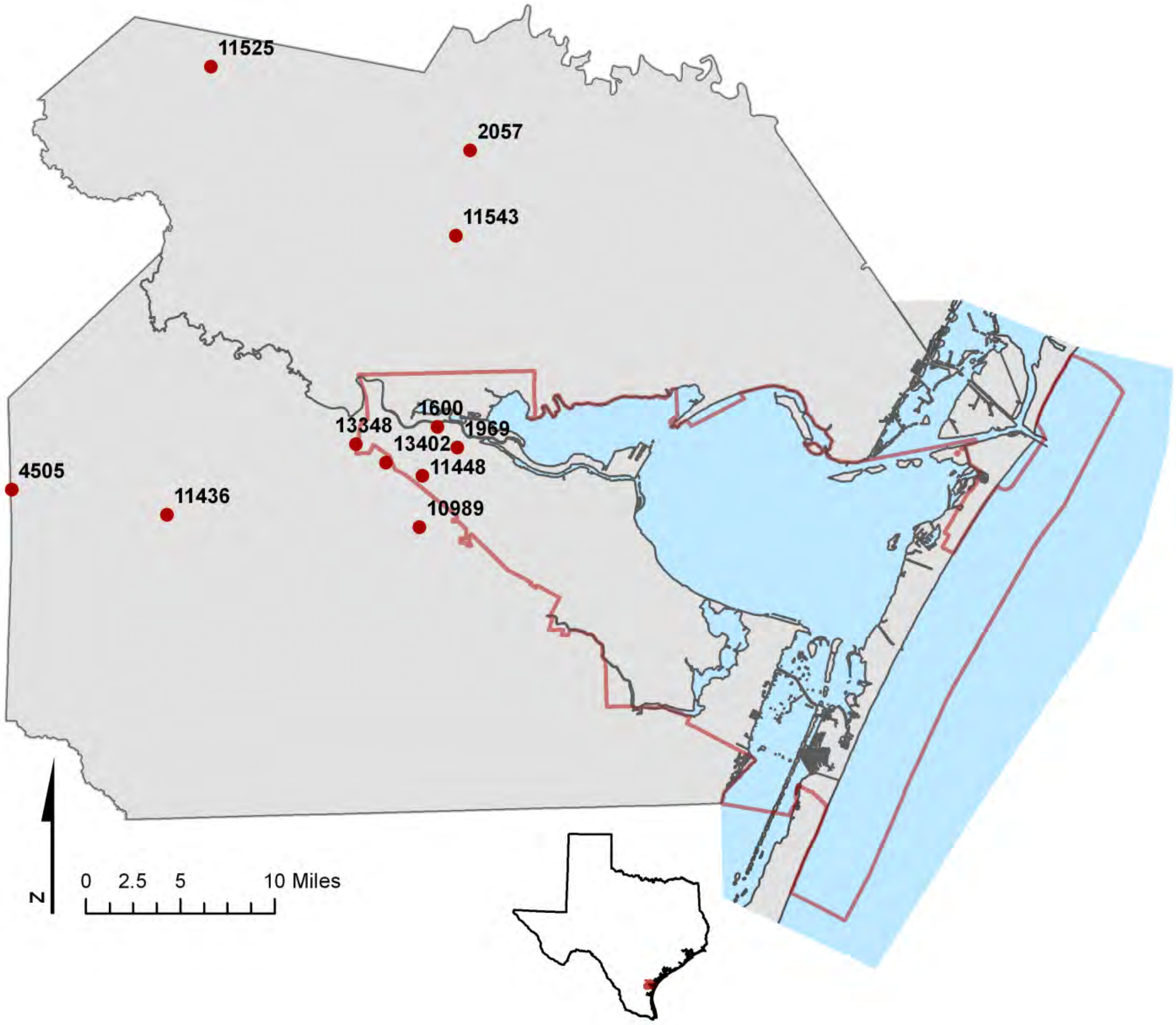


Figure 7. **Wells used for defining the relationship between deep resistivity and total dissolved solids content (11 wells) using two interpretive methods: the Modified Alger-Harrison and Rwa Minimum Total Dissolved Solids methods (Estepp, 1998). The number next to each well refers to the BRACS well identification number used in the database as a unique identification number. District boundary is shown in red.**

The objective of this task was to determine whether these approaches could produce reliable results in the study area. The interpreted total dissolved solids results from this evaluation were plotted against deep resistivity (Figures 8 and 9). The term “interpreted total dissolved solids” should not be confused with total dissolved solids measured in a water quality sample.

The wells used for the Modified Alger-Harrison Total Dissolved Solids Method analysis are shown on Figure 7. Formation resistivity ranged from 0.5 to 22 ohm-meters and interpreted total dissolved solids from 1,250 to over 16,000 milligrams per liter. The data points plotted on the graph (Figure 8) have a large scatter about the power curve with a range of a few thousand milligrams per liter for any given resistivity measurement. The maximum total dissolved solids value reached may be tens of thousands of milligrams per liter less than other methods used (Rwa Minimum; Mean Ro). Based on comparison with BRACS wells 2057 and 3819 (Figure 10), it appears that this method is not well suited to brackish groundwater that has total dissolved solids concentrations greater than approximately 1,500 milligrams per liter. This may be a

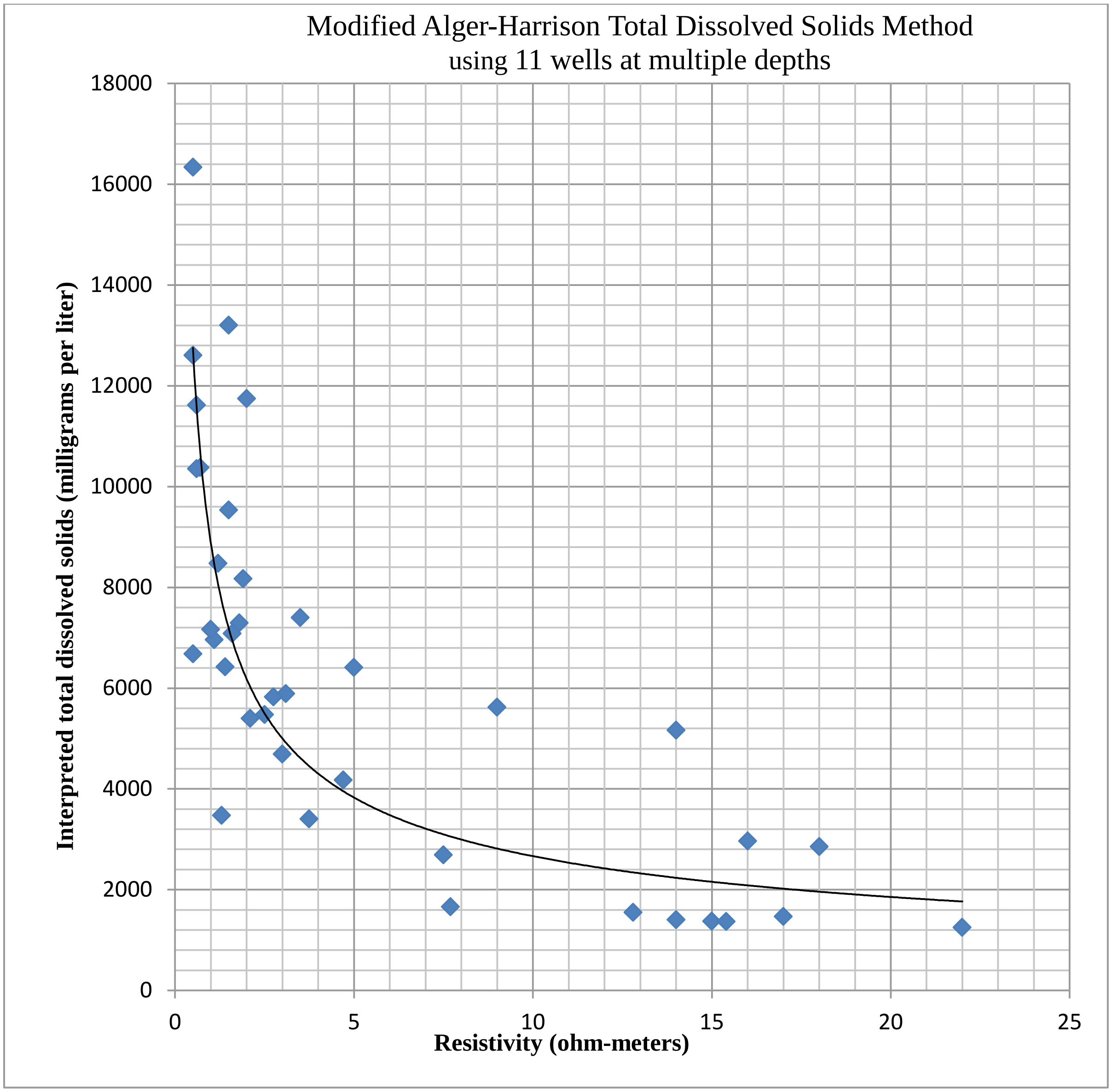


Figure 8. **Graph of interpreted total dissolved solids and deep resistivity from geophysical well logs using the Modified Alger-Harrison Total Dissolved Solids Method. Eleven wells were interpreted, with multiple depth horizons assessed in each well. The locations of these wells are shown in Figure 7.**

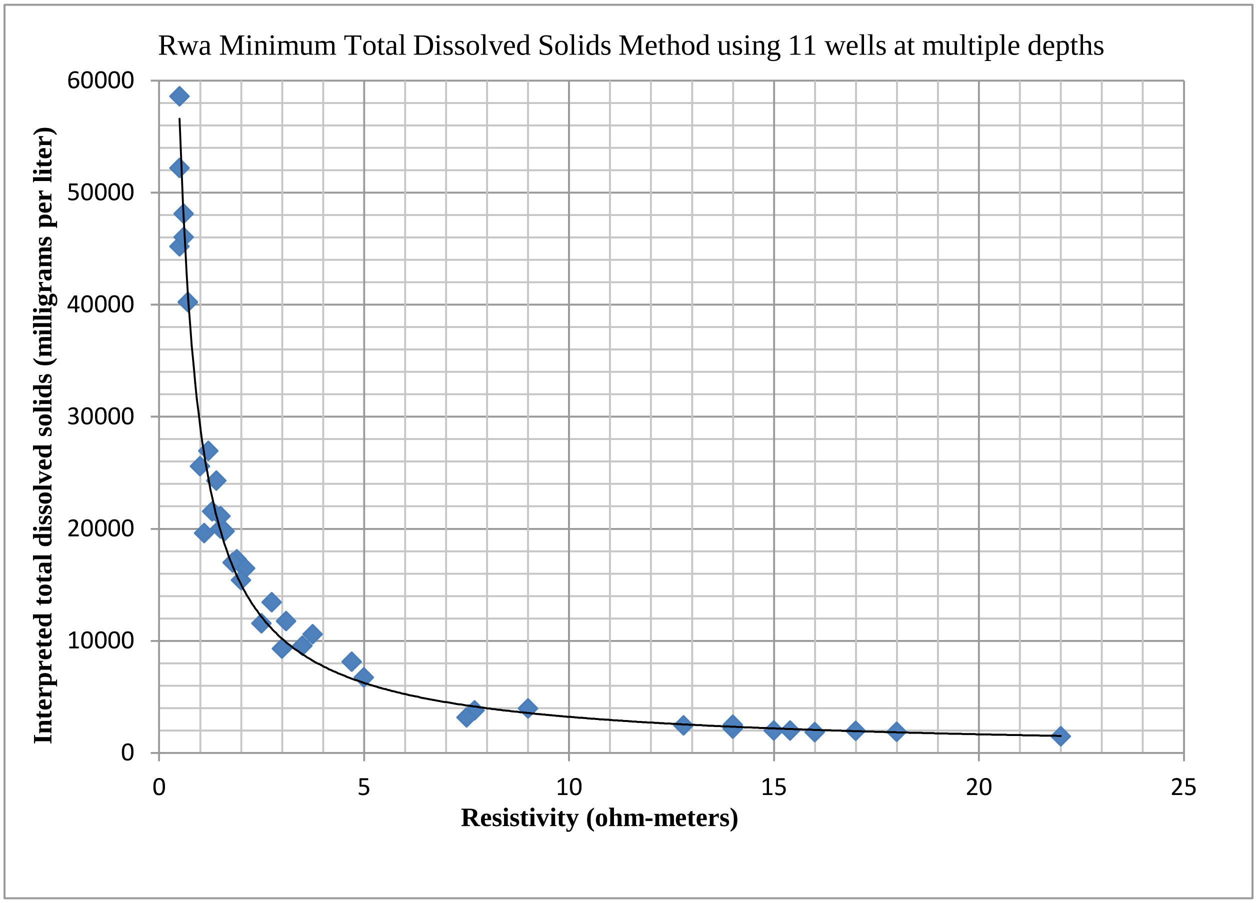


Figure 9. **Graph of interpreted total dissolved solids and deep resistivity from geophysical well logs using the Rwa Minimum Total Dissolved Solids Method. Eleven wells were interpreted, with multiple depth horizons assessed in each well. The locations of these wells are shown in Figure 7.**

function of the small number of wells (11) that were available for evaluation. In general, the result is surprising because this method uses the most input parameters of any method evaluated, and the majority of these parameters were obtained directly from log evaluation. In conclusion, the usefulness of this total dissolved solids method is questionable within the study area.

