Texas Water Development Board Report

Pecos Valley Aquifer, West Texas: Structure and Brackish Groundwater

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September 6, 2011

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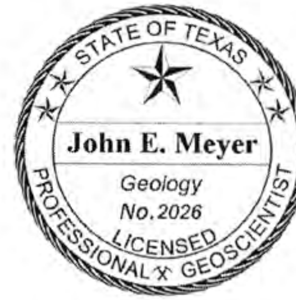

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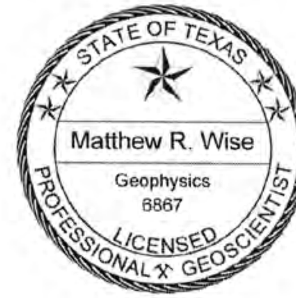

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1. Executive summary

Estimated at more than 2.7 billion acre-feet (LBG-Guyton, 2003), brackish groundwater constitutes an important desalination water supply option in Texas. However, one of the more challenging issues - and a potential roadblock to its more widespread implementation - is the lack of detailed information (especially parameters pertinent to desalination) on the brackish sections of Texas Water Development Board (TWDB) designated aquifers.

To address this issue, TWDB established the Brackish Resources Aquifer Characterization System (BRACS) program in 2009 to map and characterize brackish groundwater in the state to facilitate the planning of desalination projects. As part of this program, the Pecos Valley Aquifer in Regional Water Planning Area F was selected for a pilot study. In addition to mapping and characterizing the brackish water in the aquifer, the goals of the project were to develop techniques of data analysis and a database management system that could be used in future brackish aquifer mapping projects and other geologic studies.

The Pecos Valley Aquifer underlies an area of about 8,650 square miles in the Trans-Pecos area of West Texas and adjacent New Mexico. It is the primary source of water in the area, with smaller volumes pumped from underlying units that include the Edwards-Trinity (Plateau), Dockum, Rustler, and Capitan Reef Complex aquifers.

For the study, we collected, analyzed, and interpreted information from thousands of water wells and geophysical well logs in the project area to map the geologic units and establish stratigraphic relationships. We also gathered information on water chemistry, water levels, and aquifer tests from a wide variety of sources to characterize groundwater in the Pecos Valley Aquifer.

The aquifer consists of more than 1,700 feet of Tertiary and Quaternary alluvial sediments that are present in two hydrologically separate, approximately north-south-trending solution basins known as the Pecos and Monument Draw troughs. The chemical quality of water in the aquifer is highly variable, changing with location and depth. Furthermore, there are several sub-basins within the two solution troughs that have not been penetrated by water wells, thus complete water chemistry for the entire aquifer could not be evaluated.

Total dissolved solids concentrations in the Pecos Valley Aquifer range from less than 200 to more than 10,000 milligrams per liter; silica from 1 to 83 mg/L; iron from 0.01 to 4.5 mg/L; sulfate from 2 to 4,208 mg/L; and chloride from 3 to 7,280 mg/L. In places, water quality has deteriorated as a result of past irrigation practices and oil and gas activities.

We estimate that the Pecos Valley Aquifer contains about 15 million acre-feet of fresh water (0 to 1,000 mg/L), 85 million acre-feet of brackish groundwater (1,000 to 10,000 mg/L), and 1 million acre-feet of very saline water (>10,000 mg/L). The brackish water is present almost everywhere in the aquifer but appears to be more prevalent in the central and western parts. These are also areas where the saturated thickness of the aquifer is the greatest.

The 2010 approved Region F water plan projects water shortages of about 28,887 acre-feet in 2010 increasing to 35,342 acre-feet in 2060. Desalination of brackish groundwater present in the Pecos Valley Aquifer may be one option to meet these projected shortages.

While the project report presents important new information about the Pecos Valley Aquifer on a regional scale, the real value of the project is the new database, GIS datasets, and raw well

records that were built or assembled for the project. These data sources which are being made available to the public contain a wealth of groundwater data (raw and processed) that was hitherto not available. A water planner can customize and use this data to further explore and develop more site-specific information to meet their needs. However, information contained in the report is not intended to serve as a substitute for site-specific studies that will be required to evaluate groundwater well locations for a desalination plant.

The pilot study has helped lay the foundation for future BRACS projects by developing a database management system in which a variety of data can be stored and processed.

2. Introduction

Estimated at more than 2.7 billion acre-feet (LBG-Guyton, 2003), brackish groundwater constitutes an important desalination water supply option in Texas. However, one of the more challenging issues - and a potential roadblock to its more widespread implementation - is the lack of detailed information (especially parameters pertinent to desalination) on the brackish sections of TWDB-designated aquifers (henceforth, brackish aquifers).

Groundwater contains dissolved minerals (total dissolved solids, TDS) measured in units of milligrams per liter (mg/L) and can be classified as fresh (0-1,000 mg/L), brackish (1,000 to 10,000 mg/L), and saline (greater than 10,000 mg/L). For comparison, sea water contains approximately 35,000 mg/L of TDS.

For the purposes of the study, we define brackish groundwater as water that has a TDS concentration of between 1,000 and 9,999 mg/L.

While a 2003 TWDB-funded study (LBG-Guyton, 2003) helped lay the foundation for estimating brackish groundwater volumes in the state, the study was by design regional in scope, limited in areal extent, and narrow in its assessment of groundwater quality. To improve on the 2003 study, TWDB requested and received funding from the 81st Texas Legislature, 2009, to implement a program (Brackish Resources Aquifer Characterization System, henceforth BRACS) to more thoroughly characterize the brackish aquifers.

The goals of BRACS is to map and characterize the brackish regions within the major and minor aquifers of the state in greater detail using existing water well reports, geophysical well logs, and available aquifer data; build data sets that can be used in replicable numerical groundwater flow models to estimate aquifer productivity; and develop parameter-screening tools to help communities assess the viability of brackish groundwater supplies.

Initially, for a pilot study, we chose the Pecos Valley Aquifer in West Texas (Figure 2-1). This aquifer is designated as a major aquifer by TWDB and provides water to parts of nine counties in West Texas. More than 80 percent of water pumped from the aquifer is used for irrigation, with the rest used for municipal and industrial sources (George and others, 2011).

The selection of the aquifer for a pilot study was based on a number of factors including its potential as a source of water supply for brackish groundwater desalination, its geology, and - based on a preliminary assessment - the availability of adequate data. The pilot study provided us an opportunity to gain experience in and become familiar with the data sources, procedures, techniques, and equipment. It also brought into sharp focus the challenges of obtaining crucial data such as appropriate geophysical well logs and its impact on the proposed techniques.

For this study, we used geophysical well logs (resistivity, gamma ray, and neutron), and water well and water quality data from several different sources to map and characterize the Pecos Valley Aquifer. Geologic units underlying the Pecos Valley Alluvium were also mapped,

Figure 2-1. **Study area in Trans-Pecos, West Texas. Project boundary based on extent of the Pecos Valley Aquifer.**

although the water quality in these formations was not studied. Specifically, the goals of the study were to:

- map the geological boundaries of the Pecos Valley Alluvium and the underlying units;
- map the distribution of TDS in the aquifer;
- map the distribution of key chemical parameters of interest to desalination;
- estimate the volume of brackish water in the aquifer; and
- assemble and make-available to the public data collected for the project.

The limited availability of geophysical well logs with resistivity data from appropriate depth intervals precluded us from conducting a thorough assessment of the different techniques that can be used to estimate the concentration of total dissolved solids in the aquifer. Likewise, the lack of discrete water quality analyses from different depth intervals did not allow us to determine salinity gradients.

3. Study Area

A brief description of the study area including its location, topographic and climatic setting, and geologic history is provided below.

3.1 Location, topography, and climate

The description of the study area is largely based on and is a summary of the information presented in Anaya and Jones (2009).

The study area covers about 8,650 square miles of west central Texas and New Mexico and underlies all or part of nine counties in Texas and two in New Mexico (Figure 2-1). We included subsurface geologic mapping in the two adjacent counties of New Mexico for the purpose of developing formation data sets, although New Mexico geologic formations differ in stratigraphic nomenclature. However, we did not include these counties in the water quality and brackish water resource calculations. The study area is mostly rural, with populations typically concentrated in the county seats. Production of oil and gas in the area began in 1925 and since then more than 61,000 petroleum wells have been drilled in the project area (Figure 3-1).

Prior to 2007, the aquifer was known as the Cenozoic Pecos Alluvium Aquifer. Its boundary was modified in the 2007 State Water Plan (TWDB, 2007) to reflect updated knowledge of the aquifer, in part, as a result of the modeling efforts of Anaya and Jones (2009). The Pecos Valley Aquifer hereafter refers to an updated boundary of the former Cenozoic Pecos Alluvium Aquifer.

The study area falls almost entirely within Regional Water Planning Area F (Figure 3-2) and extends over groundwater management areas 2, 3, and 7 (Figure 3-3). There is only one groundwater conservation district (the Middle Pecos Groundwater Conservation District) in the study area (Figure 3-4).

Physiographically, the study area lies within the High Plains, Pecos Valley, and Edwards Plateau sections of the Great Plains province (Fenneman and Johnson, 1949). The sections are characterized by broad intervalley remnants of smooth fluviatile plains (High Plains section), mature to old plains (Pecos Valley section), and young plateaus with mature margins of strong to moderate relief (Edwards Plateau Section).

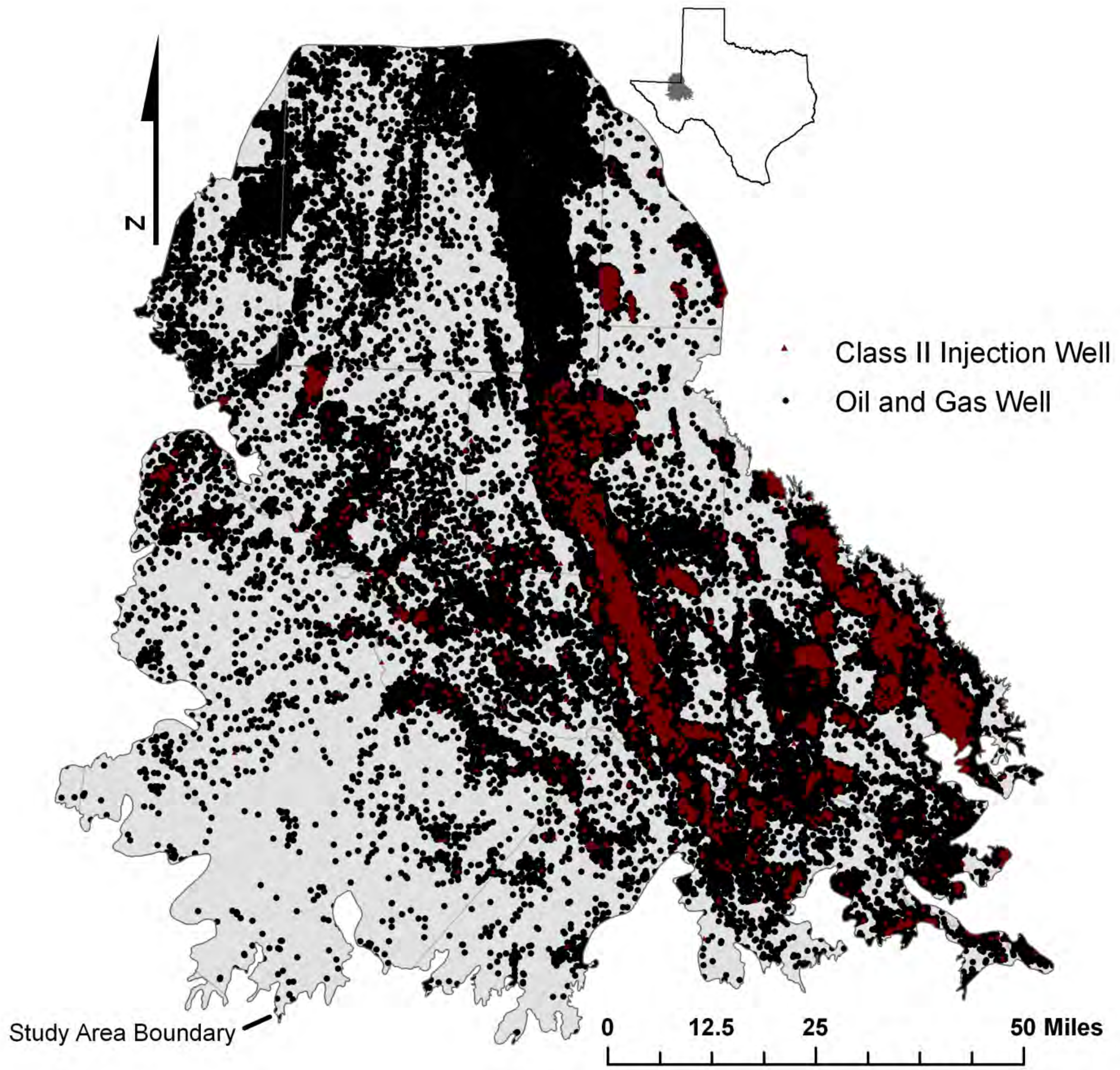

Figure 3-1. **Oil and gas activity in the project area. Oil and gas wells in the project area: 46,262 in Texas and 14,944 in New Mexico. Class II injection wells in Texas are used to dispose of produced salt water and for secondary recovery. There are approximately 4,518 Class II wells in the Texas portion of the project area. Source of this information is the Railroad Commission of Texas and the New Mexico Energy, Minerals, and Natural Resources Department.**

Topographic relief (the difference between the highest and lowest elevations) within the study area is about 1,700 feet: elevations range from about 2,200 feet above sea level along the Pecos River valley to about 3,900 feet above sea level in New Mexico.