The wells used for the Rwa Minimum Total Dissolved Solids Method analysis are shown in Figure 7. Formation resistivity ranged from 0.5 to 22 ohm-meters and interpreted total dissolved solids from 1,850 to more than 52,000 milligrams per liter. The data points plotted on the graph match the power curve quite well (Figure 9). However, based on comparison with BRACS wells 2057 and 3819 (Figure 10), it appears that this method is not well suited to water containing less than approximately 2,000 milligrams per liter of total dissolved solids. Water quality data were obtained from well 3819 with drill stem tests at six different depth intervals. The Rwa Minimum Total Dissolved Solids Method overestimated total dissolved solids concentration by 500 to 1,400 milligrams per liter in all drill stem test samples that had total dissolved solids concentrations of 2,000 milligrams per liter or less. When total dissolved solids concentration in the formation-water increased rapidly below 800 feet in depth, the Rwa Minimum Total

Dissolved Solids Method captured the trend quite well. This same trend of increasing interpreted total dissolved solids with low (< 3 ohm-meter) formation resistivity also matches the trend in Figure 11, discussed next.

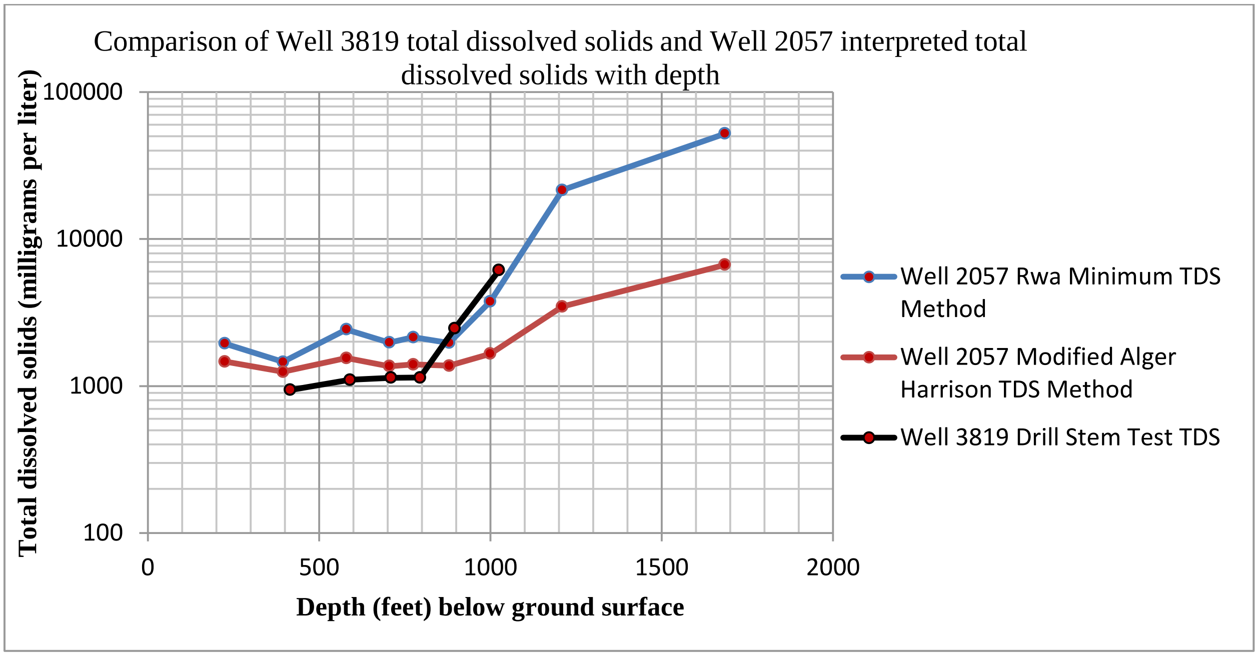


Figure 10. **Comparison of the total dissolved solids content of well 3819 drill stem test data and the interpreted total dissolved solids using the Modified Alger-Harrison and Rwa Minimum Total Dissolved Solids methods using a geophysical well log from well 2057 versus the depth below ground surface for each analysis. The depths selected for well 2057 are slightly different from well 3819 due to the slight difference in clean, thick sand depths between the two wells. The drill stem test data were obtained in 1949. The geophysical well log was performed in 1990 in a well 590 feet away from well 3819. Both methods used for interpreted total dissolved solids record higher total dissolved solids than the drill stem test data less than 800 feet. The Modified Alger-Harrison Total Dissolved Solids Method does not reflect the large increase in total dissolved solids below 800 feet in depth, whereas the Rwa Minimum Total Dissolved Solids Method captures this increase.**

The Mean Ro Total Dissolved Solids Method was evaluated by plotting deep resistivity values against total dissolved solids concentrations measured in nearby water wells or, for the higher total dissolved solids values, produced water from oil and gas wells (Figure 12). Ninety-three water quality samples were evaluated with 71 geophysical well logs. This task was designed to use water quality from many formations within the Gulf Coast Aquifer and formations with oilfield-produced water across the entire study area. The distribution of well sites with geophysical well logs is shown on Figure 13. The graph shows the presence of an inverse relationship; high resistivity relates to low total dissolved solids and low resistivity relates to high total dissolved solids. However, individual data points are spread widely on either side of the line. When these data are plotted on a log-log graph (Figure 12; refer to the orange dots representing data collected in this study), the relationship becomes linear and the spread of data points on either side of the best-fit line is readily apparent. The spread of data points at the lower formation resistivity portion of the graph is about 80,000 milligrams per liter and about 1,200 milligrams per liter at the higher formation resistivity portions.

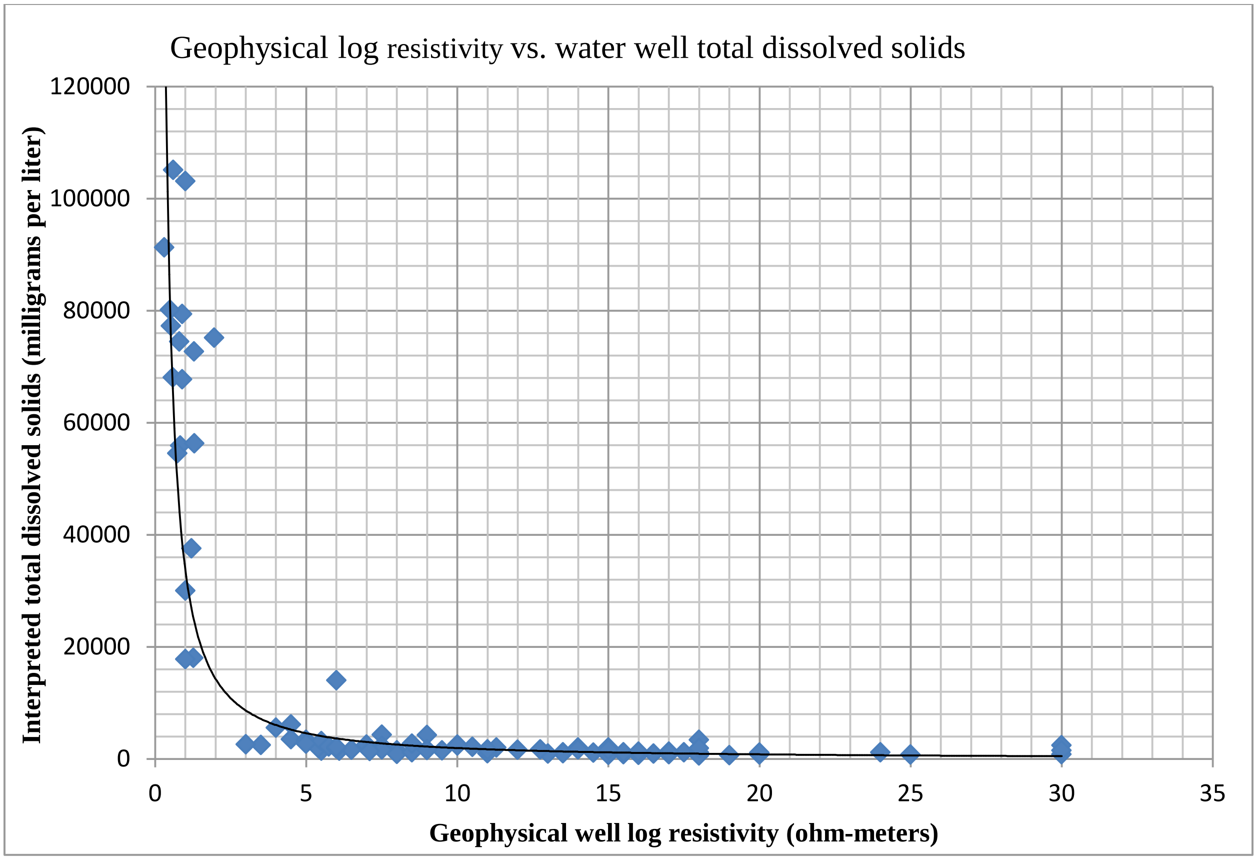


Figure 11. **Comparison of total dissolved solids content of formation water and deep resistivity from geophysical well logs. The locations of the wells used for this graph are shown in Figure 13. These are plotted in Figure 12 in a log-log graph (orange dots).**

The use of the Mean Ro Total Dissolved Solids Method and variations of this using fixed formation resistivity values as total dissolved solids indicators is common practice. Figure 12 shows data collected from three Gulf Coast studies and one statewide assessment. However, none of the authors provided data (comparison of formation resistivity to actual water quality total dissolved solids) to support the use of the fixed formation resistivity values as total dissolved solids indicators. Although the linear trends of the four studies correspond to the data collected in this study, one should be cautious using this approach for exact quantification of total dissolved solids using resistivity logs. Gross ranges of water quality may be estimated as long as an estimate of error bars, for example 7 ohm-meter = 3,000 milligrams per liter total dissolved solids +/- 2,000, is provided.

Limitations of the Mean RO Total Dissolved Solids Method from this study include the lack of a direct relationship between formation resistivity and total dissolved solids (as there is between specific conductance and total dissolved solids). Also, formation resistivity measurements were conducted with different tool types, at different depths, and over many decades. With the exception of a few samples, almost all formation resistivity measurements were conducted in wells located within an average distance of one mile from the well for which water quality data were available. While every attempt was made to measure formation resistivity at the same depth interval as the water sample, correcting for regional dip of sediments where necessary, and within the relatively same time span that the water sample was collected, this was not always possible. Thus, formation resistivity may not be an accurate reflection of the total dissolved solids at the time the geophysical well log was produced.

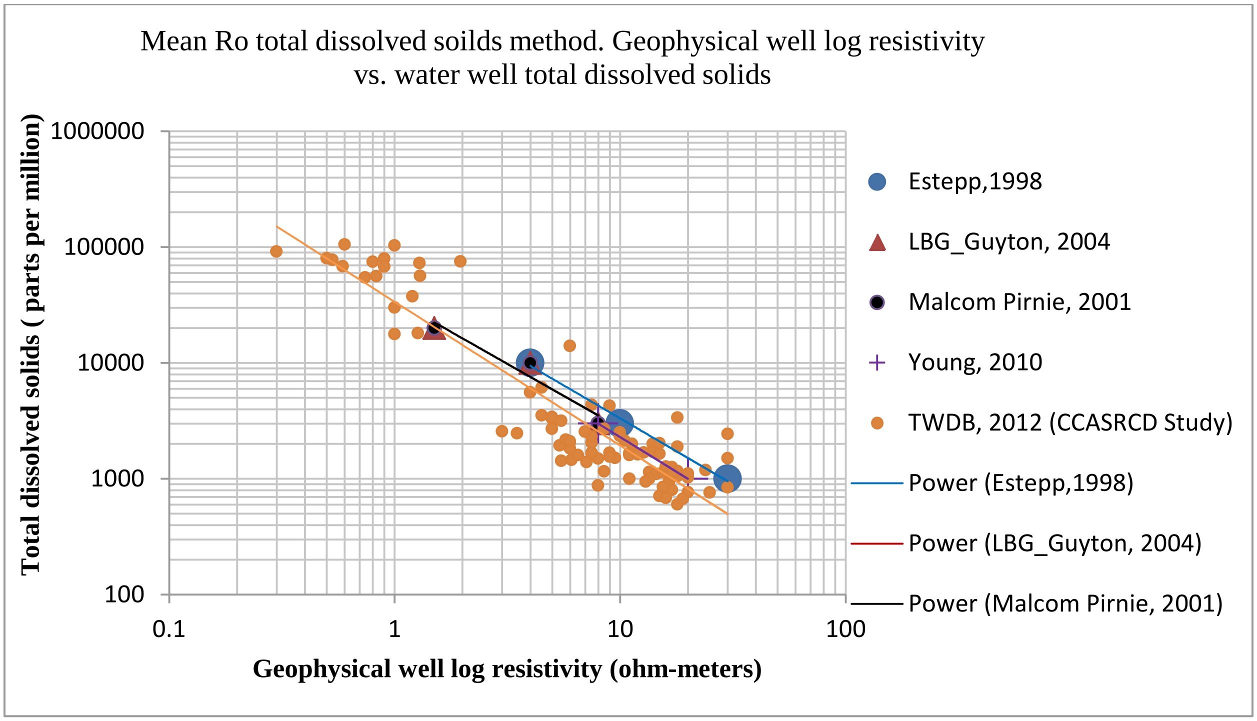


Figure 12. **Comparison of total dissolved solids content of formation water and deep resistivity from geophysical well logs. The orange points are data collected for this study. The results from four other projects are shown for comparison. The locations of the wells used for this graph are shown in Figure 13.**

Use of the spontaneous potential tool to estimate total dissolved solids analysis was not used in the study area. In the fresh water zone, this method is complicated by the presence of divalent cations. Unless water quality samples can be used to correct and calibrate the spontaneous potential response for the presence of these cations, results will be incorrect (Alger, 1966). The spontaneous potential tool response is small and rather featureless in the zone where the formation water resistivity is equal to the resistivity of the drilling mud filtrate, and the response is reduced within the transition zones both above and below (Schlumberger, 1972). In shallow aquifer settings, this is further complicated when formation waters mix with the drilling mud during the well logging process. This may cause an unequalized mud column, resulting in spontaneous potential baseline shifts (Alger, 1966).