The Pecos Valley Aquifer consists of a thick accumulation of alluvial and eolian (windblown) sediments between the westernmost plateau margin and the Mescalero Escarpment (Figure 2-1). Bands of northwest-southeast-trending migrating sand dunes approximately five miles wide and rising as much as 50 feet above the surrounding land surface (Ashworth, 1990) occur between the Pecos River and the Mescalero Escarpment. Alluvial fans emerge from the Trans-Pecos uplands and spread northeastward into the Pecos River Valley, capping the underlying Edwards-Trinity and Paleozoic sediments. A shallow drainage area is present between the Davis Mountains and the Pecos River and is commonly referred to as the Toyah Basin.

The southeast-flowing Pecos River (Figure 2-1), tributary to the Rio Grande, drains the entire southwestern half of the study area. The river drops about 500 feet in elevation along a reach from the Texas-New Mexico border to the entrance of the Pecos Canyon in northwestern Crockett County. It drops another 1,100 feet as it flows through the Pecos Canyon (with some walls reaching over 300 feet above the riverbed) to its confluence with the Rio Grande. Except for short and steep arroyos along the Mescalero Escarpment and Landreth Draw in eastern Crane County, drainage features between the Pecos River and the Mescalero Escarpment consist mainly of desert flats, potential evaporation pans, and small playas.

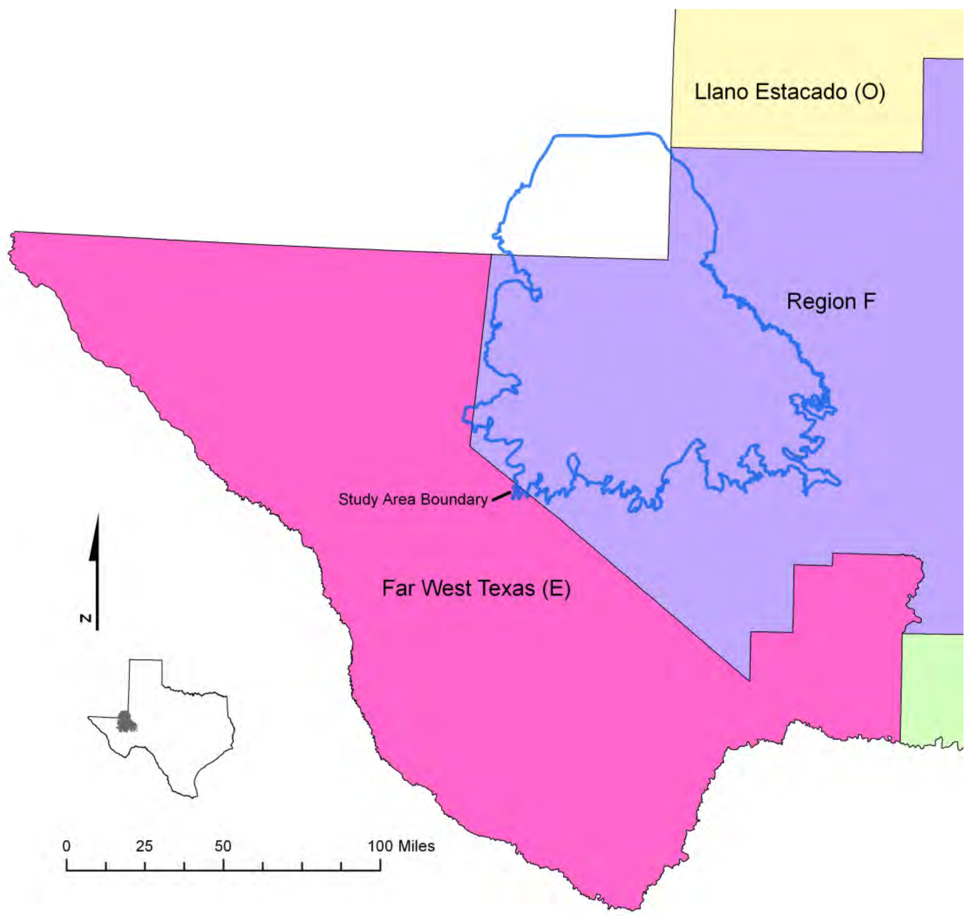

Figure 3-2. Regional water planning areas in the study area.

Although surface water flows rarely contribute to the Pecos River flow (Ashworth, 1990), the southwestern half of the Pecos Valley is drained by numerous draws dissecting the alluvial fans that have formed off of the Trans-Pecos uplands. Toyah Creek is the primary tributary to the Pecos River. Red Bluff Lake in Loving County is located along the northwestern margin of the Pecos Valley Aquifer (Figure 2-1).

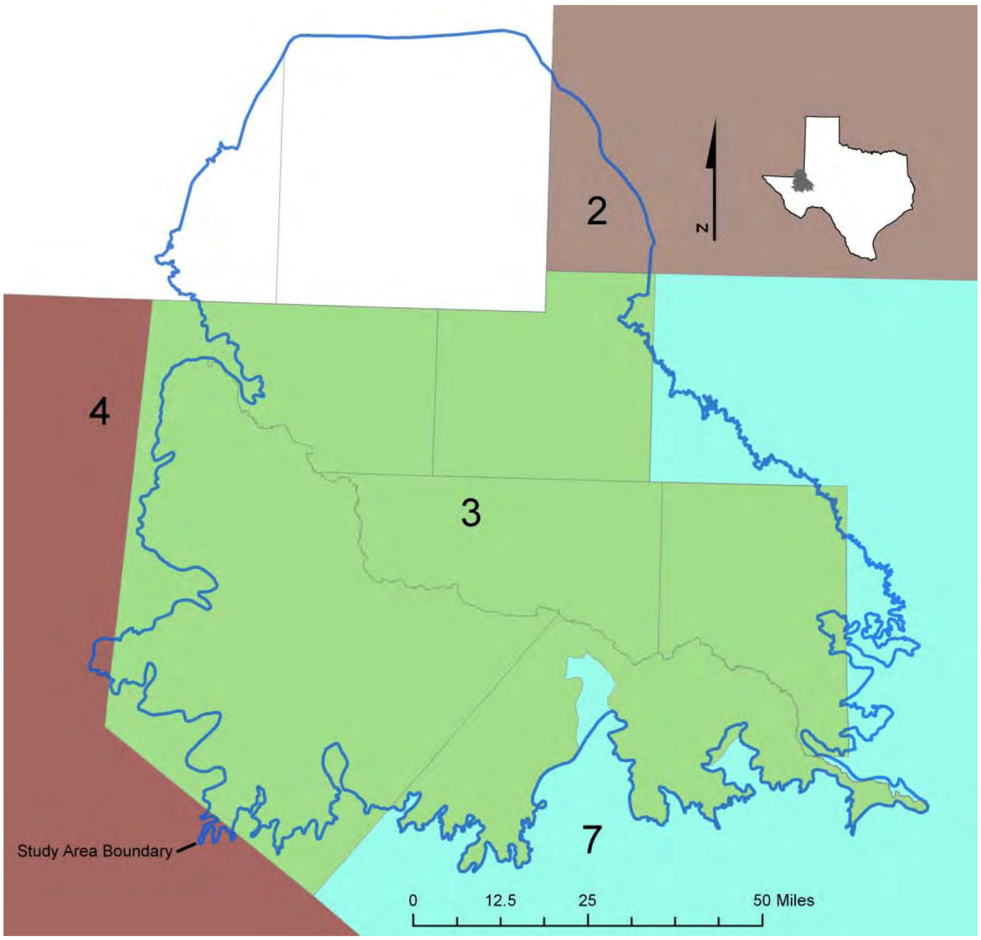

Figure 3-3. **Groundwater management areas in the study area.**

The study area receives about 12 to 16 inches of precipitation annually (Anaya and Jones, 2009). The maximum average annual temperature in the study area ranges from about 76°F to about 78°F. Evaporation rates in the study area are high, with average annual lake evaporation ranging from about 78 to 80 inches (Anaya and Jones, 2009).

3.2 Geologic history

The project area has a complicated geologic history. The following discussion summarizes the major tectonic, depositional, and erosional events that have influenced the geology of the region. An understanding of the past is key to deciphering the present relationships between the five major and minor aquifers that are located within the project area.

3.2.1 Paleozoic Era

Deposition of Cambrian through Devonian sediments occurred on a stable, shallow-water marine platform. Extensive deformation of the area began in Mississippian time as a result of the Ouachita orogeny caused by the convergence of the North American continental plate with the European and African-South American continental plates. Thick sequences of Mississippian through early Pennsylvanian sediments were deposited in the foreland basin. Thrust faulting of Paleozoic strata in a northwestern direction is exposed in the Marathon area.

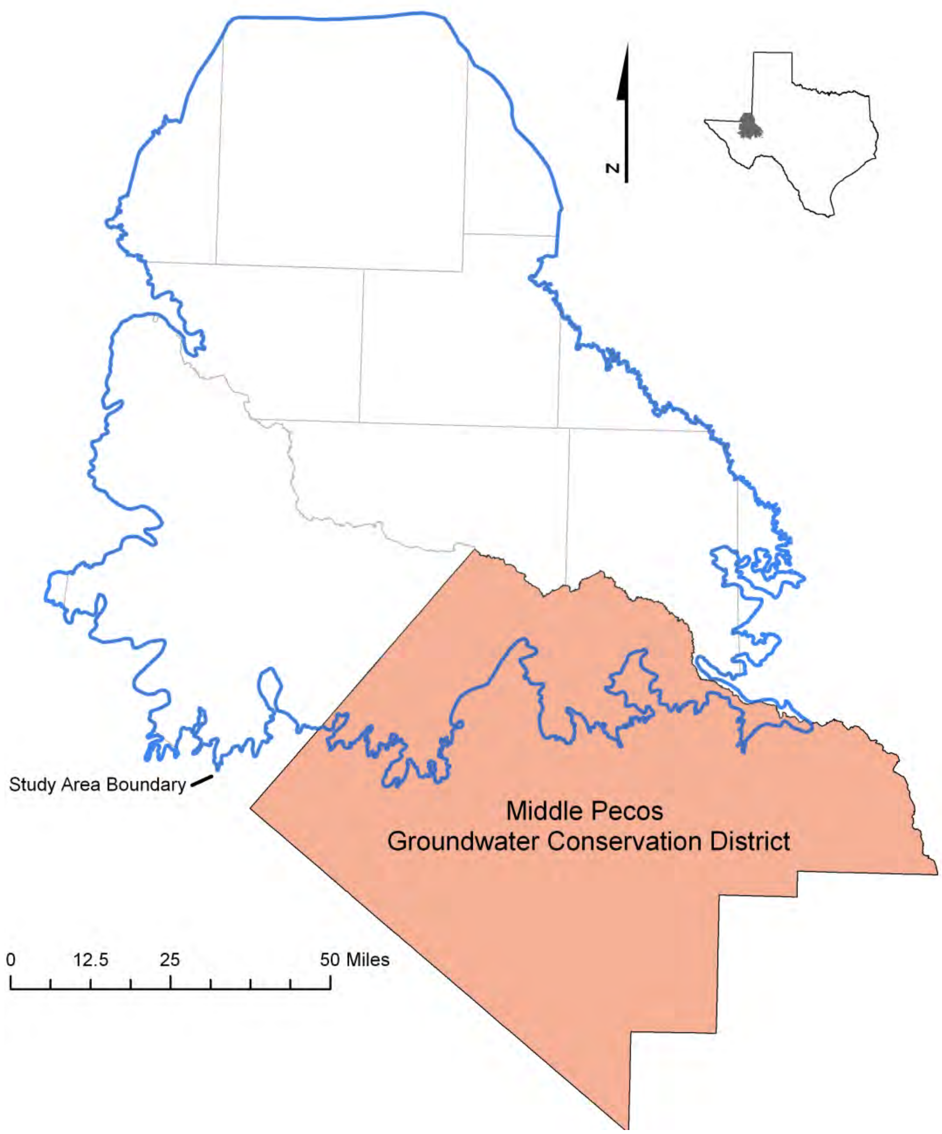

Figure 3-4. Groundwater conservation district in the study area.

The Middle Pennsylvanian to early Permian time was characterized by major subsidence of, and deposition in, the Delaware Basin and contemporaneous uplift and erosion of older rocks on the Central Basin Platform (Figure 3-5). Subsidence of the Delaware Basin continued through middle to late Permian (Ewing, 1991). The Central Basin Platform consists of a structurally complicated chain of uplifts which formed the foundation on which the Permian carbonate shelf was deposited. The Capitan Reef Complex formed along the margin of this platform, on the edge of the Delaware Basin (Standen and others, 2009). Evaporites of the Castile Formation consisting primarily of gypsum began filling the Delaware Basin and were overlain by evaporites of the Salado Formation (primarily halite) that filled the Delaware Basin and extended over the top of the Capitan Reef Complex and Artesia Group back-reef deposits. The Rustler Formation carbonates, evaporites, and clastic sediments were deposited on top of the Salado Formation (Jones and others, 2011). The red beds of the Dewey Lake Formation record the final deposition of Paleozoic strata in the project area. Bebout and Meador (1985) present cross-sections across the Central Basin Platform showing the complex stratigraphic and structural relationships of the Paleozoic and later formations in the region.