The Rwa Minimum Total Dissolved Solids method approach using Figure 9 was used to determine the formation resistivity threshold approximating the interpreted 10,000 milligrams per liter total dissolved solids (the upper limit of brackish water). The 3 ohm-meter value corresponds to approximately 10,000 milligrams per liter total dissolved solids with an error of +/- 2,000.

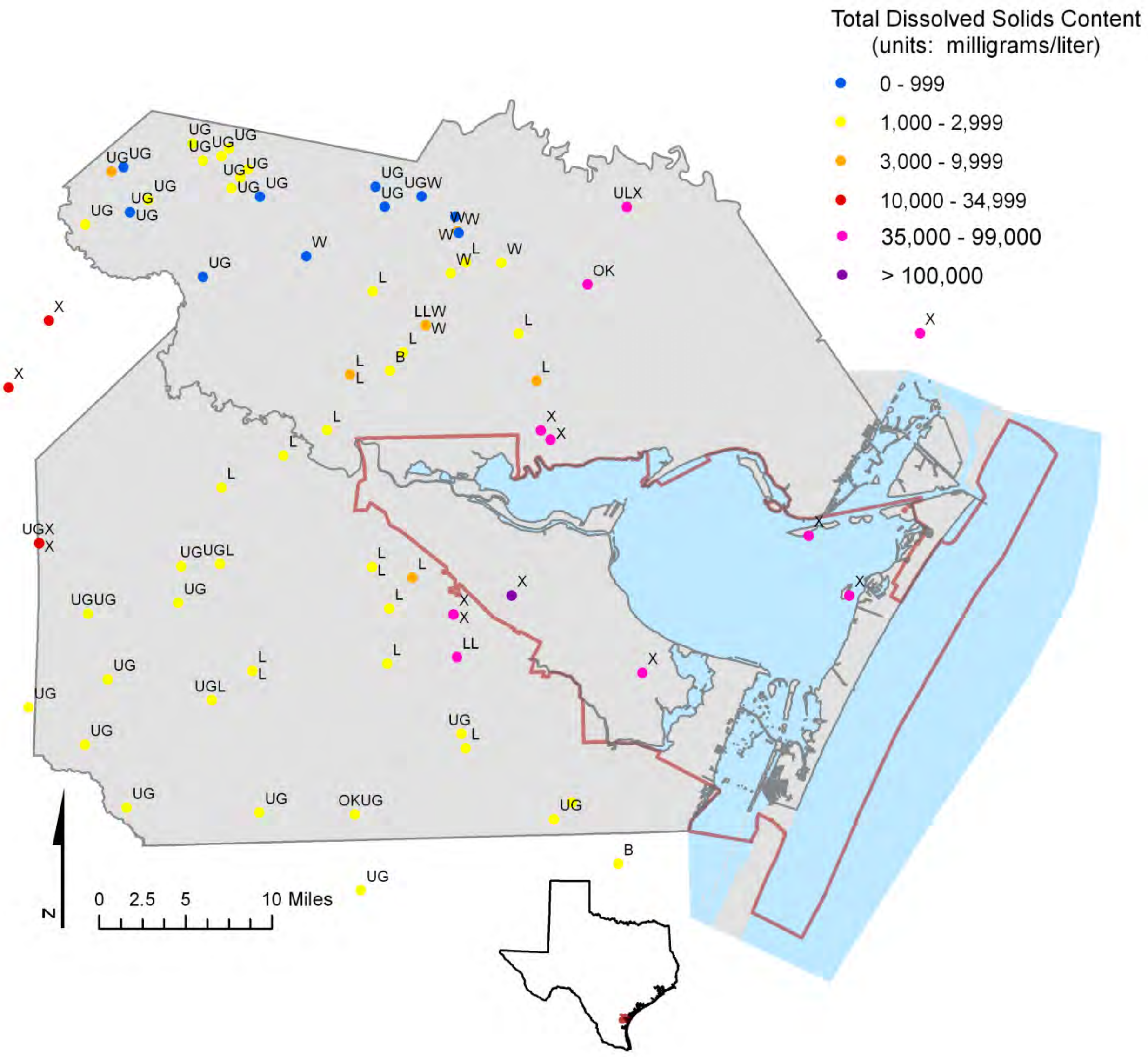


Figure 13. Wells used to define the relationship between deep resistivity and total dissolved solids content (93 samples). Each point represents a well with a geophysical well log located adjacent to a water well in the same formation for which total dissolved solids information is available. The red, pink, and purple symbol wells use elevated total dissolved solids samples from the U.S. Geological Survey Produced Water Database (U.S. Geological Survey, 2002). The blue, yellow, and orange symbol wells are water wells or, in rare cases, oil wells with drill stem test information. The letters adjacent to each well symbol indicate the formation evaluated (more than one formation was evaluated in a few wells). The letters (from shallow to deep formations) are Chicot Aquifer (B: Beaumont Fm; L: Lissie Fm; W: Willis Fm); Evangeline Aquifer (UG: Upper Goliad Fm; LG: Lower Goliad Fm; UL: Upper Lagarto); Burkeville Confining Unit (ML: Middle Lagarto); Jasper Aquifer (LL: Lower Lagarto Fm; OK: Oakville Fm); and below the Jasper Aquifer (X). The District boundary is shown in red.

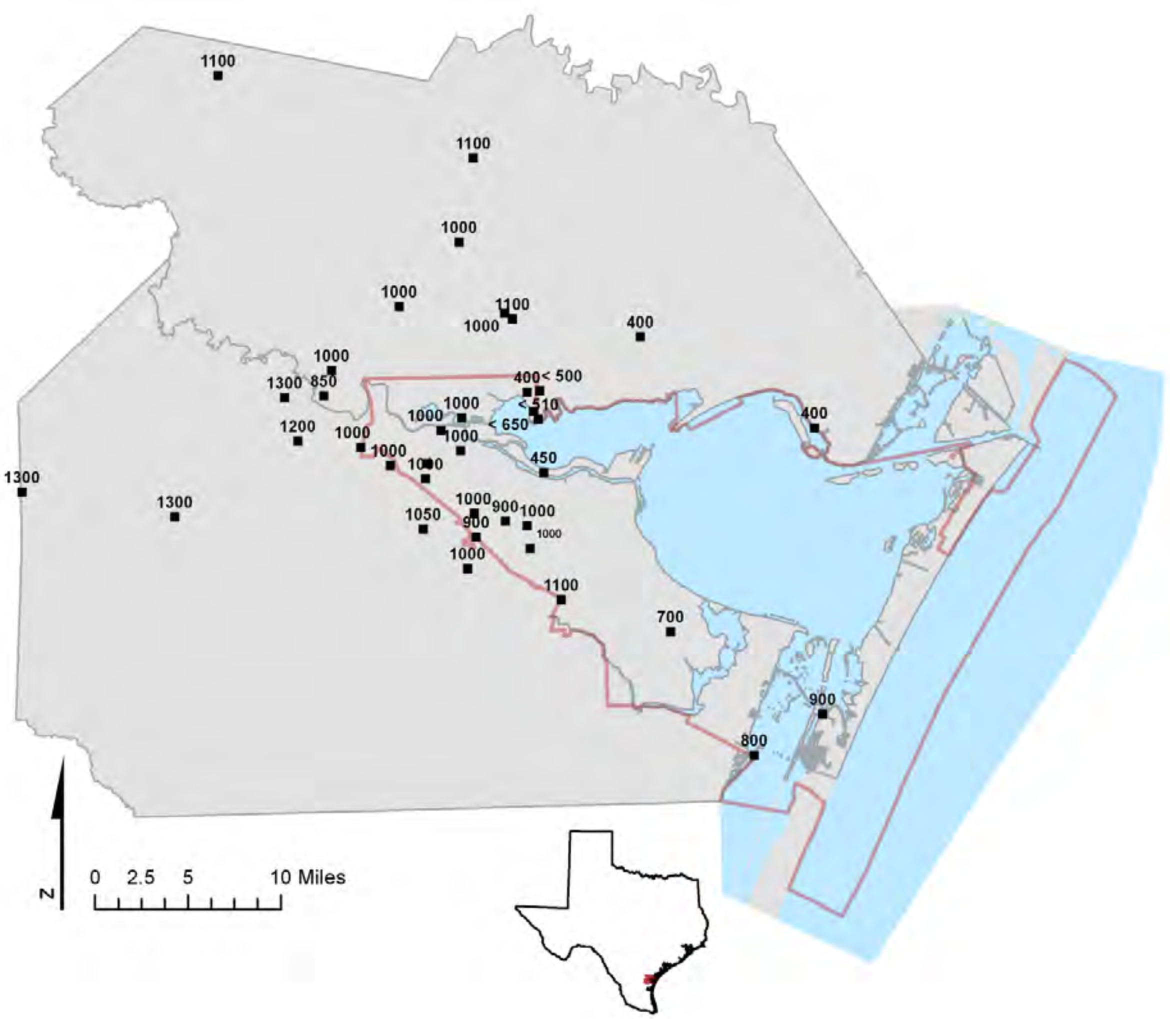


Figure 14. **Thirty-seven geophysical well logs were evaluated to determine the depth (feet below ground surface) where the deep resistivity of a sand layer is consistently 3 ohm-meters or less. The 3 ohm-meter value corresponds approximately to 10,000 milligrams per liter total dissolved solids with a standard error of +/- 2,000. Three wells in the center of the figure have the less than symbol (<) preceding the depth value; this indicates that the geophysical well log data began at a depth where the sands were already less than the 3 ohm-meter, so the depths are only approximate. The District boundary is shown in red.**

Thirty-seven wells with geophysical well logs were evaluated to determine the depth where the formation resistivity value of a sand layer is consistently 3 ohm-meters or less (Figure 14). The depth to 3 ohm-meters is approximately 1,000 feet below ground surface across much of the western third of the District, the focus of this study. The dramatic decrease in formation resistivity at this depth is readily apparent on the geophysical well logs.

Any attempt to calculate total dissolved solids concentrations with less than about 2 ohm-meters is very imprecise, as the data in Figure 9 show. Consequently, no attempt was made to define total dissolved solids concentrations higher than 10,000 milligrams per liter.

10. Lithologic descriptions

The descriptions of rocks recorded by water well drillers on well reports were appended to the well geology table in the BRACS Database either manually or by digital parsing techniques if a digital well report was available from the Texas Department of Licensing and Regulation. The database table includes the top and bottom depths, thickness of each unique lithologic unit, a description of the lithologic unit as presented by the driller, and the source of information. Although it would be beneficial to parse the lithologic description into additional fields, such as color, texture, rock type, relative hardness, fossils, and presence of water, we chose to keep the entire lithologic description in one database field. While this limited our ability to process the information into net sand maps and display more detailed lithologies on geological cross-sections, it allowed us to enter data faster.

Because well drillers frequently use non-geological terms (for example, gumbo), misapply terms (for example, talc in an alluvial deposit), and almost never describe the formations in a uniform and systematic manner, we developed a process to convert the drillers' descriptions of rocks into a simplified lithologic description. Our description consists of a short list of terms based on mineralogy and grain size. Simplifying drillers' descriptions of lithologies is not new and has been used by others (for example, Seni, 1980; Young and others, 2010).

A database lookup table relating the described lithologic name to the simplified lithologic description was prepared to accommodate the numerous variations present on well reports. Presently, the database lookup table contains more than 5,000 records and 98 simplified lithologic names.

If the well report or geophysical well log is missing information because of the presence of well casing, the term "No Record" is listed in the geology table for this depth interval. If a portion of the well report or geophysical well log is missing because the log is incomplete (only part of the log was scanned as a digital image), the term "Geology not processed–Log image cut off" is listed in the geology table for this depth interval. Tracking missing information with these terms is required during subsequent evaluation of net sand and sand percent. If a section of a geologic formation could not be fully evaluated, the sand percent was not calculated.

The simplified lithologic names represent either one predominant type of material (for example, sand) or a mixture of two (for example, sand and gravel). Each term representing a mixture assumes that each component of the mixture approximates a 50-50 mix. The creation of the database table relating lithologic name to simplified lithologic name presented challenges and also necessitated some simplifications. Formation descriptions that contained more than two terms as part of a mixture (for example, sand, clay, and limestone) were converted to only the first two terms or the two most important terms based on percentage (if provided by the driller). Formation descriptions that included percentages of material within the 35-65 percent range were categorized as a 50-50 mixture.

Three hundred and twenty eight wells (Figure 15) were evaluated for simplified lithologic description (184 water wells and 144 oil and gas wells with geophysical well logs). Sixteen of the wells were evaluated by Young and others (2010) in the study area; a similar method of geophysical well log evaluation was used in this study, so data from Young and others (2010) could be incorporated seamlessly. The simplified lithologic description was only applied

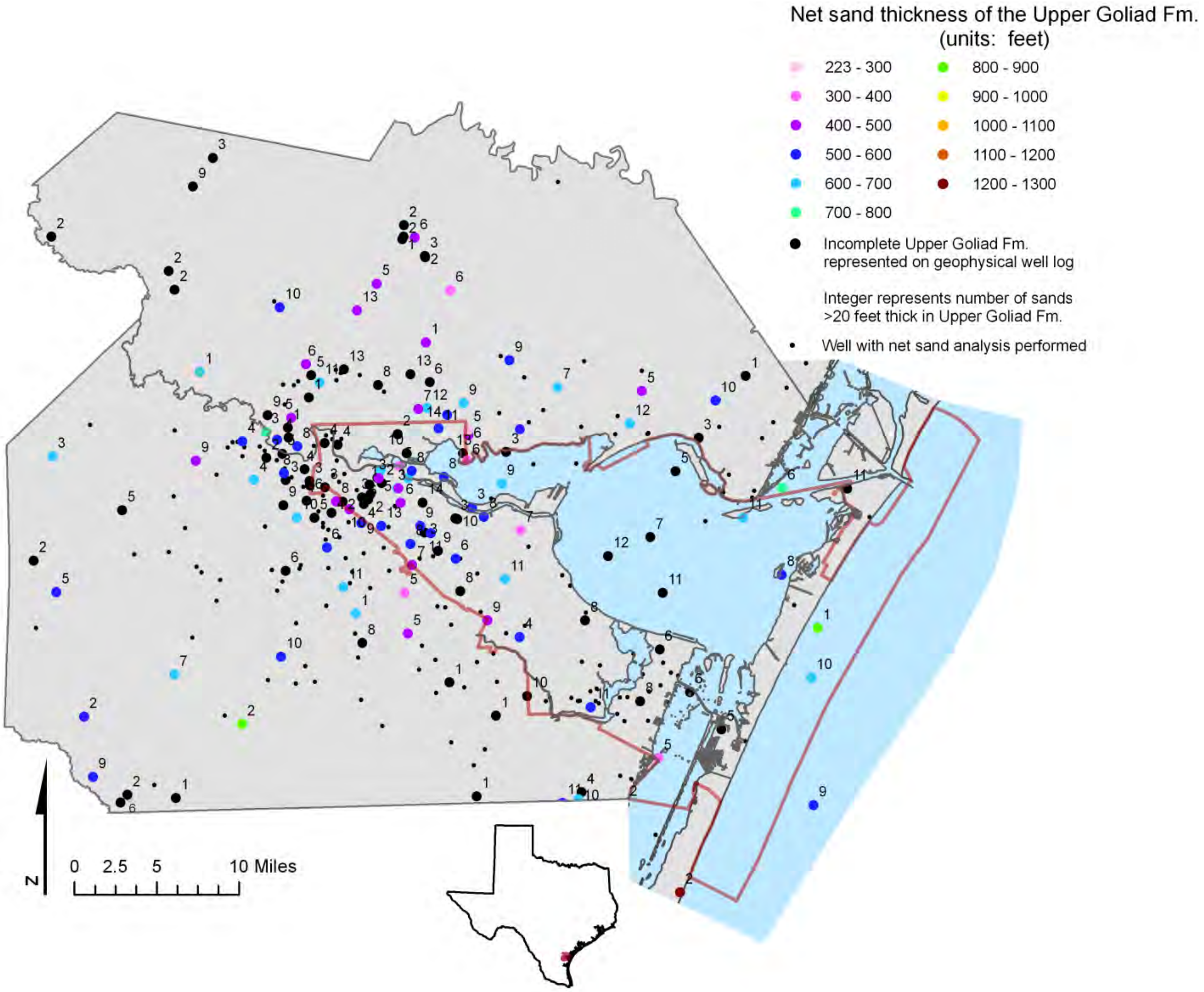


Figure 15. **The GIS files used in this map were created using simple queries in Microsoft® Access®, with files exported to ArcGIS for display. The data contained in the BRACS Database can be queried a number of ways to produce custom displays in ArcGIS. This map represents one method of evaluating the Upper Goliad Formation. Three hundred and twenty eight well logs (small black dot) were used for net sand analysis in the study area. Eighty-one well logs had the full Upper Goliad Formation represented; the colored dots refer to net sand thickness within this formation. One hundred fifty-nine well logs indicate at least one sand unit in the Upper Goliad Formation greater than 20 feet in thickness; the number next to the large dots indicates the number of sand units that met this condition. Wells with a large black dot represent incomplete Upper Goliad Formation recorded on the geophysical well log. District boundary is shown in red.**

from ground surface to the total depth of the hole for water wells. Using geophysical well logs, the simplified lithologic description was applied from the bottom of the surface casing to several hundred feet below the Oakville Formation or to the bottom of the logged interval, whichever came first. Sixteen of the geophysical well logs obtained for simplified lithologic description analysis did not have information for the entire borehole, because the log image was incomplete.

Simplified lithologic description was applied to the total depth of logging represented on the digital image.

We used deep resistivity tools in the shallow (fresher aquifer sections) because the spontaneous potential tool is ineffective in this zone. In the deeper portions of the aquifers, where the resistivity of the drilling mud filtrate is greater than the resistivity of formation water, we used spontaneous potential tools rather than deep resistivity tools. These zones produce a negative (or left) shift of the spontaneous potential log with respect to the shale baseline within permeable sands. The spontaneous potential and resistivity logs are affected by the presence of hydrocarbons; the spontaneous potential log is suppressed and the resistivity is increased (Hilchie, 1978). When these zones were encountered, a note was written in the remarks field of the geology table for these lithologic layers. This information will be helpful because hydrocarbon-bearing sands are not suitable target units for aquifer storage and recovery.

Gamma ray logs are quite rare in the study area, partly because many of the geophysical well logs that were available to us were quite old. The gamma ray tools are excellent for discriminating sand and clay sequences and, where present, were used in conjunction with the spontaneous potential and resistivity tools to identify lithology.

11. Net sand data

Net sand and sand percent values for wells penetrating the formations in the Gulf Coast Aquifer were generated from the simplified lithologic description. If a well only partially penetrated a formation, a net sand value was calculated, but not the sand percent.

The table listing all simplified lithologic names contains a field for sand percent. Values of 0, 35, 50, 65, or 100 were chosen based on the presence of sand or coarser material. For example, a value of 50 would be applied to a lithologic unit containing a mixture of sand and clay. This table is used in subsequent database queries to process well records.

Because database queries must address lithologic units that are not completely contained within one formation (the unit may straddle the formation top, bottom, or both), specific queries were written to evaluate each of these scenarios and to assign the correct thickness of a lithologic unit to the correct formation. More than 168 separate queries were performed to create a final data set for the nine formations within the Gulf Coast Aquifer. These queries were loaded into Microsoft® Visual Basic® for Applications and linked to a form to systematically process the information. A separate query was performed to assemble the information into a table for export into GIS for spatial display.

Two Microsoft® Access® tables containing net sand information were created for the study area: one table contains individual records for each layer with sand and the other table contains one record per well and is a summary of net sand and sand percent for each formation encountered. These tables can be exported into GIS for display and analysis. The two database tables can also be queried in a number of ways to develop custom approaches to analysis. Figure 15 was developed to show Upper Goliad Formation net sand thicknesses for each well with a complete section available. An additional layer of data shows the number of sand units greater than 20 feet thick within the Upper Goliad present at each well site. If the user wanted only sands greater than 50 feet thick, this query could be performed and the information exported to ArcGIS for analysis. The design of the geology and net sand tables in Microsoft® Access®, and the methods used to capture this data, afford the user a tremendous degree of flexibility in data analysis.

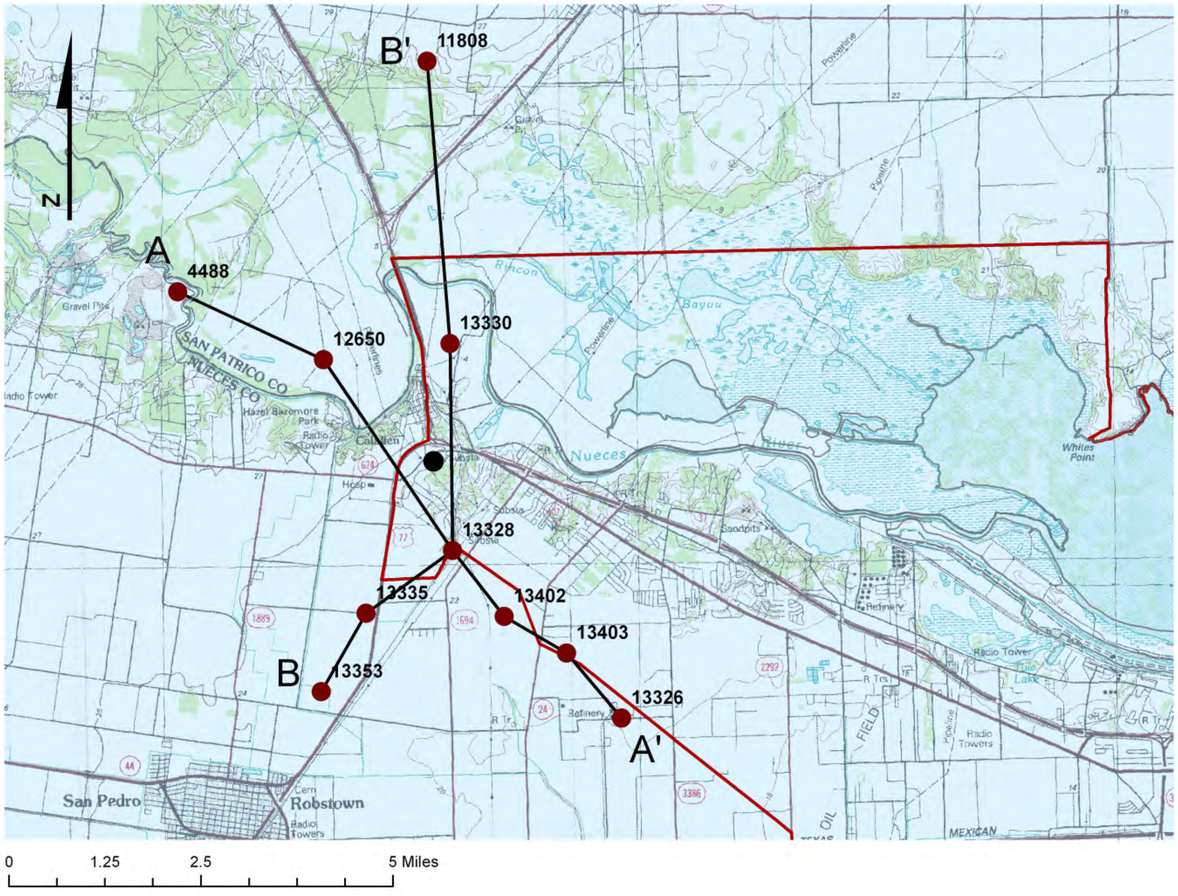


Figure 16. Location of cross-sections A-A' and B-B', west end of the District (boundary in red). Black dot represents O.N. Stevens Water Treatment Plant. Red dots and numbers refer to wells used on cross-sections (black lines). Cross-section A-A' is shown in Figure 17 and cross-section B-B' in Figure 18.

One way net sand information can be used for well site selection is in preparing cross-sections. Figure 16 shows the cross-section well and line locations used in the area of the O.N. Stevens Water Treatment Plant. Two geologic cross-sections consisting of the upper 3,000 feet of Gulf Coast Aquifer are shown in Figures 17 and 18. The lithologic data captured in the database can be scaled to meet different cross-section needs for targeting specific sections of the aquifer for evaluation. Test well lithology can be appended to the database, and later displayed in GIS and on cross-sections for site-specific evaluation.

Young and others (2010, Figure 5-4) used 28 wells for stratigraphic and 24 wells for lithologic control within the study area. Review of the datasets from their project yielded inconsistencies in net sand and sand percent maps compared with our study area wells. Our review of the same logs plus our additional well control could not confirm the existence of some of the high sand areas identified by Young and others (2010). Because many of the wells in the study area are cased through the upper part of the Gulf Coast Aquifer, we are not sure how Young and others (2010) arrived at their conclusions. We make this observation to emphasize that users need to critically review the information presented in any report and draw their own conclusions. In many situations, more recent projects with more extensive datasets will provide a level of detail that must be reconciled with previous work—especially when evaluating smaller project areas with a specific purpose differing from previous studies.

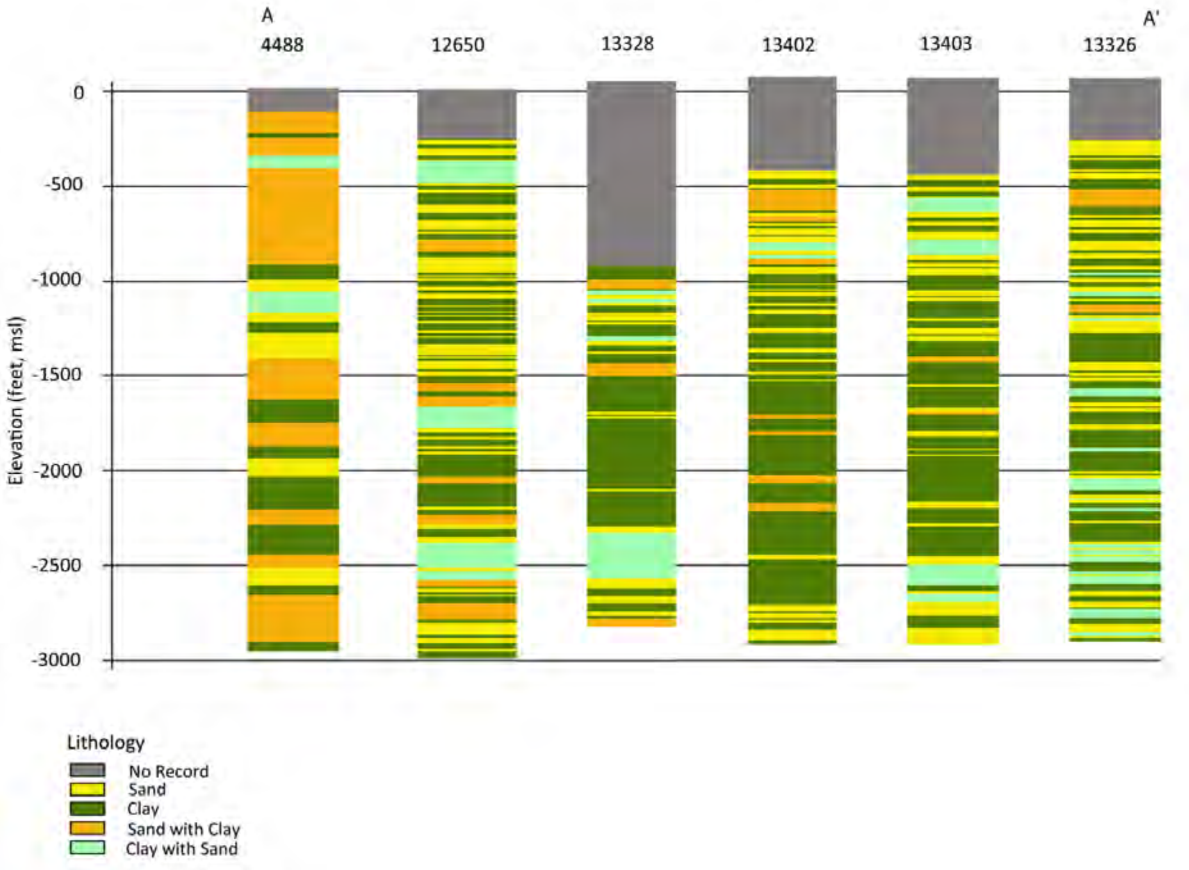


Figure 17. **Dip section A-A' in the western part of the District. The numbers at the top of each section refer to the BRACS well identification for each well. The top 3,000-foot of section for each well is displayed on this cross-section. Gray color at the top of each log represents well casing, where lithology cannot be interpreted. Note the discontinuous nature of the sands from one well to another. Total cross-section length is approximately 8.25 miles. Vertical exaggeration x10. Cross-section location is shown on Figure 16.**

12. Water quality data

We compiled information on 468 groundwater chemical samples collected from 298 wells in the study area: 427 analyses from wells listed in the two main tables in the TWDB Groundwater Database and 41 analyses from published reports (Broadhurst and others, 1950; Johnson, 1939; Lynch, 1934; Shafer, 1968). We entered the records from the reports into two BRACS Database tables but did not perform a quality control check.