3.2.2 Mesozoic Era

The Mesozoic Era began with a period of erosion that may have lasted almost 25 million years (Lucas and Anderson, 1993). Middle Triassic Dockum Group sandstones and red beds record continental deposition in an extensive basin in West Texas. The basin was filled from all directions by fluvial, deltaic, and lacustrine sediments (McGowan and others, 1977 and 1979). There is no record of Jurassic strata in the project area either because the sediments were not deposited or were deposited but eroded prior to the start of Cretaceous deposition.

The Cretaceous is marked by widespread transgression of marine seas across North America. The Trinity Group sediments represent three cycles of transgressive-regressive sequences in Texas (Barker and Ardis, 1996). Terrigenous and marine sediments unconformably overlie Triassic red beds in the project area. Fredericksburg and Washita strata were deposited in the Fort Stockton Basin consisting of the Finlay and Boracho formations. Gulfian strata including the Boquillas Formation and the Austin Chalk were deposited, with remnants found in western Pecos County (Armstrong and McMillion, 1961a). The Mesozoic Era ended with the Laramide Orogeny consisting of late Cretaceous to Paleocene uplift and eastward tilting that exposed older strata to erosion (Ewing, 1991).

3.2.3 Cenozoic Era

Substantial erosion of Cretaceous and older formations has exposed Permian strata at ground surface west of the project area, Triassic strata in a north-south trend through the middle of the project area, and produced Cretaceous outcrops along the eastern, southern, and southwestern limits of the area. From 38 to 28 million years before present, volcanism produced ash-flow tuffs and associated volcanic rocks in the Trans-Pecos Texas region (Ewing, 1991). Regional uplift of the western United States in the Miocene and later times raised the area to its present elevation.

The Monument Draw and Pecos troughs contain collapsed post-Salado formations that are overlain by the Pecos Valley Alluvium. The north-south trending Monument Draw Trough lies directly above the central and western portions of the Capitan Reef Complex (Figure 3-5). The Pecos Trough is present in the central Delaware Basin, between the outcropping Permian formations in the west and a ridge of undissolved Salado halite separating it from the Monument Draw Trough to the east (Figure 3-5). Collapse of the Pecos Trough may have post-dated the volcanism that occurred south of the project area because in central and southern Reeves County, basal Pecos Valley sediments contain eroded volcanic material.

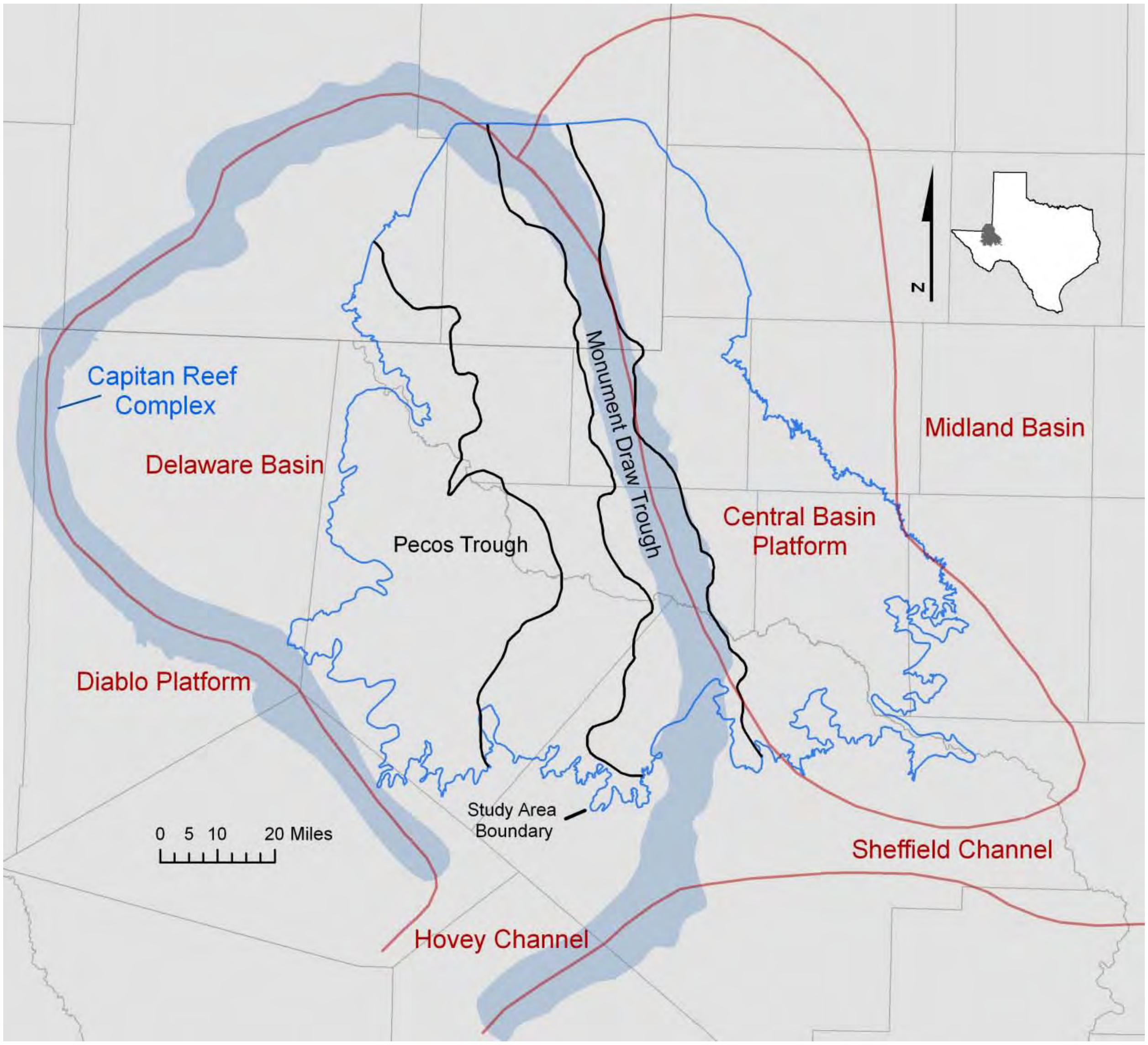

Figure 3-5. Regional geologic elements of the Trans-Pecos of West Texas. The Capitan Reef Complex (shaded blue, Standen and others, 2009) formed along the margins of the Delaware Basin. The Monument Draw Trough (bounded by black lines) overlies the Capitan Reef Complex along the western margin of the Central Basin Platform. The Pecos Trough (eastern limit represented by black line) lies in the central Delaware Basin. The study area boundary is represented by the blue line.

Uplift, erosion, dissolution of Permian evaporites, and deposition have shaped the landscape into its present form, created the structural geometry of the sediments, and influenced groundwater flow patterns within the aquifers.

3.3 Summary of water demands and supplies in the study area

The Pecos Valley Aquifer is the primary source of water in the study area and the second most used aquifer in Region F, representing approximately 31 percent of total groundwater use in the region. Agricultural related consumption (irrigation and livestock) accounts for approximately 80 percent of the total, while municipal consumption and power generation account for about 15 percent of aquifer use (RWPG F, 2010).

Table 3-1. Water demand projections by use category for counties in the Pecos Valley Aquifer, Region F. Data is from the approved Region F Water Plan, 2010.

Use Category	2010 (acre-feet)	2060 (acre-feet)	Percent change in demand 2010-2060	Percent of overall demand in 2010	Percent change in relative share of overall demand 2010-2060
Municipal	48,111	57,985	+21	15	+2
Manufacturing	3,488	4,325	+24	1	0
Irrigation	245,602	232,490	-5	75	-7
Steam Electric	11,289	25,799	+129	3	+5
Mining	15,441	17,550	+14	5	0
Livestock	4,755	4,755	0	1	0
Total	328,686	342,904	+4		

The 2010 Region F Water Plan indicates that demand for water in the eight counties that overlie the Pecos Valley Aquifer will increase by about four percent from the year 2010 to 2060. (Table 3-1). While municipal demand is projected to increase by about seven percent in the 2010-2060 time period, irrigation demand is projected to decrease by about five percent over the same time period. Although the overall increase in water demand of four percent is not large, the increase will be from manufacturing, steam-electric, and municipal demand which require water of higher quality delivered consistently throughout the year compared to irrigation demand which generally requires water of lower quality delivered seasonally.

Existing water supplies in Region F in 2010 are 299,799 acre-feet and projected to increase to 307,562 acre-feet in 2060. Nevertheless, demand exceeds supply and shortages are expected to increase from 28,887 acre-feet in 2010 to 35,342 acre-feet in 2060 (RWPG F, 2010).

Because demand is projected to exceed available supplies, the area will experience shortages unless water management strategies are implemented. For the eight counties in the study area, the recommended water management strategies include water conservation, water reuse, desalination (Dockum Aquifer), and new groundwater sources (Pecos Valley Aquifer).

4. Previous Investigations

Maley and Huffington (1953) wrote one of the first papers linking the dissolution of underlying Permian evaporites to the deposition of Cenozoic alluvial fill in the Delaware Basin. County-wide hydrological studies by the Texas Water Development Board (and predecessor agencies) and the U.S. Geological Survey began in the late 1950's for Pecos, Reeves, Ward, and Winkler counties and in the Sand Hills region of Crane County (Armstrong and McMillion, 1961a and 1961b; Garza and Wesselman, 1959; Ogilbee and others, 1962a and 1962b; Shafer, 1956; White, 1971). Characterization of the Pecos Valley Aquifer in the multi-county project area includes studies by Ashworth and Hopkins (1990), George and others (2011) and Jones (2001, 2004 and 2008). The TWDB groundwater availability model for the Pecos Valley and Edwards-Trinity (Plateau) aquifers is presented in Anaya and Jones (2009).

Geologic mapping at a scale of 1:250,000 was conducted by the University of Texas at Austin, Bureau of Economic Geology (BEG 1976a, 1976b, 1994). This work was subsequently processed into a statewide digital geologic map in a geodatabase format.

Brackish resource studies involving the Pecos Valley Aquifer were conducted by Winslow and Kister (1956) and LBG-Guyton (2003). These studies were regional in scope and did not contain detailed information needed to fully characterize the aquifer.

For our study, we conducted an extensive literature review on water quality interpretation using geophysical well logs and regional geology including the underlying aquifers. We entered the references into a relational database and collected paper and digital documents.

5. Data Collection and Analysis

One of the primary objectives of the project was to assemble all available well-control data from existing water well reports, geophysical well logs, water chemistry samples, and aquifer tests. This information augmented existing well information contained in the Groundwater Database maintained by TWDB. Because many of the anticipated data sets and analysis features were new to the TWDB and did not fit into the structure or met the purpose of the existing Groundwater Database, a new relational database named BRACS was designed specifically for this project. Another equally important objective was to make the information readily available to the public. The information included raw data such as water well reports and digital geophysical well logs; processed data such as lithology, simplified lithologic descriptions, stratigraphic picks, water chemistry; and interpreted results in the form of GIS data sets and geological cross-sections.

With these goals in mind, we appended information from 2,639 wells to the BRACS database that were new records, and from an additional 492 wells that are present in the TWDB Groundwater Database (Figure 5-1). The project area contained 2,672 existing wells from the Groundwater Database, some of which contained critical information such as water chemistry, aquifer tests, and static water levels.

The new well records were obtained from publicly available sources that were not subject to copyright restrictions. We attempted to collect at least one well report or geophysical well log from every 2.5 minute grid cell in the project area; where necessary, more than one well was obtained.

We did not verify the location of every well that was obtained from other agency data sets unless there seemed to be a problem, such as a mismatch in the geology. When locations were verified or when digital locations were not available, the Original Texas Land Survey GIS data from the Railroad Commission of Texas was 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.

5.1 Data sources and processing

A description of the method that we used to identify water wells and geophysical well logs, the various agencies and sources from which these data were obtained, and a brief discussion on the hydraulic properties of the aquifer are provided below.

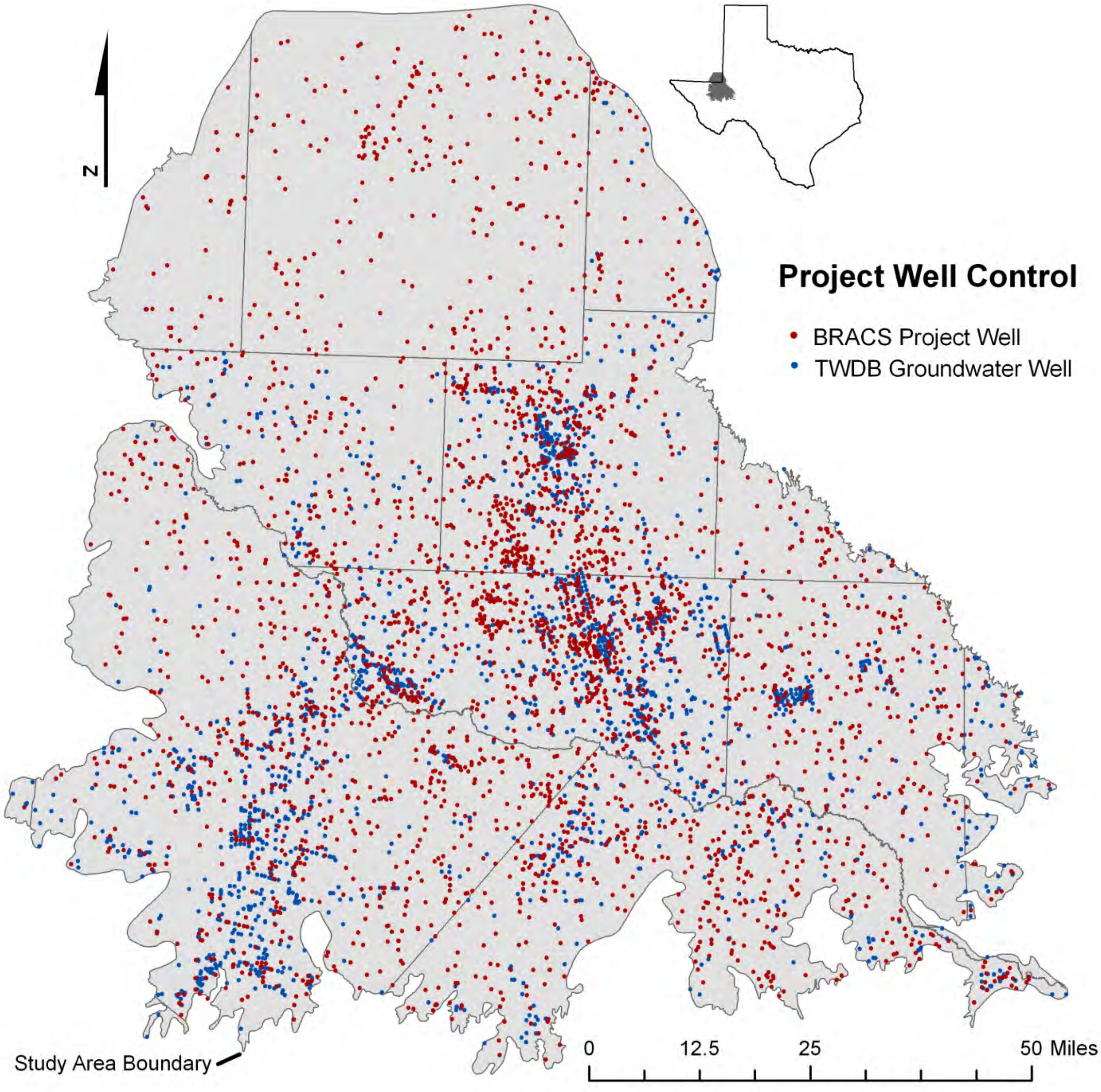

Figure 5-1. **BRACS project well control included 2,639 new wells collected for this project plus an additional 492 wells from the existing TWDB groundwater database. Well control included water wells and oil and gas wells. The project area contained a total of 2,672 wells in the TWDB groundwater database.**

5.1.1 Well identification numbers

Each well record may have zero to many unique identification names or numbers assigned to it; these are also referred to as foreign keys. There is no universal well numbering system in Texas. Every effort was made to cross-reference and record these identifiers in a database table. As the project progressed, more and more unique well numbers were discovered from the many agencies that collect and disseminate well information and from entities that collect and process well information into reports.

Table 5-1. Well identification numbers used in the BRACS project database.

Well Identification Name	Purpose	Agency that uses this id number
API Number	Each new oil/gas well is assigned this unique number	American Petroleum Institute assigns number
Track Number	Water well reports loaded digitally	Texas Department of Licensing and Regulation
State Well Number	Wells in the Groundwater Database	Texas Water Development Board
Water Source	Public water supply wells	Texas Commission on Environmental Quality
Q Number	Geophysical well logs, used in the Surface Casing Program	Texas Commission on Environmental Quality
POD	POD (point of diversion) wells in the State Engineers Database	New Mexico Office of State Engineer
Well Number	Owner name/number for well; Previous well number	Well Owner; well number assigned in published report by Texas water agencies, prior to development of State Well Number
Well ID	Well records in the BRACS database	Texas Water Development Board

The unique identifier serves as a link between the BRACS database and another database. Well information can be loaded into the BRACS database automatically, thus saving data entry time. Other agency data sets contained information that was not necessary for our project at the present time. However, the compilation of these unique identifiers provides an opportunity for data mining and analysis in the future. Table 5-1 lists common well identification numbers in the BRACS database.

5.1.2 Water well reports

A total of 1,694 water well records were obtained and entered into the BRACS database tables. The primary information obtained from these reports was the driller's description of the formations encountered in the borehole. These descriptions were used to make the stratigraphic picks and determine aquifer lithology. Water well information was also appended if it had water chemistry or aquifer test data that did not already exist in the Groundwater Database.

The data entered for each water well included owner information; well identification number(s); depth; location attributes; drill date; well type; and source of well information. Elevations were determined for each well using a seamless statewide 30 meter digital elevation model.

Texas Commission on Environmental Quality (TCEQ)

We obtained 325 water well reports from TCEQ's Water Well Report Viewer, a Web-based portal that contains scanned well reports in a portable document format. These wells are organized using a numerical system representing a grid cell consisting of 2.5 minutes of latitude and longitude. The five-digit grid cell is equal to the first five digits of the TWDB State Well Number. The TCEQ had all well reports in a grid cell folder as one or more documents. The front and back of each paper water well report was captured on screen. County maps showing well locations as plotted by drillers were also imaged as separate documents. The TCEQ estimates that the collection contains more than 800,000 water well records.

Every grid cell in the project area (1,130 cells) was searched for potential logs for the project. Obtaining adequate location information on the well report was the biggest challenge in using this resource. The majority of selected wells contained legal descriptions that were used for plotting with the Original Texas Land Survey GIS data sets. Driller locations plotted on county maps and latitude and longitude coordinates were also used. The information contained in these well reports was manually appended into the BRACS database and the paper well reports filed in a BRACS program folder.

An additional 24 water well records were obtained from the TCEQ Public Drinking Water, Source Water Assessment Program (SWAP) database. Well lithology obtained from the SWAP database was appended to the BRACS database along with latitude and longitude coordinates obtained from a variety of methods.

Texas Water Development Board (TWDB)

We copied 311 well records from TWDB's Groundwater Database in order to supplement the well lithology and aquifer test information. The well reports were downloaded from TWDB's Water Information Integration and Dissemination (WIID) system. Lithologic descriptions were entered manually into the BRACS database.

A review of published reports (Armstrong and McMillion, 1961a and 1961b; Garza and Wesselman, 1959; Ogilbee and others, 1962a and 1962b; Shafer, 1956; White, 1971) provided an additional 576 well records. Because these wells did not have corresponding records in TWDB's Groundwater Database, the well attributes were manually appended to the BRACS database.

Texas Department of Licensing and Regulation (TDLR)

The TDLR's submitted drillers report database contained 353 digital well reports. The reports can be downloaded individually from TWDB's WIID Web portal or obtained in a statewide database from the TWDB Web site. The database was redesigned to meet the requirements of the project. Wells were selected from a GIS shape file showing locations relative to the project area. Once selected, the well attributes such as location, depth, and owner information were automatically loaded into the BRACS database. The driller's description of the geological formations exists in a memo field in the database. This data was reprocessed using a parser technique so that individual lithologic records could be extracted to show the lithologic name, depth to the top and bottom of the lithologic unit, its thickness, and source of data. Well lithologic records were then appended to the BRACS database.

New Mexico Office of State Engineer (NMOSE)

New Mexico Water Rights Reporting System of NMOSE provided 23 digital well reports. Some of the digital files contained a simplified lithologic description of the screened portion of the well. This proved to be inadequate for determining stratigraphic picks in the study area.

An additional 78 paper well reports were obtained directly from the NMOSE office. The well attributes were loaded manually into the BRACS database. Four wells from NMOSE containing aquifer test index data were also appended to the BRACS database.

5.1.3 Geophysical well logs

Geophysical well logs are produced when a tool is lowered into a well bore and raised to the surface recording different types of information as it is brought to the surface. The type of information recorded depends on the type of tool used. The project area has more than 61,000 oil and gas wells that are recorded in the Railroad Commission of Texas' statewide database and in the New Mexico Energy Minerals Natural Resources Department. However, only a fraction of these logs are publicly available, and an even smaller number met project requirements for tool type, and start and bottom depths. The initial objective was to obtain resistivity logs for interpreting TDS in groundwater. Unfortunately, a majority of the logs were recorded at depths starting from below the base of the Pecos Valley Aquifer and could not be used for this purpose.

A total of 1,437 digital geophysical well logs were obtained and appended to the BRACS database tables. The primary information obtained from the logs was stratigraphic picks and interpreted simplified lithologic descriptions (from gamma ray logs). A small number of logs were used to estimate the TDS concentrations using resistivity or Spontaneous Potential (SP) log analysis. The digital logs were mainly obtained in a Tagged Image File (TIF) format while a few were obtained in a Log ASCII Standard (LAS) format.

Data entered for each geophysical well log included tool type; start and end depth for each tool; digital file name and type; owner; well number; depth; location attributes; drill date; kelly bushing (rig floor, derrick floor, rotary turntable) height; and source of well information. Elevations for all wells were determined using a seamless statewide 30 meter digital elevation model.

Railroad Commission of Texas (RRC)

The RRC Web site contained 299 digital geophysical well logs for the study area. The wells can be selected from a map-based interface or by entering an API number directly into a search feature. The RRC also maintains a spreadsheet of digital logs that are added to their database each month. We downloaded these spreadsheets and appended the well records to one of the BRACS supporting databases. A GIS map of available logs was maintained in our program for use in selecting project wells.

University Lands, University of Texas System (ULUTS)

The ULUTS Web site provided 188 digital geophysical well logs for the study. The logs are organized by county and API number. Although the geographic coverage of this data set is limited, the quality and completeness of the data are excellent. Additionally, many of the well logs already have annotations for stratigraphic picks. A GIS shapefile containing well locations can be downloaded from the ULUTS Web site. This information was converted into a relational database for use in selecting project wells for the study area.

Bureau of Economic Geology (BEG)

The BEG maintains an extensive paper log collection of geophysical well logs in the Geophysical Log Facility. We selected 438 paper geophysical well logs from this collection for the study area. A contractor then scanned these into digital files. A subset of the BEG paper well log collection is also available in BEG's Integrated Core and Log (IGOR) database. The IGOR dataset for each county in the project area was processed and appended to a relational database designed to support the BRACS program.

Texas Commission on Environmental Quality (TCEQ)

TCEQ's Surface Casing program contained 162 digital geophysical well logs that were used in the study. The BEG scanned the entire collection of logs available for Reeves and Ward counties and some in Pecos County for the project.

For the Surface Casing program, each well or group of wells is assigned a unique number, termed the Q number. The Q number is assigned to one or more wells and represents a specific geographic location or area. However, the location of each well must be verified with the legal description on the log header before latitude and longitude coordinates can be assigned. The Q number is often noted on well records in the TWDB groundwater database, especially if a water-well has been logged and added to the TCEQ surface casing collection.

Texas Water Development Board (TWDB)

Thirty-five water wells with paper geophysical well logs were selected from TWDB's Groundwater Database in the project area. A contractor then scanned these into digital files. An additional 137 digital logs were obtained from the Capitan Reef Complex Structure and Stratigraphy project that was completed for TWDB by Daniel B. Stephens and Associates (Standen and others, 2009).

We also received more than 1,100 logs from New Mexico and several hundred logs from the Rustler Aquifer groundwater availability model project conducted for TWDB by Intera, Inc. (Jones and others, 2011). Although these logs were acquired late in the project and could not be used in the stratigraphic analysis, they have been added to the TWDB collection of geophysical well logs and made available for use in future projects.

New Mexico Energy Minerals Natural Resource Department (NMEMNRD)

We downloaded 178 digital geophysical well logs from the NMEMNRD's Oil Conservation Department Web site. We also downloaded a database of all oil and gas wells from the same Web site and reformatted the database to meet project requirements. A GIS file of well locations was created to support the selection of project wells.

U.S. Geological Survey (USGS)

We obtained 61 digital geophysical well logs and supporting files from USGS. They are presently conducting a study of the Edwards-Trinity Plateau Aquifer in Pecos and adjacent counties. Although these logs were acquired late in the project and could not be used in our study, they have been added to the TWDB collection of geophysical well logs and made available for use in future projects.

5.1.4 Water quality data

Information on 3,509 groundwater chemical samples was compiled from wells in the project area. Information from 1,548 wells was obtained from two main tables in the TWDB Groundwater Database and from 389 wells in published reports (Armstrong and others, 1961; Garza and Wesselman, 1959; Ogilbee and Wesselman, 1962; Shafer, 1956; White, 1971). We entered the records into two BRACS database tables but did not check for quality control.

All records were appended to one master table in the BRACS database. The source of each record was noted in the table, along with all applicable well identification numbers. Information on 561 radionuclide samples were compiled from 187 wells in the TWDB infrequent constituents table and written to a table in the BRACS database. The samples were analyzed for uranium, radium, alpha, and beta from multiple aquifers in the project area.

5.1.5 Static water level data

Static water level measurements (15,130) were compiled from wells in the project area. Information from 2,108 wells was obtained from the TWDB Groundwater Database and the TDLR water well reports. A small number of measurements were also obtained from water well reports from the TCEQ paper well reports and Public Water Supply data sets.

All records were appended to one master table in the BRACS database. The source of each record and the method of water level measurement were noted, along with all relevant well identification records.