All records were appended to one master table in the BRACS Database, which facilitates the creation of a water quality GIS shape file. The source of each record was noted in the table along with all applicable well identification numbers. The wells with water quality data were assigned

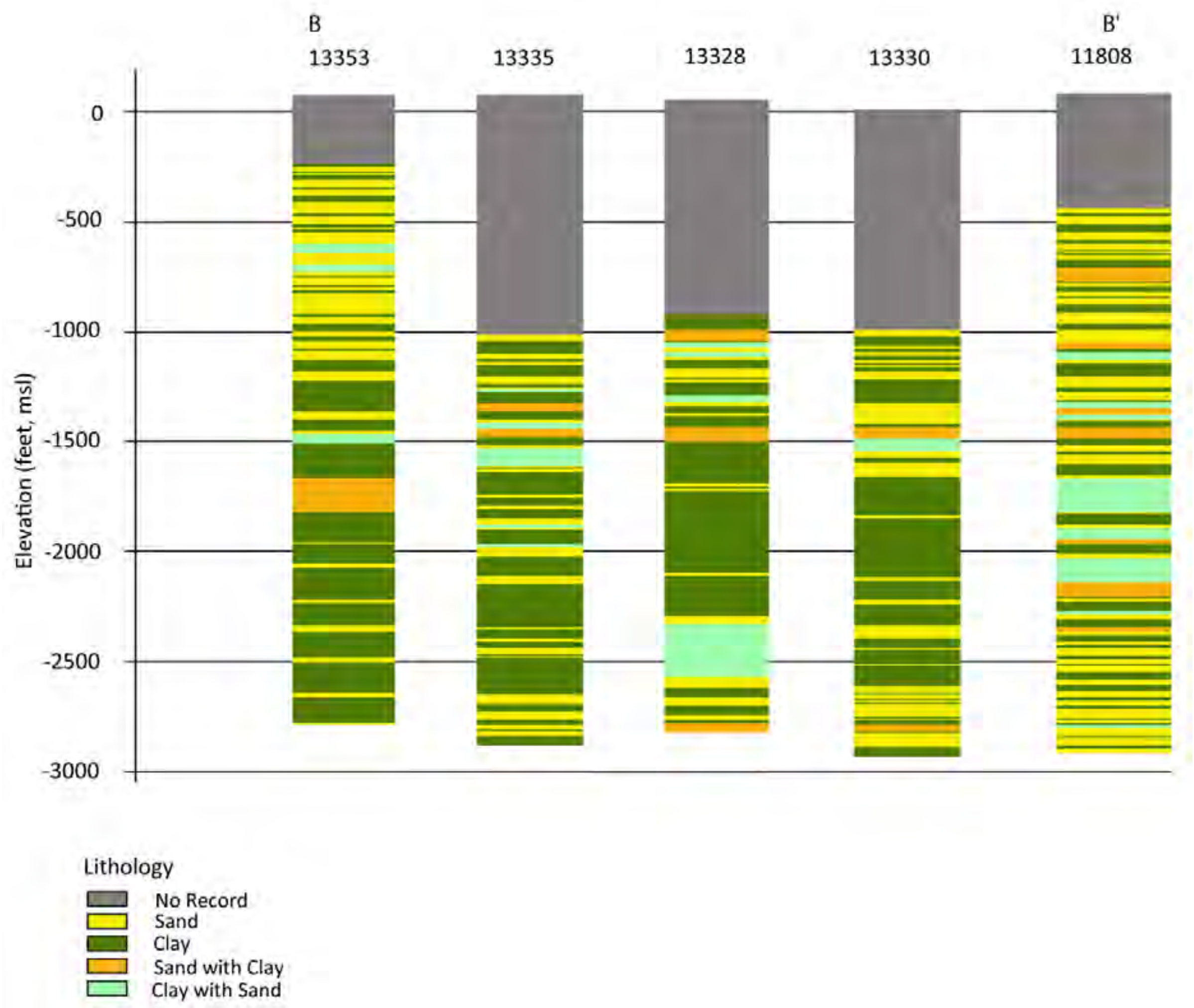


Figure 18. Strike section B-B' in the western part of the District. The numbers at the top of each section refer to the BRACS well identification for each well. The top 3,000-foot section for each well is displayed on this cross-section. Gray color at the top of each log represents well casing, where lithologic interpretation is not possible. Note the discontinuous nature of the sands from one well to another. Total cross-section length is approximately 8.9 miles. Vertical exaggeration x8. Cross-section location is shown on Figure 16.

aquifer designations based on location and depth to the hydrostratigraphic units developed by Young and others (2010). Water quality samples (Figures 19, 20, and 21) represent the Chicot Aquifer (291), Chicot and Evangeline aquifers (89), Evangeline Aquifer (75), and non-Gulf Coast aquifers (13). A full discussion on water quality of the Gulf Coast Aquifer is beyond the scope of this study. The reader is referred to Chowdhury and others (2006) for a comprehensive discussion on the topic.

Water quality data in the Gulf Coast Aquifer are highly variable. Groundwater is generally fresh in the outcrop and becomes more saline toward the coast. Groundwater also increases in salinity with depth, as evidenced by state well number 7960601, which had six drill stem tests performed between 416 and 1,025 feet below ground surface. In these drill stem tests, total

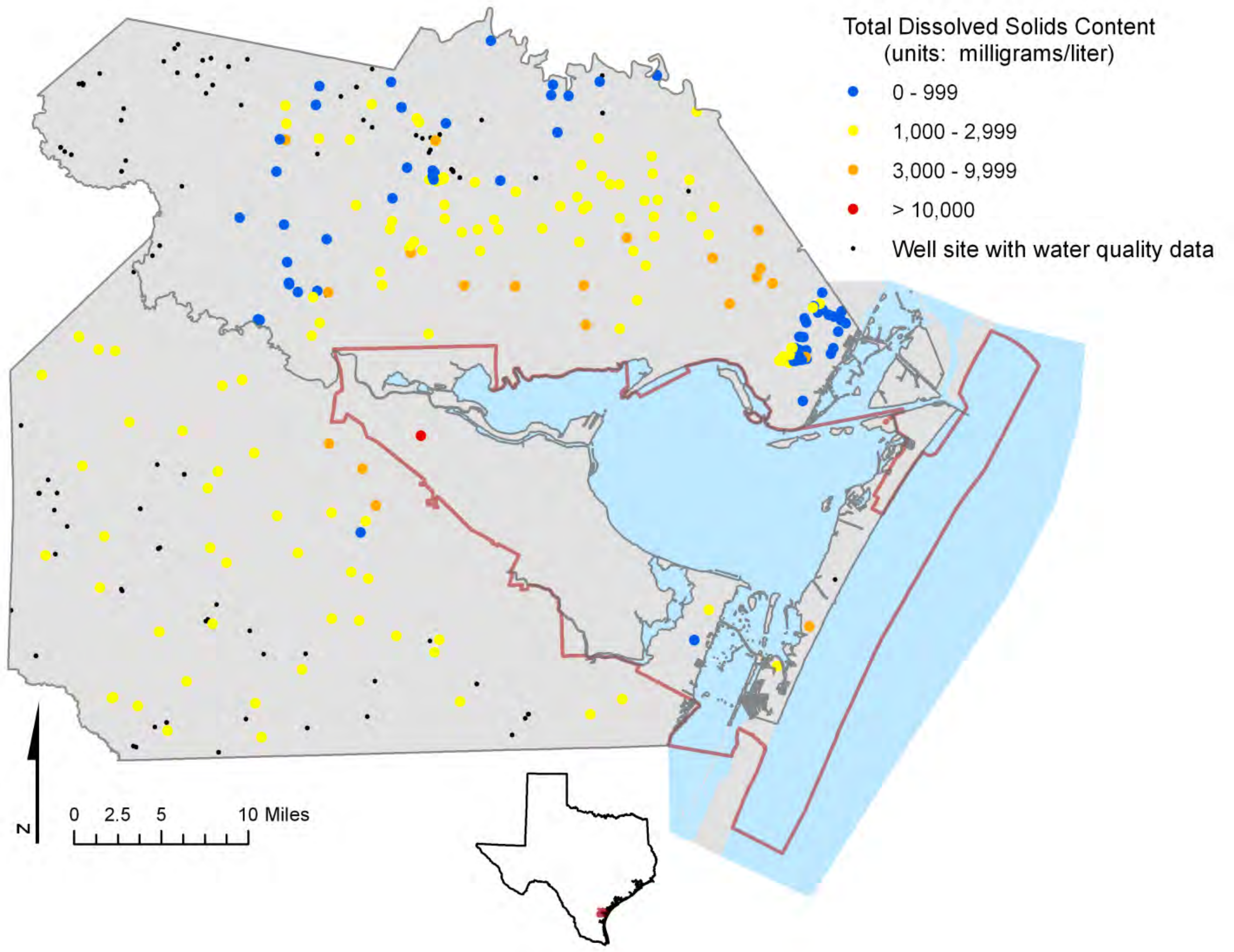


Figure 19. **Total dissolved solids content of wells completed in the Chicot Aquifer (291 analyses; 202 wells). The District boundary is shown in red.**

dissolved solids concentration increased with depth from 942 to 6,138 milligrams per liter. Complicating the natural system is the impact of human activity in the area, particularly oil and gas development. Prior to the no-pit rule established by the Railroad Commission of Texas in 1969, produced water was disposed in pits and surface water bodies. Higher salinity water can also move along abandoned or improperly completed or plugged wells in the study area. Several examples in TWDB's Groundwater Database show increasing total dissolved solids in wells over time. An example is state well number 7951705 completed in the Evangeline Aquifer in which total dissolved solids increases from 1,024 to 1,733 milligrams per liter between 1952 and 1965. There may also be examples of higher saline water at shallow depths, underlain by fresher water, which in turn is underlain by the normal sequence of higher salinity water at depth. This may be a result of shallow disposal or spills of higher salinity produced water from oil and gas field activities. Several geophysical well logs indicate this occurrence based on resistivity; however, very few wells in the study area have water quality samples taken from different depth intervals to substantiate this interpretation.