5.1.6 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, 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 879 wells from a variety of published sources and database tables. Values from wells consist of: transmissivity (49); hydraulic conductivity (28); specific capacity (287); and well yield (875). The sources of information included: aquifer tests from a TWDB spreadsheet; the TWDB Groundwater Database remarks table; spreadsheets compiled for the Pecos Valley and Edwards-Trinity Plateau groundwater availability model (Anaya and Jones, 2009); published reports (Garza and Wesselman, 1959; Myers, 1969; Ogilbee and Wesselman, 1962; White, 1971); TDLR submitted driller log database; and the NMOSE aquifer test index data spreadsheet. These measurements were appended to a database table.

Anaya and Jones (2009) reviewed hydraulic property records for the Pecos Valley Groundwater Availability Model (GAM) and determined a mean hydraulic conductivity of 8.6 feet per day. Based on this value, transmissivity ranged from less than 1 foot-squared per day to approximately 14,000 feet-squared per day. Anaya and Jones (2009) reported that specific yield values were not available for the Pecos Valley Aquifer. Specific yield values for alluvium may range from 0.02 to 0.27 (Johnson, 1967).

Well records with hydraulic property data were assessed using the aquifer determination process Section 6-2). A GIS shapefile was created reflecting aquifer properties and aquifers (Figure 5-2).

Processing hydraulic properties into GIS grid files was not performed for this project because groundwater modeling was outside the scope of the study.

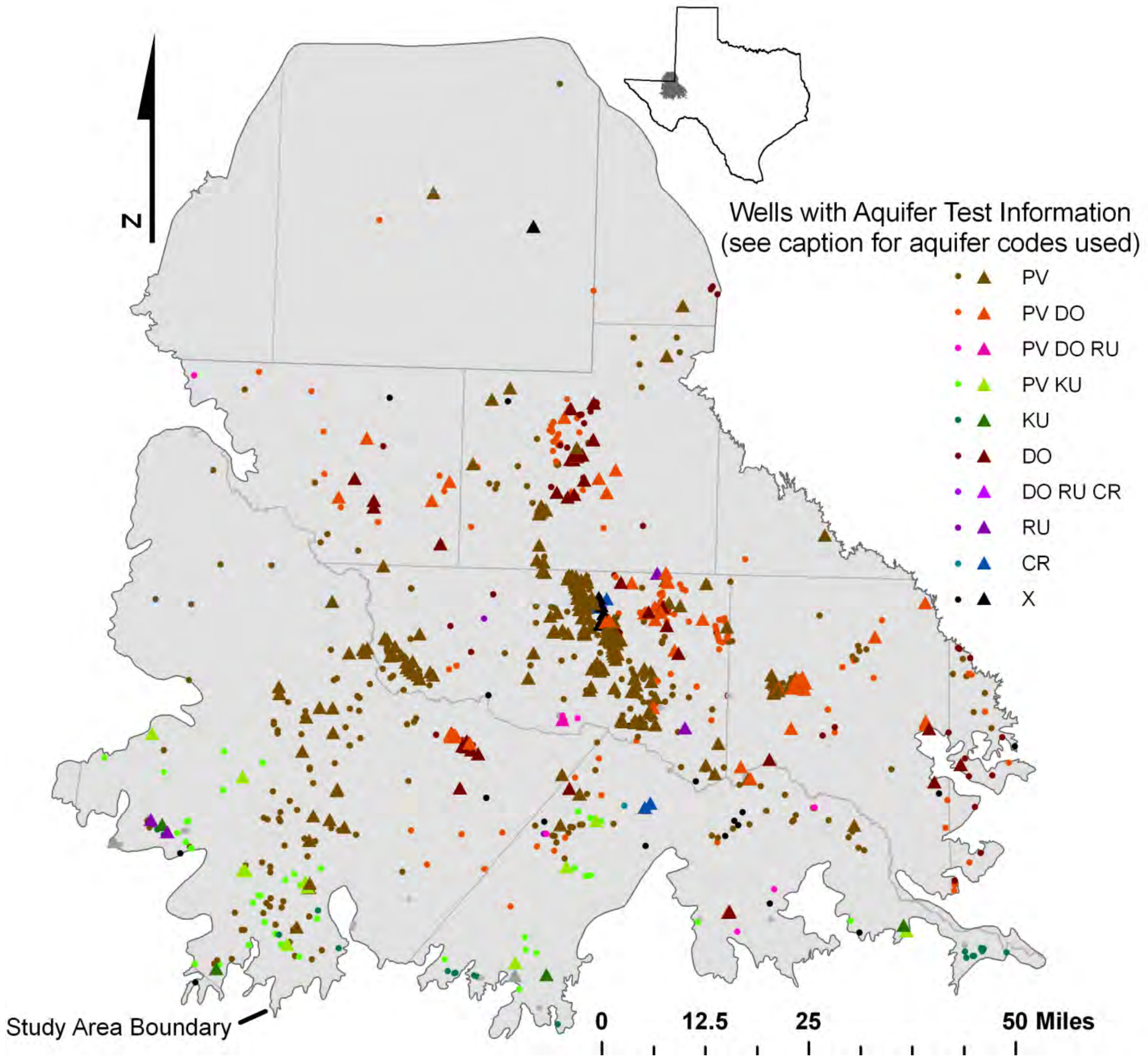

Figure 5-2. **Wells with aquifer test information obtained from written reports and TWDB files. Triangle symbols represent wells with transmissivity, hydraulic conductivity, or specific capacity values. Circles represent wells with well yield values. Wells color-coded based on aquifer encountered based on well screen or well depth analysis. Aquifer codes used in figure are: PV (Pecos Valley Aquifer); KU (Edwards-Trinity (Plateau) Aquifer; DO (Dockum Aquifer); RU (Rustler Aquifer); CR (Capitan Reef Complex Aquifer); X (not a major or minor aquifer).**

5.2 Availability of project data to customers

One of the primary objectives of our study - and of the BRACS program - is to prepare and make available to the public data sets that can be customized to meet specific needs. This information includes original well data, database tables, GIS datasets, and supporting documentation such as a database dictionary and project-related technical reports. At the time of this report, TWDB was redesigning the Groundwater Database and Web portal for the WIID system. The future Groundwater Database will include the BRACS database tables and analysis, and users will have the ability to download digital geophysical well logs from it. However, until these upgrades are completed, users can acquire Pecos Valley Aquifer project data by contacting TWDB.

The original well data includes digital geophysical well logs and paper copies of water well reports. A copy of the BRACS database in MS Access 2007 format is available with a supporting data dictionary. The database will include all tables and forms to view the information. The GIS datasets listed in Appendix 14.1 is available with metadata in the ESRI formats specified in Section 9. Project reports in Portable Document Format are also will also be available for download from the TWDB Web site. The WIID Webpage includes a point shapefile showing the location of and limited attributes for each well in the BRACS database. This layer is titled Brackish Groundwater Database and will be updated periodically.

6. Hydrogeologic Setting

The hydrogeologic setting of the Pecos Valley Aquifer presented below provides information about the aquifer including its framework, hydraulic properties, and the chemistry of the water in the aquifer.

6.1 Hydrostratigraphy

The Pecos Valley Aquifer overlies portions of the Edwards-Trinity Plateau, Dockum, Rustler, and Capitan Reef Complex aquifers. The geographical extent of these aquifers based on the different stratigraphic relationships present in the region is shown in Figure 6-1 and Table 6-1. After reviewing published literature and GIS mapping of the region, we decided that more detailed mapping was required to fully define the lateral and vertical relationships between these aquifers. Because one of the main objectives of our study was to delineate the brackish water resources in the aquifer, we avoided mapping geologic units at the formation level with its inherent stratigraphic complexity and controversies about nomenclature.

Accordingly, we mapped the following geologic units as undifferentiated units: Pecos Valley Alluvium; Cretaceous Undivided; Dockum Group – Dewey Lake Formation; and only the top surface of the Rustler Formation. A groundwater flow model for the Rustler Aquifer is currently being developed by TWDB. When completed, it will provide information on the bottom surface of the formation (Jones and others, 2011). The Capitan Reef Complex was not mapped for our study because it was investigated in another TWDB-funded project (Standen and others, 2009).

6.1.1 Stratigraphic unit interpretation

Water wells, geophysical well logs, and published reports were the most important data sources that we used to define the stratigraphic top and bottom of each geologic unit. We used an iterative process of correlating logs and defining stratigraphic picks; picks were revised several times as we became more familiar with the area and new wells were added to the project. If a stratigraphic pick was not possible using information presented on a well log, no value was added to the database table. If a water well did not fully penetrate the stratigraphic base a value of ">" was inserted into the table field to denote partial penetration of the formation. The lithology and partial depth information was extremely useful for preparing contour maps.

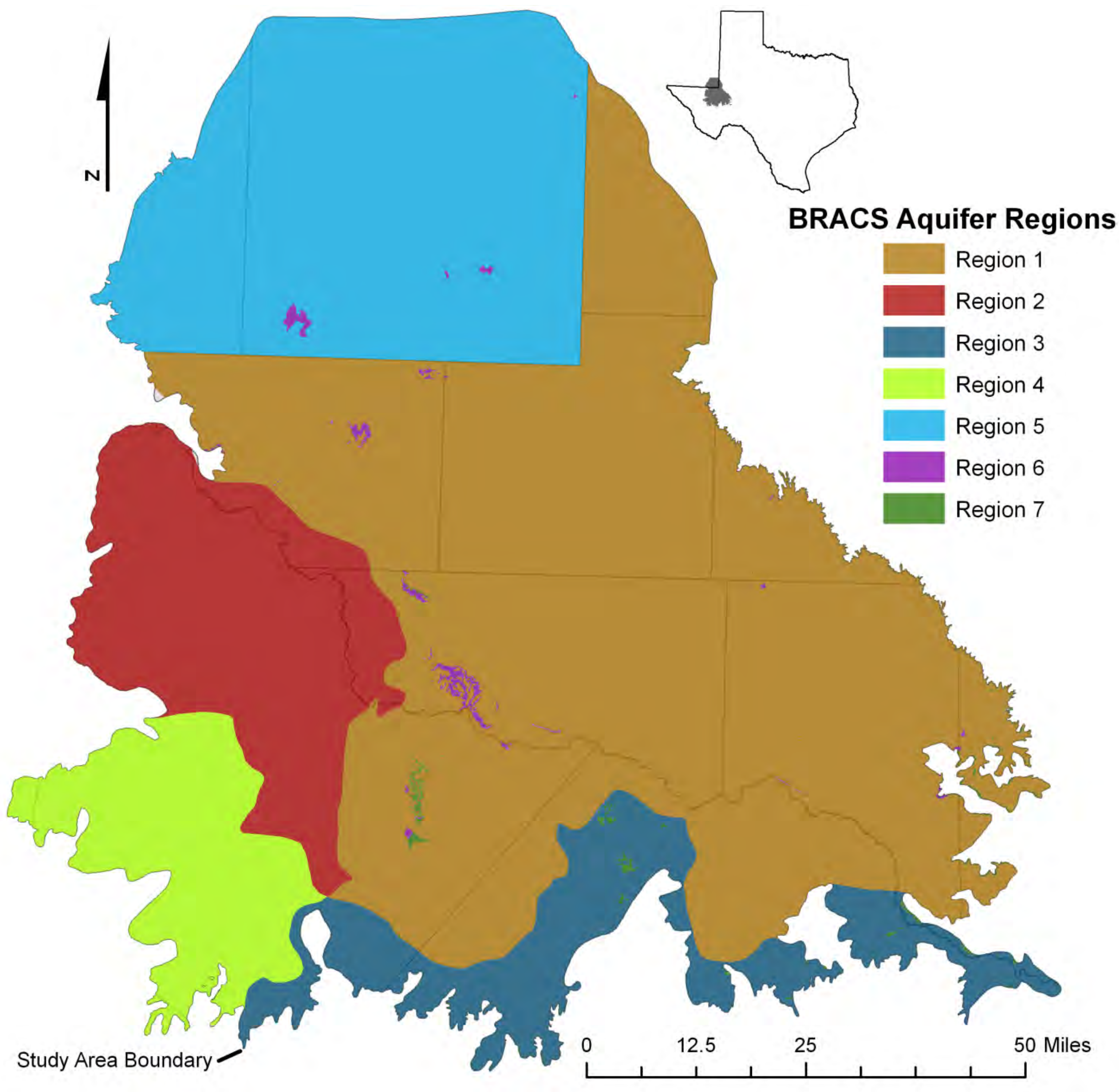

Figure 6-1. **BRACS aquifer regions divide the project area into separate stratigraphic relationships. Refer to Table 6-1 for stratigraphic chart. Regions 6 and 7 represent areas where the Dockum Group and Cretaceous Undivided strata are exposed at the ground surface.**

As the project progressed, we found that no single source of data was perfect for correlation purposes. Limitations on using the descriptions of geological formations on water-well driller reports included imprecise and inconsistent lithologic terminology and interpretation; the possibility of drill cuttings from different depths becoming mixed during the drilling process; the likelihood that top/bottom depth values may be inaccurate because of lag time between drilling and retrieving the cuttings; and the existence of water wells that do not fully penetrate the aquifer.

Geophysical well logs were used throughout the project area, with gamma ray logs providing the most information. Gamma ray logs normally reflect the clay content in sedimentary formations (Schlumberger, 1972). Potassium-bearing clays such as illite and micas produce gamma rays in shale units due to the presence of the radioactive potassium-40 isotope. The advantages of using the gamma ray log is that it is present on most logging runs; it can be recorded in cased holes; it is generally started near ground surface; and, in many situations, the clay content can be used to interpret the boundaries of geologic units or depositional environments. The disadvantages include attenuation of the overall log signature in cased holes; masking of the more subtle changes in log response with transition from uncemented to cemented formations; absence of caliper logs prior to casing the well preclude evaluation of borehole washouts; lack of tool calibration or complete casing records on the log header precludes accurate interpretation; available geophysical well logs in the project area included a variety of older gamma tool types where documentation of tool parameters is limited or impossible to acquire; and inability to differentiate clay-free sand, silt, and gravel. Additionally, in the study area, the gamma ray track on geophysical well logs often started as much as a few hundred feet below ground surface.

Table 6-1. Stratigraphic relationships within the different regions of the project area. Refer to Figure 6-1 for the study area regions. Shaded formations are not aquifers. The formations shown in this table may not occur everywhere in the region. The wavy line represents an unconformity and the solid line a conformable contact between two formations.

Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7
Pecos Valley Alluvium	Pecos Valley Alluvium	Pecos Valley Alluvium	Pecos Valley Alluvium	Ogallala Formation		
		Cretaceous Undivided	Cretaceous Undivided			Cretaceous Undivided
Dockum Group		Dockum Group		Dockum Group	Dockum Group	Dockum Group
Dewey Lake Formation	Dewey Lake Formation	Dewey Lake Formation	Dewey Lake Formation	Dewey Lake Formation	Dewey Lake Formation	Dewey Lake Formation
Rustler Formation	Rustler Formation	Rustler Formation	Rustler Formation	Rustler Formation	Rustler Formation	Rustler Formation
Salado Formation	Salado Formation	Salado Formation	Salado Formation	Salado Formation	Salado Formation	Salado Formation
Castile Formation	Castile Formation	Castile Formation	Castile Formation	Castile Formation	Castile Formation	Castile Formation
Capitan Reef Complex		Capitan Reef Complex		Capitan Reef Complex	Capitan Reef Complex	Capitan Reef Complex

We reviewed published reports in the project area for formation descriptions, maps, and cross-sections (Armstrong and others, 1961; Bebout and Meador, 1985; Garza and Wesselman, 1959; Ogilbee and Wesselman, 1962; Shafer, 1956; Small and Ozuna, 1993; West Texas Geological Society, 1961; White, 1971). Geological cross-section well points and lines were loaded into GIS (Figure 6-2) and used to evaluate stratigraphic picks from project wells. The published reports also served as a reference for the interpretation, composition, thickness, and areal distribution of the geological units.

Pecos Valley Alluvium, top and bottom

The Pecos Valley Alluvium consists of Tertiary and Quaternary sediments deposited unconformably on older formations (Table 6-1). The sediments consists of caliche, clay, silt, sand, gravel, and boulder-sized material deposited in a variety of continental depositional settings including eolian, lacustrine, fluvial, valley-fill, and solution-collapse material environments. We mapped these sediments as undifferentiated Pecos Valley Alluvium and they constitute the hydrostratigraphic unit for the Pecos Valley Aquifer. In the northeastern project area, the Pecos Valley Aquifer is correlative with the Ogallala Aquifer; the watershed divide of the Rio Grande serving as the mapped boundary between the two aquifers. For the purpose of this project, our mapping of the Ogallala Formation in New Mexico is equivalent to the Pecos Valley Alluvium.

Table 6-2. The number and types of wells used to define the tops and bottoms of the stratigraphic units in the study area.

Formation Pick	Total Wells	Wells with partial penetration of FM	Pick based on geophysical well log	Pick based on water well report
Pecos Valley Top	1851	N/A	849	1002
Pecos Valley Base	1851	433	849	1002
Ogallala Top	206	N/A	114	92
Ogallala Base	206	24	114	92
Cretaceous Undivided Top	188	73	71	117
Cretaceous Undivided Base	171	73	60	111
Dockum Group Top	1379	467	793	586
Dewey Lake Top	167	18	134	33
Dewey Lake Base	1343	20	1256	87
Rustler Top	1350	15	1281	69

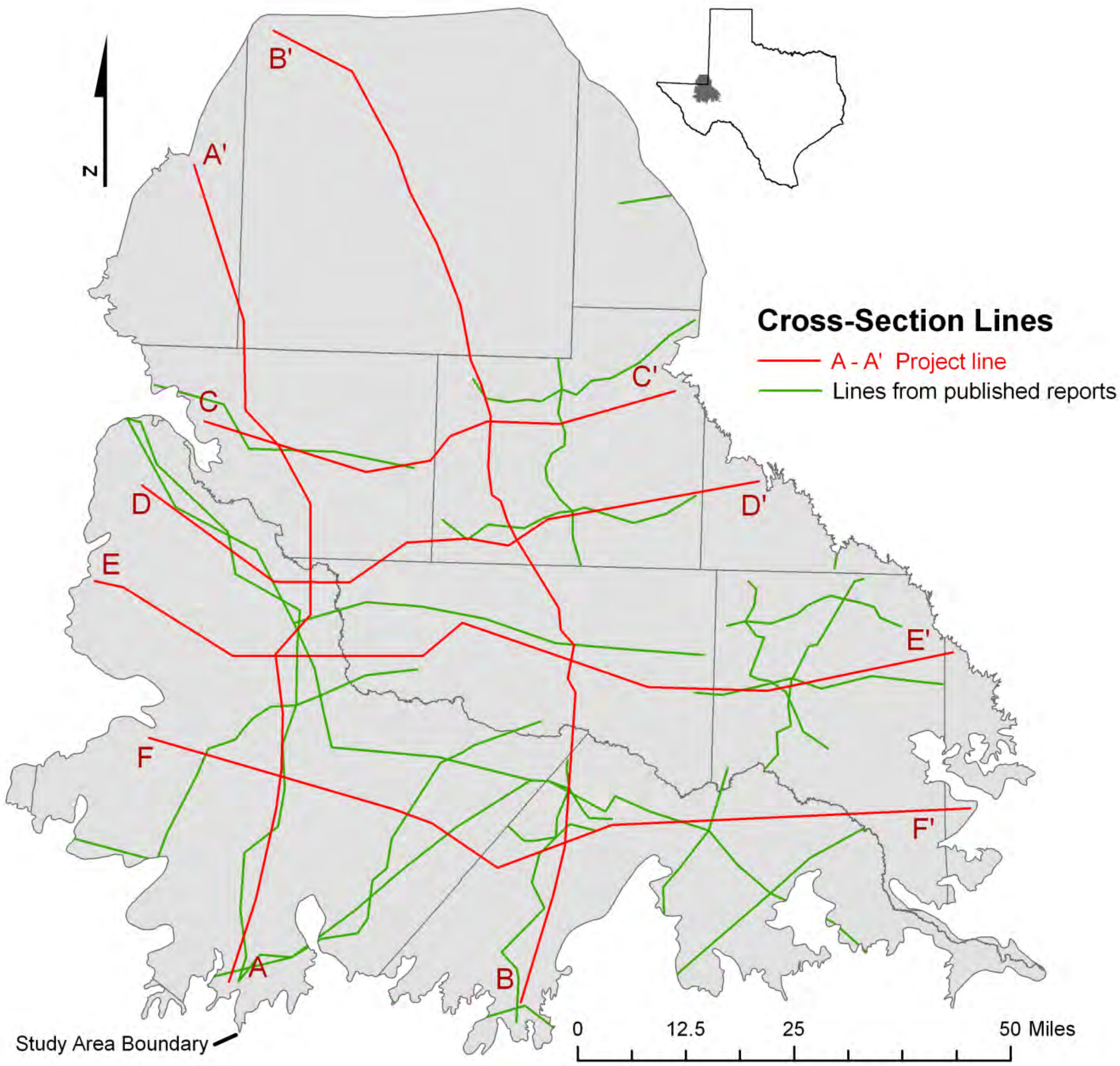

Figure 6-2. **Location of cross-sections lines created in this project and those from published reports containing information on the Pecos Valley Alluvium and underlying aquifers. The well point and line shapefiles are available as a GIS data set.**

The Pecos Valley Aquifer, previously known as the Cenozoic Pecos Alluvium is designated as a major aquifer in Texas (Ashworth and Hopkins, 1995; George and others, 2011). It is an unconfined aquifer, although deeper sections may have local confining layers. The name and lateral extent of the Pecos Valley Aquifer were modified in 2007 (TWDB, 2007).

The stratigraphic top of the Pecos Valley Alluvium is formed by all post-Cretaceous sediments exposed at ground surface in the project area. Mapping the stratigraphic bottom proved more complicated because basal Pecos Valley sediments consist of reworked Permian and Triassic red beds across most of the project area. The collapse of older consolidated material into solution voids and infilling with younger basin materials creates extremely complicated correlation issues that make it impossible in some cases to accurately define contacts using water well lithology and geophysical well logs (Armstrong and McMillion, 1961a; Maley and Huffington, 1953; Shafer, 1956; Snyder and Gard, 1982).

Geological correlations were made using geophysical well logs and lithology from nearby water wells. In order to maintain consistency of stratigraphic picks, the base was chosen using, wherever possible, the following criteria: contact between unconsolidated sediments and consolidated red beds as described on water well logs by the well-driller; contact between lighter colored sediments and predominantly red-colored, lithified red beds; contact between low gamma ray response and a higher gamma ray response using geophysical well logs (Figures 6-3 and 6-4).

With respect to picking the base of the Pecos Valley Alluvium, the technique of using geophysical well log correlation was inherently biased toward a signature that indicated a coarse, unconsolidated geological unit overlying a more uniform siltstone or shale unit. This bias may preclude the inclusion of basal fine-grained deposits in the Pecos Valley Alluvium that are almost indistinguishable from the underlying Triassic and Permian units.

Table 6-2 lists the numbers of wells and their type that were used to define the Pecos Valley Alluvium and the equivalent Ogallala Formation in New Mexico. In all, we interpreted 2,057 wells to define the formations and build the 3-D top and bottom surfaces in GIS. We loaded these picks into a database table with the stratigraphic pick name, top depth, bottom depth, and source of information.

The Pecos Valley Alluvium ranges in thickness from 0 to 1,745 feet (Figure 6-5). The most significant factor controlling the accumulation of sediment was solution-collapse within the Monument Draw and Pecos troughs. The timing of this solution collapse played a large role in the distribution and character of the sediment infill.

The timing of solution collapse and infill has been debated in the literature over the years. It is thought to have occurred anywhere from the Late Permian to the Present (Bachman, 1974; Bachman and Johnson, 1973; Hiss, 1975; Hovorka, 1998; Johnson, 1993). Bachman (1974) presented information gathered in New Mexico indicating three significant periods of dissolution: post Triassic and pre-middle Pleistocene; middle Pleistocene; and late Pleistocene. Events during these periods most likely influenced the accumulation of Pecos Valley Alluvium sediments.

Several wells in Reeves County encountered significant thicknesses of eroded volcanic material, ash, and bentonitic clay in basal Pecos Valley Alluvium sediments; the deepest units are over 1,400 feet below ground surface. The eroded volcanic detritus were identified in wells located more than 25 miles from the nearest igneous outcrop. Volcanism in Trans-Pecos Texas occurred from Eocene though Miocene epochs of the Tertiary Period (Ewing, 1991). The deposition of these volcanic-rich sediments occurred after the erosion and removal of Cretaceous units and was related to and occurred during the initial subsidence of the Pecos Trough.

Previous authors have grouped aquifers in the study area using the following hydrostratigraphic terminology: Pecos Aquifer (Pecos Valley aquifer overlying the hydraulically-connected Cretaceous formations in Pecos County; Richey and others, 1985); Allurosa Aquifer (Pecos Valley aquifer overlying the hydraulically-connected Dockum Group Santa Rosa Sandstone; Richey and others, 1985; White, 1971); Toyah Aquifer (Pecos Valley Aquifer overlying the hydraulically-connected Cretaceous formations in Reeves County; LaFave, 1987). While these terms are not used in our report, we mention them to illustrate the complexity of mapping the aquifers in the region.

Cretaceous undivided, top and bottom

The unit mapped as Cretaceous Undivided consists of Cretaceous sediments deposited unconformably on the Triassic Dockum Group or the Permian Dewey Lake Formation (Table 6-1). The sediments consist of clay, sand, and limestone deposited in continental to marine depositional settings at the onset of the marine transgression in West Texas. These sediments were collectively mapped as undifferentiated Cretaceous Undivided and constitute the hydrostratigraphic unit for the Edwards-Trinity (Plateau) Aquifer, classified as a major aquifer in Texas (Ashworth and Hopkins, 1995; George and others, 2011).

The stratigraphic top of the Cretaceous Undivided is marked by a sharp lithologic change from the overlying Pecos Valley Alluvium to the underlying limestone. This boundary is clearly represented on water well reports and on geophysical well logs by a distinct low gamma ray profile. Many geophysical well logs obtained from the TCEQ surface casing collection are already annotated with Cretaceous top and bottom picks. This served as an invaluable resource for our study. Where the limestone is missing due to erosion, the contact between Pecos Valley Alluvium and Cretaceous sands is not readily apparent and may be misinterpreted altogether. The TWDB has mapped the Edwards-Trinity (Plateau) Aquifer as a contiguous unit including outcropping Cretaceous sediments in eastern Reeves County. Our mapping indicates that the outcrop in eastern Reeves County may be an isolated erosional remnant, separated from mapped Cretaceous sediments to the south by a southeastern extension of the Pecos Trough.