Prediction of water quality within the Gulf Coast Aquifer in the District is not possible with any degree of certainty, because of the general lack of water quality samples in the region and the

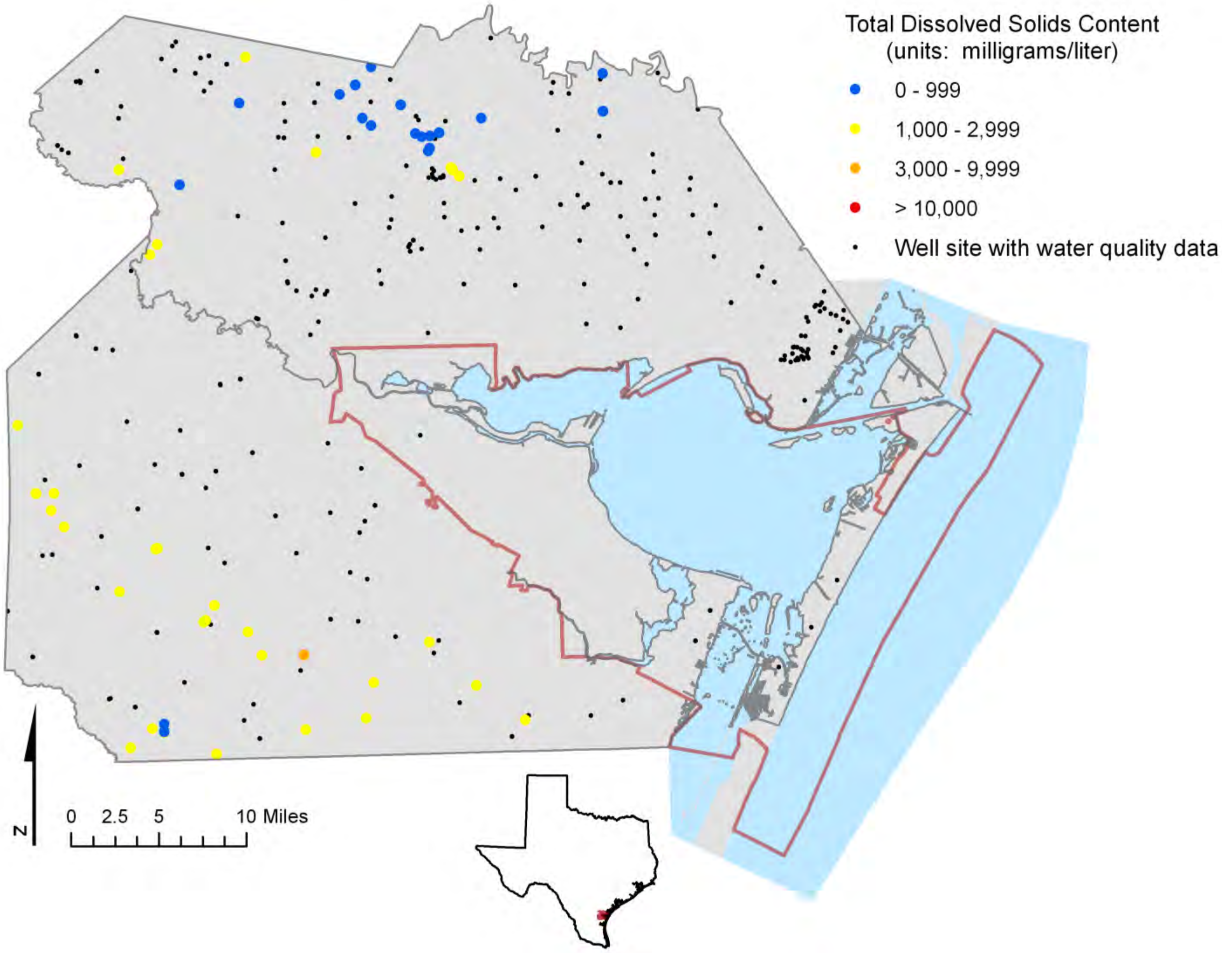


Figure 20. **Total dissolved solids content of wells completed in the Chicot and Evangeline aquifers (89 analyses; 54 wells). The District boundary is shown in red.**

inability to accurately evaluate resistivity or spontaneous potential geophysical well logs. To accurately define the water quality of formations in the study area, it will be necessary to drill test wells and collect and analyze the aquifer water directly.

Water wells with radionuclide analyses were extracted from the TWDB Groundwater Database and are shown in Figure 22. Forty-one wells with a total of 112 samples are present within the Gulf Coast Aquifer in the study area. The term maximum contaminant level refers to the contaminant drinking water limit set by the U.S. Environmental Protection Agency. Alpha activity was analyzed 48 times from 40 wells with the following results: 14 samples were non-detect; 23 were less than and 11 greater than the maximum contaminant level. Alpha activity ranged from 2.2 +/- 2.2 to 174 +/- 9.5 picocuries per liter. The maximum contaminant level for alpha activity is 15 picocuries per liter (TCEQ, 2011). Uranium was analyzed 12 times from 12 wells with sample results of three non-detect; six were less than and three greater than the maximum contaminant level. Uranium concentration ranged from 1.6 to 211 micrograms per liter (maximum contaminant level is 30 micrograms per liter, TCEQ, 2011). Radium-226 and radium-228 were sampled 16 times from eight wells with sample results of two non-detect and

14 less than the maximum contaminant level. The maximum contaminant level for combined radium-226 plus radium-228 is 5 picocuries per liter (TCEQ, 2011).

Geophysical well logs with a gamma ray tool located within 10 miles of the District boundary were evaluated for the presence of abnormally high gamma ray "spikes" within the Gulf Coast sediments (Figure 22). These spikes are a few feet thick and likely indicate the presence of radionuclides in concentrations higher than background shale concentration of the potassium-40 isotope. Twenty-six of the 29 wells evaluated had a cumulative total of 107 spikes with upwards of 300 American Petroleum Institute units (the unit of measure on the gamma ray log). Many logs did not have full coverage of the Gulf Coast sediments, so the total number of spikes is unknown. Spikes were present within the entire Gulf Coast sequence of sediments. The depths and American Petroleum Institute unit values were recorded in the geology table. The source material cannot be determined by the gamma ray tool, and tools capable of providing this information were not available in the collection of logs for the study area. It is likely that the source of elevated radionuclides in the Gulf Coast sediments is altered volcanic ash which was

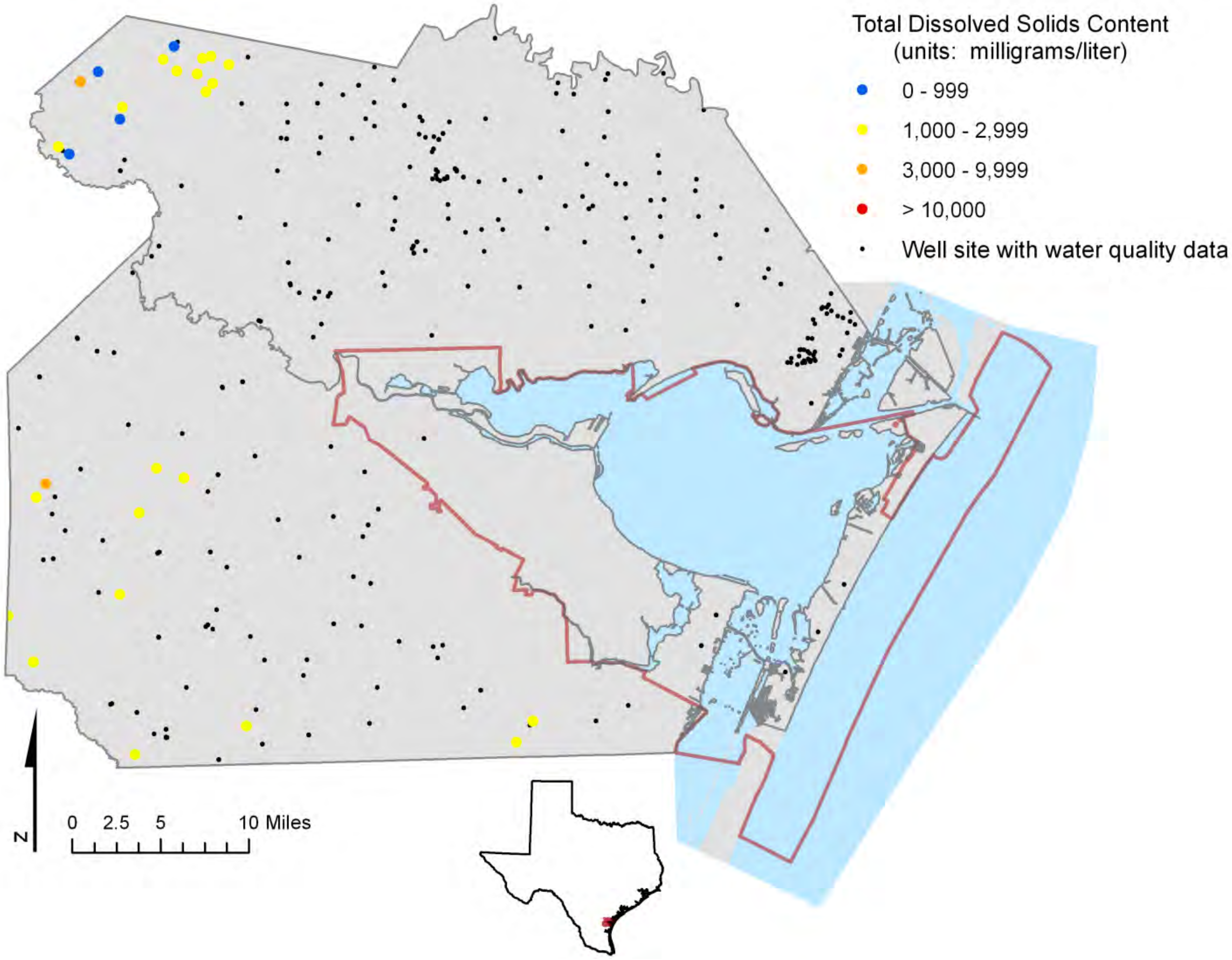


Figure 21. **Total dissolved solids content of wells completed in the Evangeline Aquifer (75 analyses; 31 wells). The District boundary is shown in red.**

deposited in the Tertiary sediments. Radionuclides can become soluble in oxidizing solutions and migrate with groundwater until reducing conditions result in precipitation.

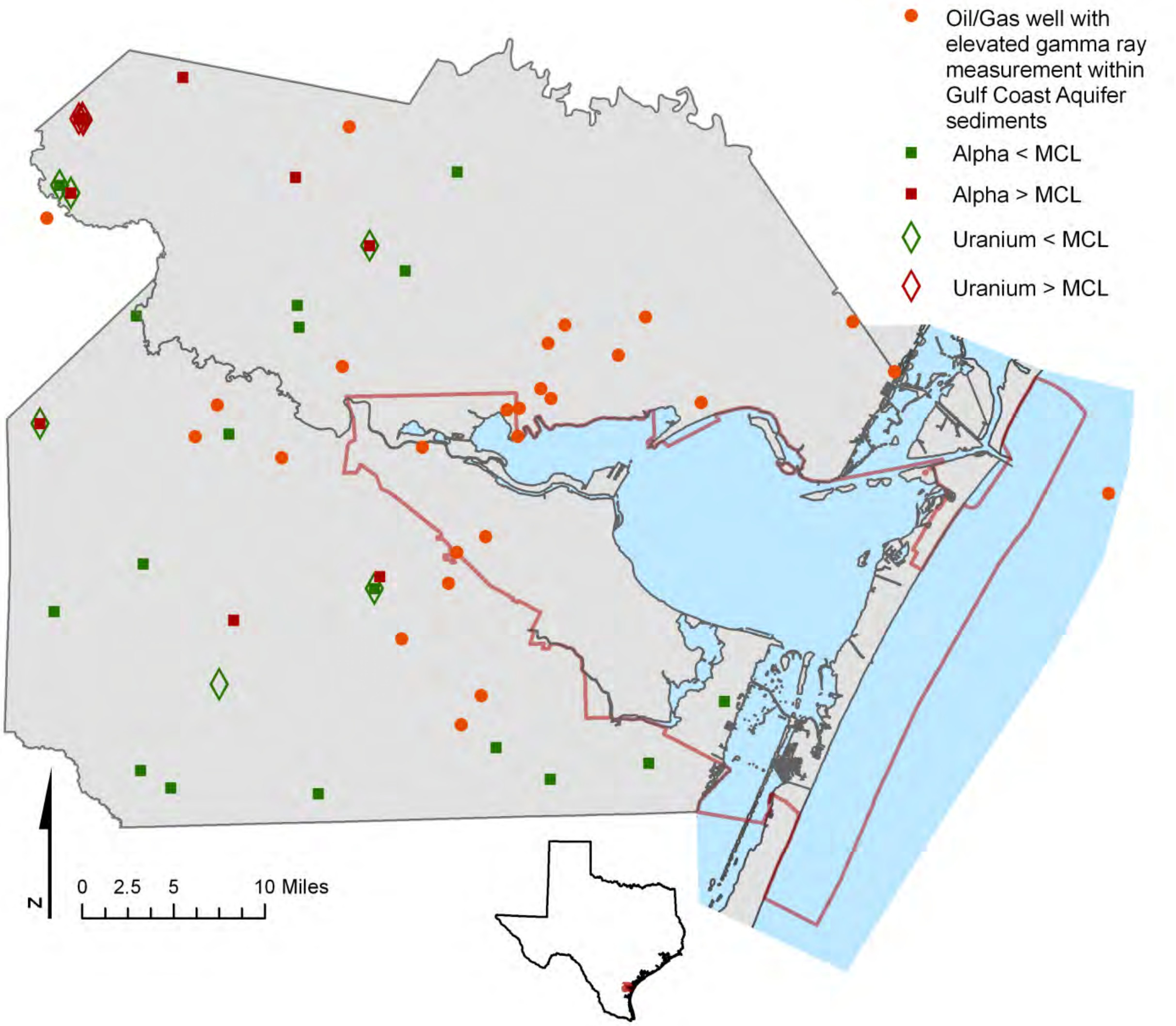


Figure 22. **Water wells within the Gulf Coast Aquifer sampled for alpha or uranium are displayed with the solid square symbol and open diamond symbol, respectively. The green-colored symbols represent samples less than the maximum contaminant level for the contaminant, and the red symbols represent samples greater than the maximum contaminant level. The drinking water maximum contaminant level for alpha is 15 picocuries per liter, and the maximum contaminant level for uranium is 30 micrograms per liter. These sample results were obtained from the TWDB Groundwater Database. Oil and gas well locations (orange dots) within 10 miles of the District (boundary shown in red) were evaluated for elevated gamma ray log measurements within the Gulf Coast Aquifer. The gamma ray spikes occur throughout the Gulf Coast sediments, are usually less than 10 feet thick, and range up to 300 American Petroleum Institute units. Gamma ray spikes are above the background level for shale in the formations and indicate enrichment in radionuclides. Twenty-six of the 29 wells within the study area had gamma ray spikes, and the remaining three logs did not fully penetrate the entire Gulf Coast sequence.**

Water wells with radionuclide samples greater than the maximum contaminant level located in close proximity to oil and gas wells showing gamma ray spikes were compared to determine whether the same zones were represented in both wells. Unfortunately, a comparison could not be made, because in each of the three cases where the wells were located reasonably close together, the shallowest geophysical log zone started deeper than the water quality sample zone.