The stratigraphic bottom of the Cretaceous Undivided unit was selected on the basis of a significant change in the character of the sediments with the underlying Dockum Group or Dewey Lake Formation red beds as seen on geophysical well logs. This pick is subject to misinterpretation along the northwestern limits of the Cretaceous sediments in Reeves County, where the nature of the Cretaceous sediments also changes with the presence of the Cox Sandstone.

Table 6-2 lists the numbers of wells and their type used to define the undivided Cretaceous unit. We used 188 wells to interpret the top of the unit and 177 wells for the base. These were used to develop the 3-D top and bottom surfaces in GIS.

Dockum Group-Dewey Lake Formation, top and bottom

The Dockum Group consists of Upper Triassic sediments deposited unconformably on the Upper Permian Dewey Lake Formation. The unconformity represents approximately 25 million years (Lucas and Anderson, 1993). The Dockum Group represents the filling of the Dockum basin which received sediments (eroded Paleozoic rocks) from all directions (McGowen and others, 1979). The sediments consist of alternating shale, siltstone, sandstone, and gravel that were deposited in a variety of fluvial, lacustrine, and deltaic environments (Bradley and Kalaswad, 2003).

The Dockum Group constitutes the hydrostratigraphic unit for the Dockum Aquifer which is classified as a minor aquifer in Texas (Ashworth and Hopkins, 1995; George and others, 2011). The terms Santa Rosa and Allurosa aquifers have been applied to the Santa Rosa Sandstone of the Dockum Group and to the Santa Rosa Sandstone plus Pecos Alluvium in the study area by previous authors (Richey and others, 1985; White, 1971).

The individual formations within the Dockum Group were not differentiated in this project. The lithology was recorded from numerous water well reports and geophysical well logs; sandstone within the lower Dockum Group has been referred to as the Santa Rosa Sandstone or the Camp Springs member, the principal water-bearing unit of the aquifer.

The Dewey Lake Formation consists of Upper Permian continental sediments deposited on the Permian Rustler Formation. The sediments consist of alternating shale, siltstone, and red sandstone (BEG, 1976b) that are believed to have originated from areas to the north, west, and south of the Delaware Basin (Jones and others, 2011). The Dewey Lake Formation is not considered an aquifer in the Trans-Pecos region. It is equivalent to the Quartermaster Formation in the Texas Panhandle (Lucas and Anderson, 1993).

The stratigraphic top of the Dockum Group was mapped across the project area where it is unconformably overlain in places by Cretaceous sediments or by the Pecos Valley Alluvium Figure 6-1; Table 6-1). The Dockum Group is exposed at ground surface in several areas within the project area.

The contact between the Dockum Group and underlying Dewey Lake Formation was not mapped in this study. This unconformity is indistinct on both water well reports and geophysical well logs, and often confusing in outcrop exposures. Some previous authors have attempted to map this contact in the subsurface (for example, Garza and Wesselman, 1959), but we could not replicate their interpretation on geophysical well logs in the project area. McGowen and others (1979, Figure 33 on p. 37) indicated that the contact was clearly distinguished on geophysical well logs within the Midland Basin to the east of the project area and only a small portion of northeastern Winkler and part of Ward counties within the project area. Lucas and Anderson (1993) provide a detailed discussion of this contact including the ages of the formations.

We mapped the stratigraphic top of the Dewey Lake Formation in Reeves County, west of the western extent of the Dockum Group, and the bottom across the entire project area. The bottom of the formation rests on the stratigraphic top of the underlying Rustler Formation.

The western extent of the Dockum Group is represented by the western limit of Region 1 in Figure 6-1. The western limit is problematic, in part because the contact between the Dockum Group and Dewey Lake Formation cannot be clearly delineated. The Pecos geologic atlas map (BEG, 1976b) shows Dockum Group sediments in the northwestern corner of Loving County with exposed Dewey Lake sediments immediately to the west. It is possible that these Dockum Group outcrops are erosional remnants or, as Lucas and Anderson (1993) suggest, Dewey Lake sediments, or even Cenozoic alluvium. We chose to include this area as the western limit for the Dockum Group and extended this line to the southeast along the eastern margin of the Pecos Trough.

Table 6-2 lists the numbers and type of wells that were used to define the top of the Dockum Group and the bottom of the Dewey Lake. Over 1,300 wells were interpreted to define the formations and to build the 3-D top and bottom surfaces in GIS.

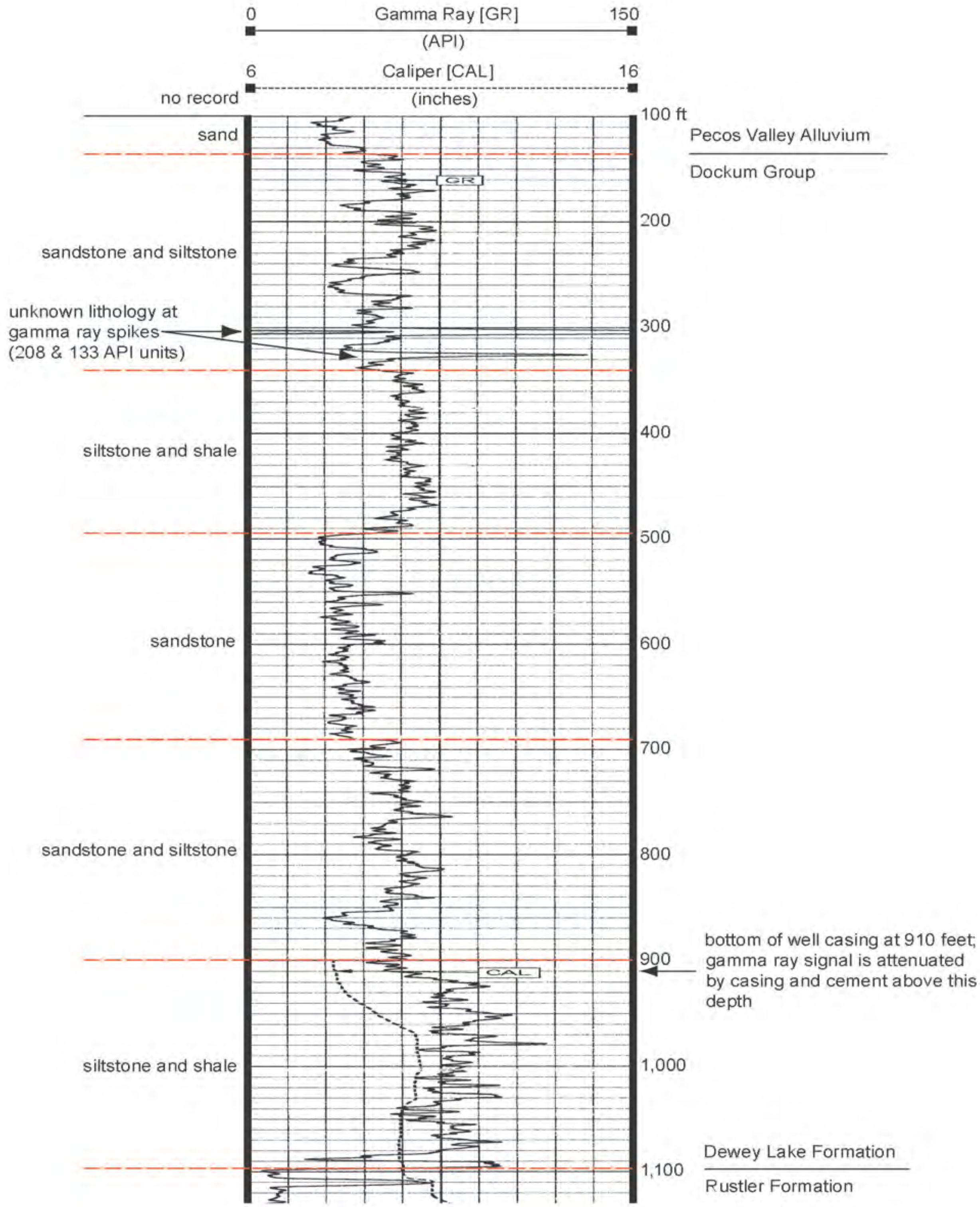

Figure 6-3. **BRACS well 1258 showing stratigraphic picks for the Pecos Valley Alluvium, Dockum Group, and Dewey Lake Formation and simplified lithologic units interpreted from the gamma ray log.**

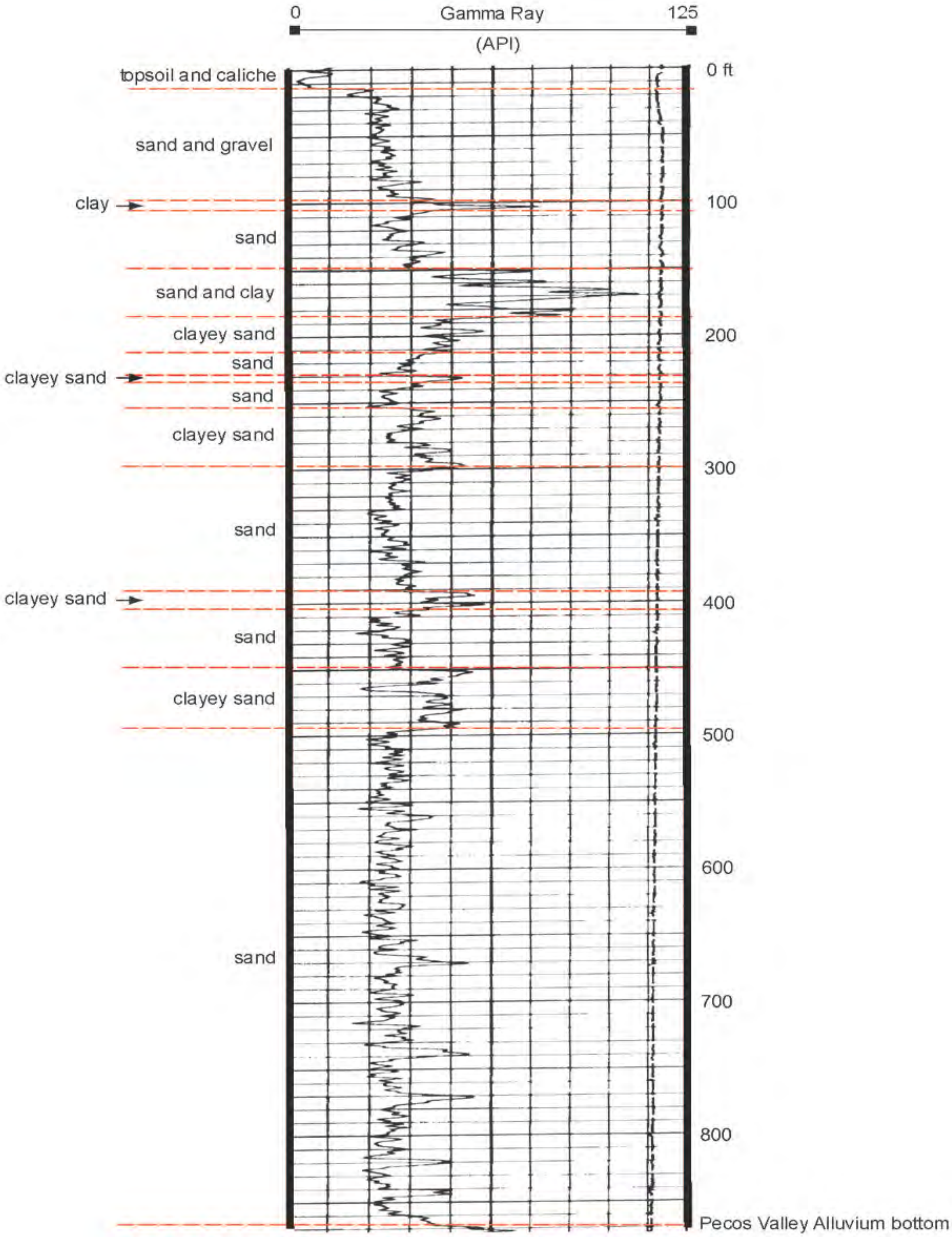

Figure 6-4. BRACS well 2079 showing simplified lithologic units and the Pecos Valley Alluvium bottom stratigraphic pick.