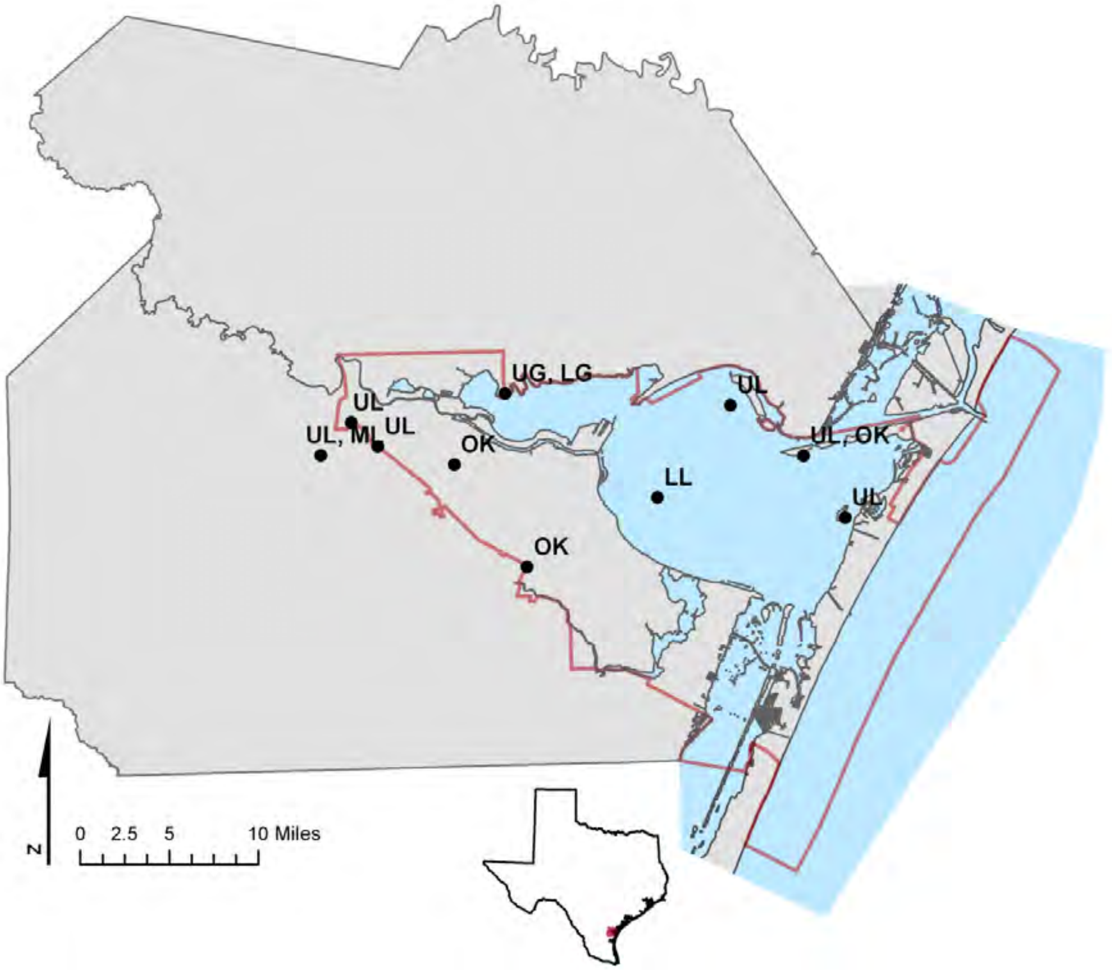


Figure 23. **Oil and gas well locations (black dots) showing the presence of hydrocarbons (oil and gas) within the Gulf Coast Aquifer. Oil and gas occurs within Gulf Coast sediments, and geophysical well logs reviewed for lithology indicated potential hydrocarbons. Only a fraction of the wells reviewed in this study area were evaluated using this approach. The letters adjacent to each well symbol show the formation containing the potential hydrocarbons (some wells show hydrocarbons in more than one formation). The letters are, from shallow to deep formations, Chicot Aquifer (B: Beaumont Fm; L: Lissie Fm; W: Willis Fm); Evangeline Aquifer (UG: Upper Goliad Fm; LG: Lower Goliad Fm; UL: Upper Lagarto); Burkeville Confining Unit (ML: Middle Lagarto); Jasper Aquifer (LL: Lower Lagarto Fm; OK: Oakville Fm); and below the Jasper Aquifer (X). The District boundary is shown in red.**

Geophysical logs with spontaneous potential and resistivity tools were used to evaluate the lithology of the Gulf Coast sediments. Ten of the wells reviewed within or immediately adjacent to the District showed the presence of hydrocarbons within Gulf Coast formations (Figure 23).

The presence of hydrocarbons in sands is marked by a suppressed spontaneous potential response coupled with an increased resistivity response relative to the adjacent sands (Hilchie, 1978). This information was recorded in the geology table for each of these wells. The presence of hydrocarbons in the study area is not unusual: oil and gas is produced from the Gulf Coast formations and underlying units. However, for aquifer storage and recovery, the presence of hydrocarbons is significant because sands with oil and/or gas are unsuitable storage units.

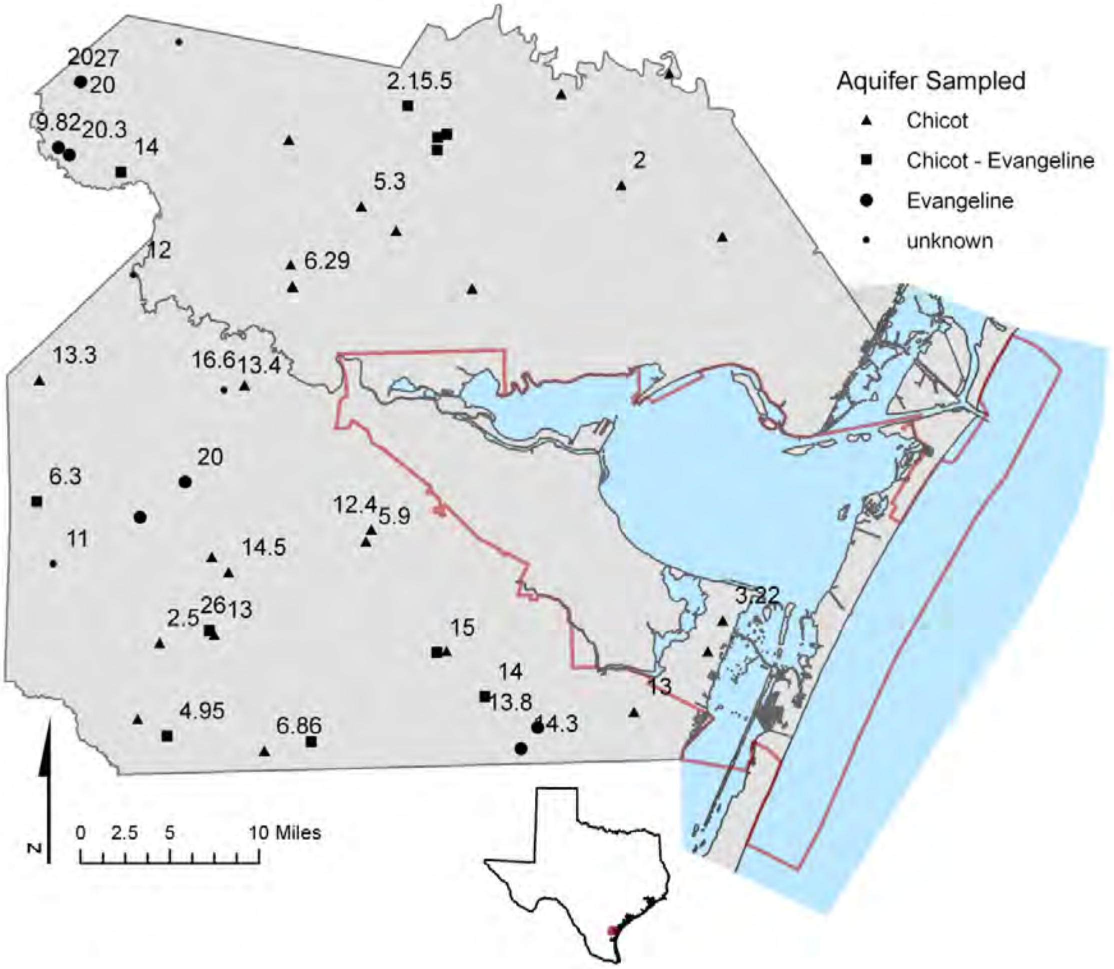


Figure 24. **Distribution of arsenic in the study area. Fifty-one wells were sampled, and the most recent sample value per well is displayed on this map. Wells with no value are non-detect. The value next to each symbol represents sample results in micrograms per liter. The well symbols are based on the aquifer sampled by the well. The small dot represents an unknown aquifer; wells without a well depth or screen did not have an aquifer assigned. The District boundary is shown in red.**

Fifty-one wells (82 water samples) in the study area were analyzed for arsenic (Figure 24). Concentrations ranged from non-detect to 27 micrograms per liter. Table 3 summarizes the results by aquifer. The source of arsenic in groundwater of the Gulf Coast Aquifer is presumed to be geologic in origin, related to volcaniclastic deposits and reworked sediments within the Gulf Coast Aquifer materials (Chowdhury and others, 2006). The maximum contaminant level for arsenic is 10 micrograms per liter (TCEQ, 2011). The prevalence of arsenic in groundwater and sediments has implications for aquifer storage and recovery including compatibility issues of injected water chemistry and the potential release of additional arsenic during the recovery phase.

Table 3. **Arsenic samples from the Gulf Coast Aquifer within the study area. Sample results were obtained from the TWDB Groundwater Database. Samples listed as unknown were obtained from wells lacking well depth or screen information, so determination of the aquifer was not possible. Samples from the Jasper Aquifer were not available. The number of samples that exceed the drinking water limit of 10 micrograms per liter is shown in parentheses.**

Aquifer sampled	Total number of samples	Number of samples: non-detect	Number of samples with detection (samples > 10 micrograms per liter)	Range of sample values (micrograms per liter)
Chicot	43	21	22 (10)	1.7 to 16.6
Chicot-Evangeline	16	6	10 (5)	2.2 to 26
Evangeline	13	3	10 (9)	9.82 to 20.3
Unknown	9	3	6 (6)	11 to 27

The U.S. Geological Survey developed the Produced Water Database containing water quality data from oil and gas wells in the United States (U.S. Geological Survey, 2002). This dataset contained 125 samples from the study area. Samples with higher total dissolved solids water in the Gulf Coast Aquifer and deeper formations were used to evaluate the relationship between geophysical well log resistivity and total dissolved solids. The records that were used had total dissolved solids and complete sample depth information in close proximity to wells with geophysical well logs logged within the sample depth zone.

13. Future work

The characteristics for an aquifer storage and recovery well field will need to be defined before site selection can be evaluated. This includes items listed in HDR (2009, Section 3.4). For example, once the injection zone sand thickness is determined, queries can be performed in the database and maps prepared (for example, Figure 15) showing the number of sands within a specific formation or group of formations that meet this objective. The database and geophysical well logs will need to be further evaluated to determine the thickness of clay units (which may act as leaky units) and the potential for interconnected sand layers.

The future evaluation of aquifer storage and recovery development in the District will require test well drilling as indicated in HDR (2009, Section 3.4.2). Each test well should be drilled with complete lithologic evaluation of drill cutting mineralogy (especially clay minerals) and a full suite of geophysical well logs including, but not limited, to spontaneous potential, resistivity, and gamma ray. In addition, natural gamma ray spectrometry equipment can discriminate radioactivity from the uranium-radium series, potassium, and thorium-series minerals. This tool should be considered because most of the wells evaluated with gamma ray logs detected abnormally high concentrations of radioactivity within the Gulf Coast sediments. Aquifer characterization can be accomplished with pumping tests that help determine site-specific hydraulic properties. A full suite of chemical constituents, including radionuclides from potential sand units, should be targeted for laboratory analysis. The results of these investigations can be incorporated into the BRACS Database and used not only for site evaluation, but also to fine tune the geologic characterization of wells used in this study.

During the well field site selection process, additional geophysical well logs may become available from non-public sources such as log libraries. TWDB could not access these sources, because of cost, membership, and confidentiality restrictions. However, this may not be a problem with a private contractor.

Groundwater modeling will be required as indicated in HDR (2009, Section 3.4.1). The brackish to saline water quality within the District indicates that variable density modeling is appropriate. Deeds and Jones (2011) provide guidance on selecting an appropriate variable density modeling code.

14. Project deliverables

Well information was appended to a Microsoft® Access® database named BRACS that is being used to store data from all Brackish Resources Aquifer Characterization System projects. The BRACS Database is fully relational, meaning that the information is distributed throughout many tables, each with a different design but containing similar types of information, such as lithology or hydraulic properties of aquifers. The tables are linked by key fields; the first key field is a unique well identification number assigned to each well record. Information in the BRACS Database can be displayed on forms; the data can be manipulated using queries and exported into a variety of formats for display (using GIS) and analysis (using Microsoft® Excel®).

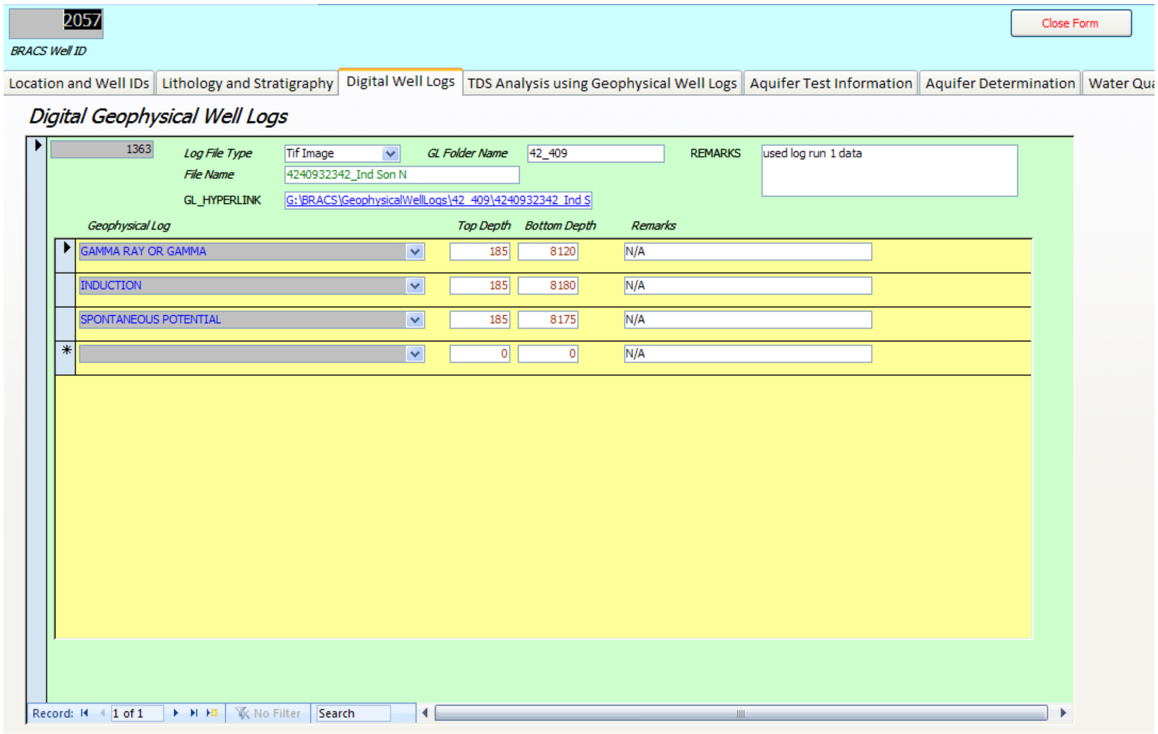
A copy of the BRACS Database named Bracs_Public.accdb will be provided to the District with this report. This database will contain the primary and lookup tables and custom tables of information developed for this study. It will also contain forms for easy display of information. The database provided will contain records statewide, not just for the study area. This will be easier to provide, naturally, but will also offer the future user of this dataset the opportunity to review records for the entire Gulf Coast Aquifer as defined by Young and others (2010). This database is updated on a daily basis and will be available to any customer to meet his or her needs.

A data dictionary explaining the database design, field content, and relationships between the different tables will also be provided with the study deliverables.

Copies of digital geophysical well logs located in Nueces and San Patricio counties will be provided in their county folders: 42_355 (Nueces County), 42_409 (San Patricio County), and 42_777 (offshore). Nueces County currently has 394 digital files and is 12 gigabytes in size, while San Patricio County currently has 1,802 files and is 12.1 gigabytes in size. Six offshore wells include 14 digital files.

The logs can be opened either by navigating to the folder and selecting the log image or by selecting the log file from a Microsoft® Access® form (Figure 25) using a hyperlink field. Database users will need to update the hyperlink field with a new pathname to select the log files using the Microsoft® Access® form. An example of how to perform this update query using Microsoft® Access® query by design is shown in Figure 26, and the Structured Query Language code for this query is

```
UPDATE tblGeophysicalLog_Header SET tblGeophysicalLog_Header.GL_HYPERLINK = "#B:\
GeophysicalWellLogs\" & [GL_FOLDER_NAME] & "\" & [GL_DIGITAL_FILE_NAME] & ".tif#"
WHERE (((tblGeophysicalLog_Header.GL_FILE_TYPE)="TIF IMAGE"));
```



BRACS Well ID: 2057

Digital Geophysical Well Logs

1363

Log File Type: Tif Image

GL Folder Name: 42_409

REMARKS: used log run 1 data

File Name: 4240932342_Ind Son N

GL_HYPERLINK: G:\BRACS\GeophysicalWellLogs\42_409\4240932342_Ind S

Geophysical Log	Top Depth	Bottom Depth	Remarks
GAMMA RAY OR GAMMA	185	8120	N/A
INDUCTION	185	8180	N/A
SPONTANEOUS POTENTIAL	185	8175	N/A
	0	0	N/A

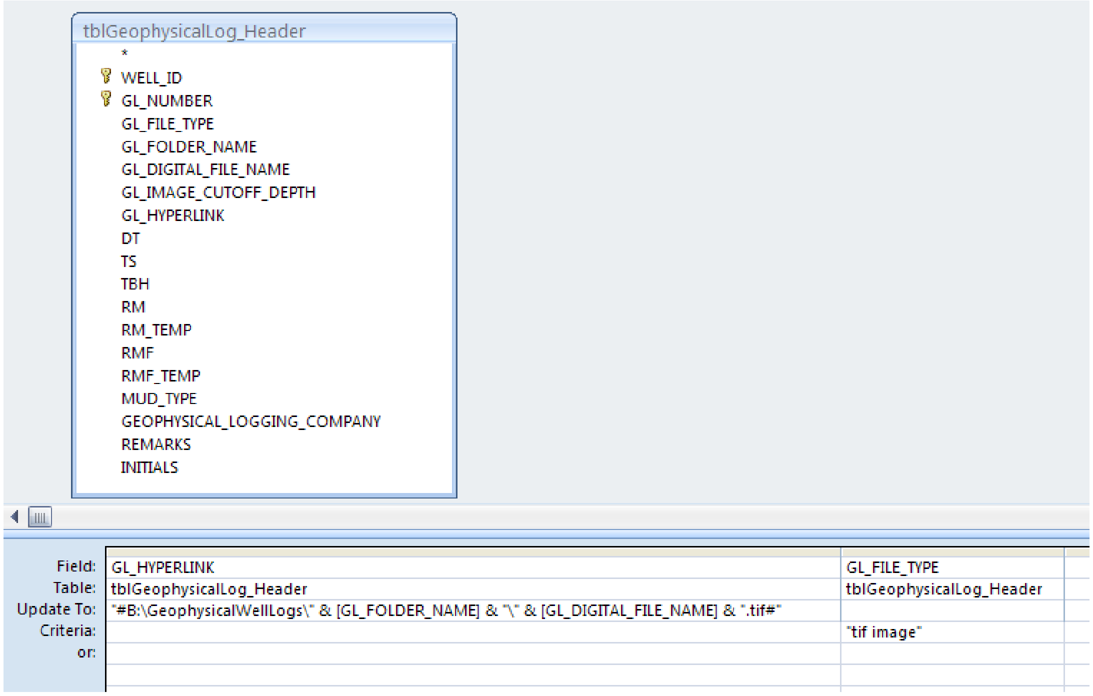
Figure 25. **Microsoft® Access® form showing the geophysical well log hyperlink field (blue font) that allows digital log files to be opened from within the form. The table lists each tool type and top and bottom depths for each log in the collection.**

The pathname "#B:\ GeophysicalWellLogs\" in the Structured Query Language code will need to be replaced with a pathname consistent with the log image pathname on the user's computer or network. The file extension will also need to be changed based on the file type field, as indicated in the "where" clause. Five successive queries will need to be performed based on the five different file types in the table.

Geographic information system data files prepared for this report will be included as deliverables. The geodatabase prepared by Young and others (2010) will also be provided because it was the basis on which the stratigraphy for the Gulf Coast Aquifer was organized. All files prepared for this report will have metadata describing their creation. Files prepared for this study are presented in Table 4.

15. Conclusions

The District is underlain by sand and clay sediments of the Gulf Coast Aquifer. If the geologic, hydrologic, chemical, and other conditions are right, some of these sand layers can be used as reservoirs in an aquifer storage and recovery system. The objectives of the study were to assemble water and oil and gas well data in Nueces and San Patricio counties and append this information into a relational database. This information included geologic descriptions, water quality, aquifer hydraulic properties, and well logs. This information was used to characterize the geology of the Gulf Coast Aquifer within the District and adjacent areas, with an emphasis on the western third of the District near the O.N. Stevens Water Treatment Plant. The information was collected to augment the existing Gulf Coast hydrostratigraphy study conducted by Young and others (2010), but with a greater degree of well control to meet the needs of the District.


tblGeophysicalLog_Header
*
WELL_ID
GL_NUMBER
GL_FILE_TYPE
GL_FOLDER_NAME
GL_DIGITAL_FILE_NAME
GL_IMAGE_CUTOFF_DEPTH
GL_HYPERLINK
DT
TS
TBH
RM
RM_TEMP
RMF
RMF_TEMP
MUD_TYPE
GEOPHYSICAL_LOGGING_COMPANY
REMARKS
INITIALS

Field:	GL_HYPERLINK	GL_FILE_TYPE
Table:	tblGeophysicalLog_Header	tblGeophysicalLog_Header
Update To:	"#B:\GeophysicalWellLogs\" & [GL_FOLDER_NAME] & "\" & [GL_DIGITAL_FILE_NAME] & ".tif#"	
Criteria:		"tif image"
or:		

Figure 26. Example of a Microsoft® Access® update query used to change the value in the geophysical well log hyperlink field to a new pathname. The hyperlink field allows the digital files to be opened from a Microsoft® Access® form. The hyperlink is built with values within the table; the only portion of this query that would need to be changed is the relative pathname, "B:\GeophysicalWellLogs\" in the above example, recording where the files are located. It is recommended the digital geophysical well log files remain in subfolders based on state/county name as provided in the deliverables. Each type of well log file (tif image/jpg image/pdf image) must have a unique query run to add the proper file extension to the hyperlink. The example in this figure shows the format used for a tif image listed in the criteria field.

Information about water quality and hydraulic properties of the aquifer(s) in the District is lacking or limited because of the presence of brackish or saline water. Therefore, the study area was extended to areas outside of the District boundaries to extrapolate information from these areas into the District. Geophysical well log analysis was used on the oil and gas wells in the study area to provide the required aquifer geology and potential groundwater quality.

Table 4. List of GIS files provided as a deliverable with this report.

GIS file name	Description
BRACS_GIS_NSP.shp	Point shapefile of all wells assembled in the study area. Contains well identification numbers, attributes. Created from queries in Microsoft® Access® using the tblWell_Location and tblBracs_ForeignKey tables.
BRACS_AT_GC.shp	Point shapefile of all the wells having aquifer hydraulic property data.
BRACS_WQ_GC.shp	Point shapefile of all the wells having water quality data.
BRACS_GC_Radionuclide.shp	Point shapefile of all the wells having water quality radioactivity data.
BRACS_GC_Arsenic.shp	Point shapefile of all the wells having water quality arsenic data.
BRACS_GC_NS.shp	Point shapefile of all the wells having net sand data.
BRACS_RoTDS.shp	Point shapefile of all the wells used in the comparison of deep resistivity and total dissolved solids.
BRACS_GC_GRspikeWells.shp	Point shapefile of all the wells showing elevated gamma ray spikes within the Gulf Coast Aquifer.
BRACS_GC_Depth_3ohmm.shp	Point shapefile of all the wells evaluated for depth to the 3 ohm-meter sands.
Gulf_Coast_Stratigraphy_Final.mdb	Geodatabase of the Gulf Coast Stratigraphy project funded by TWDB. Source: Young and others, 2010
355_OTLS.shp	Polygon shapefile of Nueces County Original Texas Land Survey. Source: Railroad Commission of Texas
409_OTLS.shp	Polygon shapefile of San Patricio County Original Texas Land Survey. Source: Railroad Commission of Texas
Cross_Section_Points.shp	Point shapefile showing cross-section points from studies across Texas. This file may be used with the work of previous studies to locate wells, stratigraphic picks, and so on.
Cross_Section_Lines.shp	Polyline shapefile showing cross-section lines from studies across Texas. This file may be used with the work of previous studies to locate wells and stratigraphic picks.
Estimated_Cross_Section_Points.shp	Point shapefile showing cross-section points from studies across Texas. This file may be used with the work of previous studies to locate wells, stratigraphic picks, etc. The exact location of these points is unknown; this shows the estimated location based on the location map in the original report.
Estimated_Cross_Section_Lines.shp	Polyline shapefile showing cross-section lines from studies across Texas. This file may be used with the work of previous studies to locate wells, stratigraphic picks, etc. The exact location of these points is unknown; this shows the estimated location based on the location map in the original report.
GCDs_12010_dd83.shp	Polygon shapefile of groundwater conservation districts in Texas. The District has an identification number of 18.

The results of our study indicate that there are a number of sand layers of varying thicknesses that could potentially serve as reservoirs for aquifer storage and recovery depending on the project design goals. The water quality changes from brackish to saline (total dissolved solids greater than 10,000 milligrams per liter) at approximately 1,000 feet below ground surface in the western third of the District. Exact water quality determinations for sands at different depths are not possible using geophysical well log analysis. Existing water quality samples from the Gulf Coast Aquifer in the study area show the presence of arsenic and radioactive substances. The presence of radioactive materials is also evident on the gamma ray logs as are hydrocarbons.

The data collected in this study can be used during the next phase of aquifer storage and recovery evaluation to determine likely well field sites based on aquifer storage and recovery design criteria. Drilling test wells will be required to determine site-specific aquifer properties, reservoir lithology and continuity, and water quality.

16. Acknowledgments

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The well logs critical to this study could not have been collected without the open access to collections at the TWDB, the Railroad Commission of Texas, Bureau of Economic Geology Geophysical Log Facility, and the Texas Commission on Environmental Quality. Special thanks go to the staff of the Groundwater Advisory Unit, Railroad Commission of Texas, for access to the Q-log and map collection and for the desk space to complete digital log scanning.

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