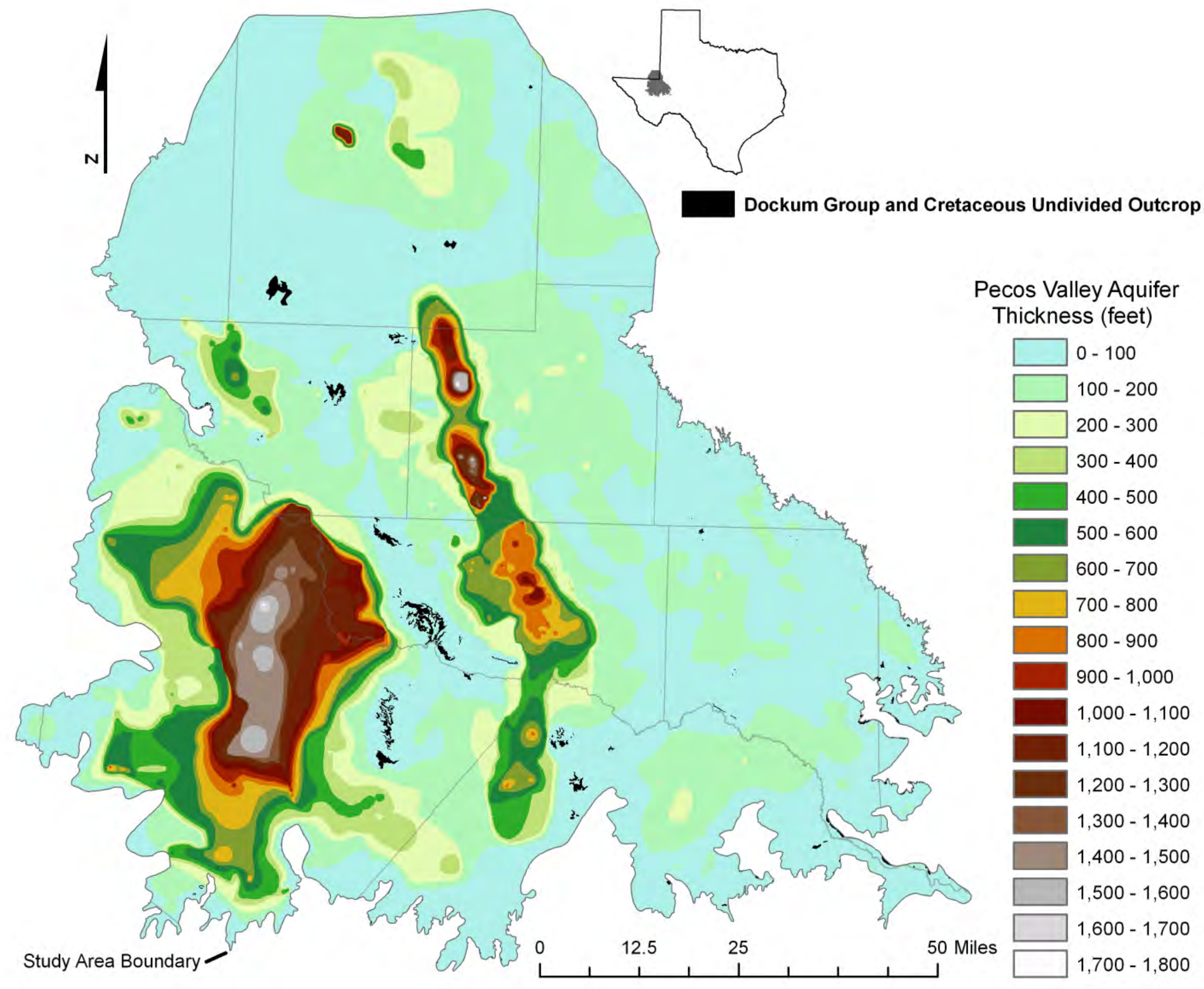

Figure 6-5. **Thickness of the Pecos Valley Aquifer. Well control included 2,057 sites in Texas and New Mexico.**

Rustler Formation, top

The Rustler Formation consists of Upper Permian sediments deposited unconformably on the Permian Salado Formation. The sediments consist of shale, silt, sandstone, dolomite, and the evaporites, halite and gypsum (anhydrite at depth). The Rustler Formation constitutes the hydrostratigraphic unit for the Rustler Aquifer, although the areal extent of the formation is much greater than the mapped limits of the aquifer. The Rustler Aquifer is considered a minor aquifer in Texas with the subsurface boundary defined on the basis of a TDS content of 5,000 mg/L (Ashworth and Hopkins, 1995; George and others, 2011).

Only the top of the formation was mapped for this project because the surface is critical in understanding the location, extent, and magnitude of solution collapse into the underlying Salado Formation. This is the only formation in the project area that can be utilized as a regional marker (Maley and Huffington, 1953). The surface provided needed control when correlating the 3-D extent of the overlying Pecos Valley Alluvium. We did not map below the top surface of the formation because this work is being completed as part of a groundwater flow model for the Rustler Aquifer (Jones and others, 2011).

The stratigraphic top of the Rustler Formation is easily recognized on geophysical well logs across the entire project area and beyond with the following exceptions. In southern Pecos County, the Rustler Formation is equivalent to the Tessey Limestone (Jones and others, 2011); the contact in this region is difficult to interpret because of local structures and lithologic changes. In southwestern Loving County, northwestern Reeves County, and in other localized areas the top of the Rustler Formation is difficult to interpret due to possible evaporite dissolution and/or chaotic mixing of strata resulting from solution collapse.

The typical geophysical well log response for the Rustler Formation in New Mexico was described by Snyder (1985) and, in an example from Ward County, by White (1971). We compared our Rustler-top stratigraphic picks with that of Hiss (1976) and traded data sets with Jones and others (2011) to ensure that our interpretations were consistent. Additionally, many digital geophysical well logs that we used in the project were already annotated with picks for the top of the Rustler Formation.

Table 6-2 lists the numbers of wells and their type that we used to define the top of the Rustler surface. We used 1,350 wells to define this surface in the project area, while many more were correlated outside of the study area to help construct the 3-D top surface in GIS.

6.1.2 Lithologic descriptions

The descriptions of rocks recorded by water well drillers on well reports were appended to the BRACS well geology table either manually or by digital parsing techniques if a digital well report was available from the TDLR. 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 allowed us to enter data faster, it limited our ability to process the information into net sand maps and display more detailed lithologies on geological cross-sections.

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 which we refer to as SLD. Our description consists of a short list of terms based on mineralogy and grain size. The technique of simplifying driller's descriptions of lithologies is not new and has been used by others (for example, Seni, 1980; Young and others, 2010) to suit project needs.

A database lookup table relating the described lithologic name to the simplified lithologic name was prepared to accommodate the numerous variations present on well reports. Presently, the database lookup table contains more than 4,300 records and the table of simplified lithologic names 89 terms.

The simplified lithologic names represent either one type of material (for example, sand), or mixtures of two types of materials (for example, sand and gravel). Each term that represents a mixture assumes that each component approximates a 50-50 percent mix. The creation of the database table relating lithologic name to simplified lithologic name presented both challenges and some inherent 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. Formation descriptions that included non-geological terms (for example, cut hard) were listed as unknown. Units that were listed as lost circulation or hole-deepened or variations thereof were listed as no record.

We interpreted 470 digital gamma ray logs for SLD. This represents 36 percent of the 1,300 geophysical well logs in the project area that contain a gamma ray tool. Many logs could not be used for interpretation because the logged interval was too deep; attenuation of the gamma ray log was unacceptable; or well density in the area was so high that interpreting all logs proved impractical. The SLD was interpreted from ground surface to the top of the Rustler Formation. Simplified lithologic names, top and bottom depths, and source of information were entered into the BRACS database using a custom data entry form that we developed.

Within clastic sequences, a low gamma ray response was interpreted as sand and a sand line was established on the log. A high gamma ray response was interpreted as clay/shale and a shale line established on the log. An intermediate response was interpreted as sand and clay mixtures. Two exceptions to this were the presence of very low gamma ray response near the ground surface that was interpreted to be caliche and extremely high gamma ray response in very thin beds that was attributed to naturally-occurring uranium or thorium series minerals (Figure 6-3). There were 46 wells that showed lithologic units with an elevated gamma ray response, 22 in the Pecos Valley Alluvium, 32 in the Dockum Group-Dewey Lake Formation, and one in the Cretaceous Undivided. Caliche and high gamma ray kicks were recorded in the simplified lithology description field, with the latter indicating “unknown” and a lithologic description indicating the highest API unit reading. The gamma ray response does not indicate grain size within shale-free sands and gravels. When the SLD for a record in the geology table shows a grain size other than sand or clay, it is based on adjacent water-well lithologic descriptions.

The gamma ray response was evaluated after reviewing nearby water well log driller formation descriptions. Bed boundaries were generally interpreted as the mid-point between high and low gamma ray response (Collier, 1993a, 1993b). Generally, units thicker than 20 feet were recorded as a separate lithologic unit. Thick sequences of interbedded sand and clay, where the relative thickness of each unit was approximately the same, were recorded as 50-50 mixtures: for example, sand and clay. The transition from basal Pecos Valley Alluvium to Dockum Group or Dewey Lake Formation required a change in lithologic terminology from unlithified to lithified forms (for example sand to sandstone). Dockum and Dewey Lake red beds were generally interpreted as siltstones unless very low gamma ray response indicated sandstone or high gamma ray response indicated shale (Figures 6-3 and 6-4).

Figures 6-3 and 6-4 provide examples of gamma ray log interpretation using SLDs to classify units.

6.1.3 Net sand and sand percent maps

Net sand and sand percent values for wells penetrating the Pecos Valley Alluvium and/or the Dockum Group sediments were generated from the SLD. If a well only partially penetrated a formation, a net sand value was calculated, but not the sand percent. The sand percent values for the Dockum Group-Dewey Lake Formation will be lower than if we had been able to map the base of the Dockum Group.

The top and bottom depths of formations encountered at each well site in the project area were determined using GIS analysis. This technique is described in section 6.5.1, Aquifer determination.

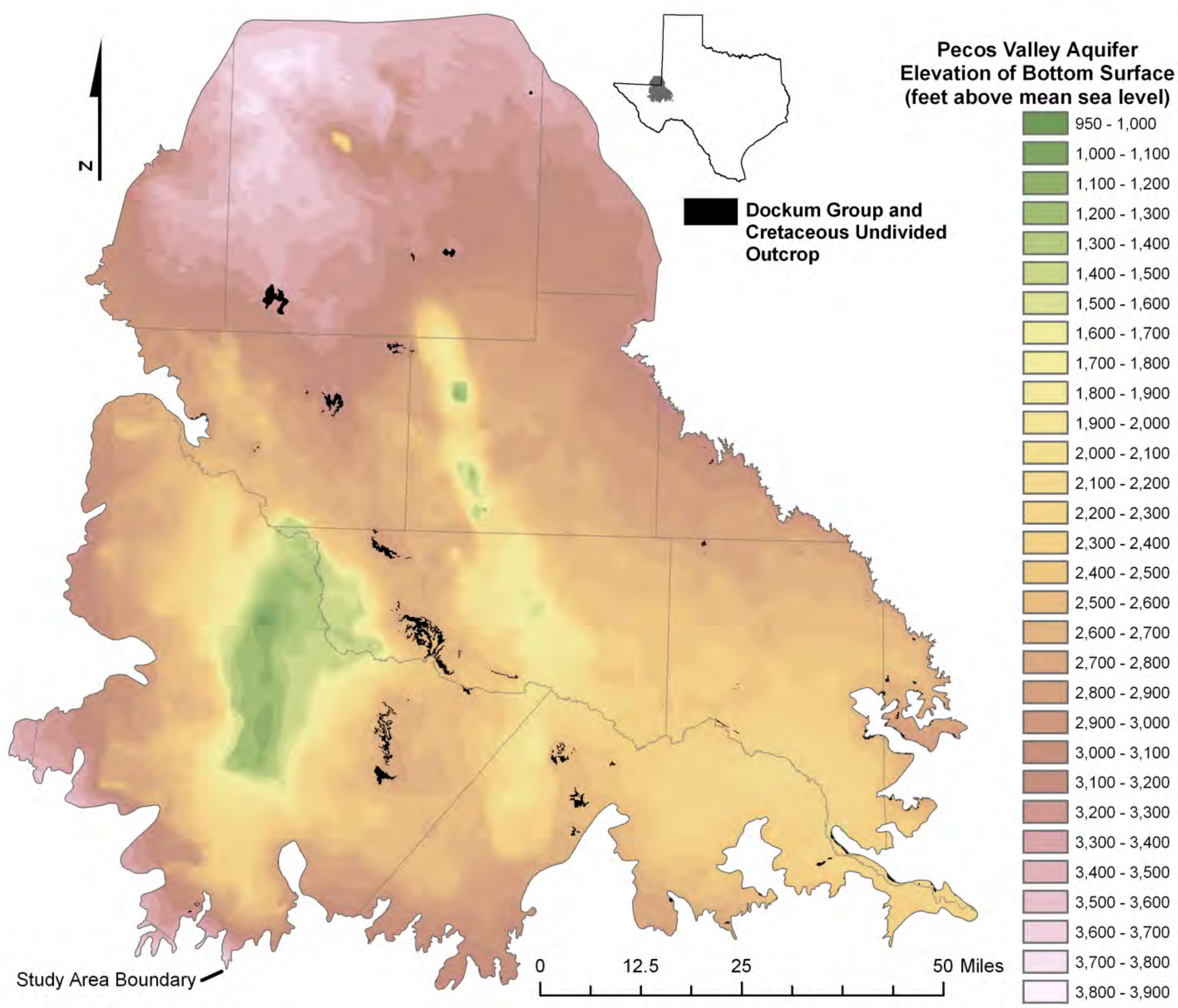

Figure 6-6. Elevation of the bottom surface of the Pecos Valley Aquifer.

An examination of the thickness and bottom elevation maps of the Pecos Valley Aquifer (Figures 6-5 and 6-6) and geological cross-sections (Figures 6-7 through 6-13) shows significant differences in geometry between the Pecos and Monument Draw troughs, suggesting different mechanisms of solution collapse.

The table that lists all simplified lithologic names contains a field for sand percent. Values of 0, 50, 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.

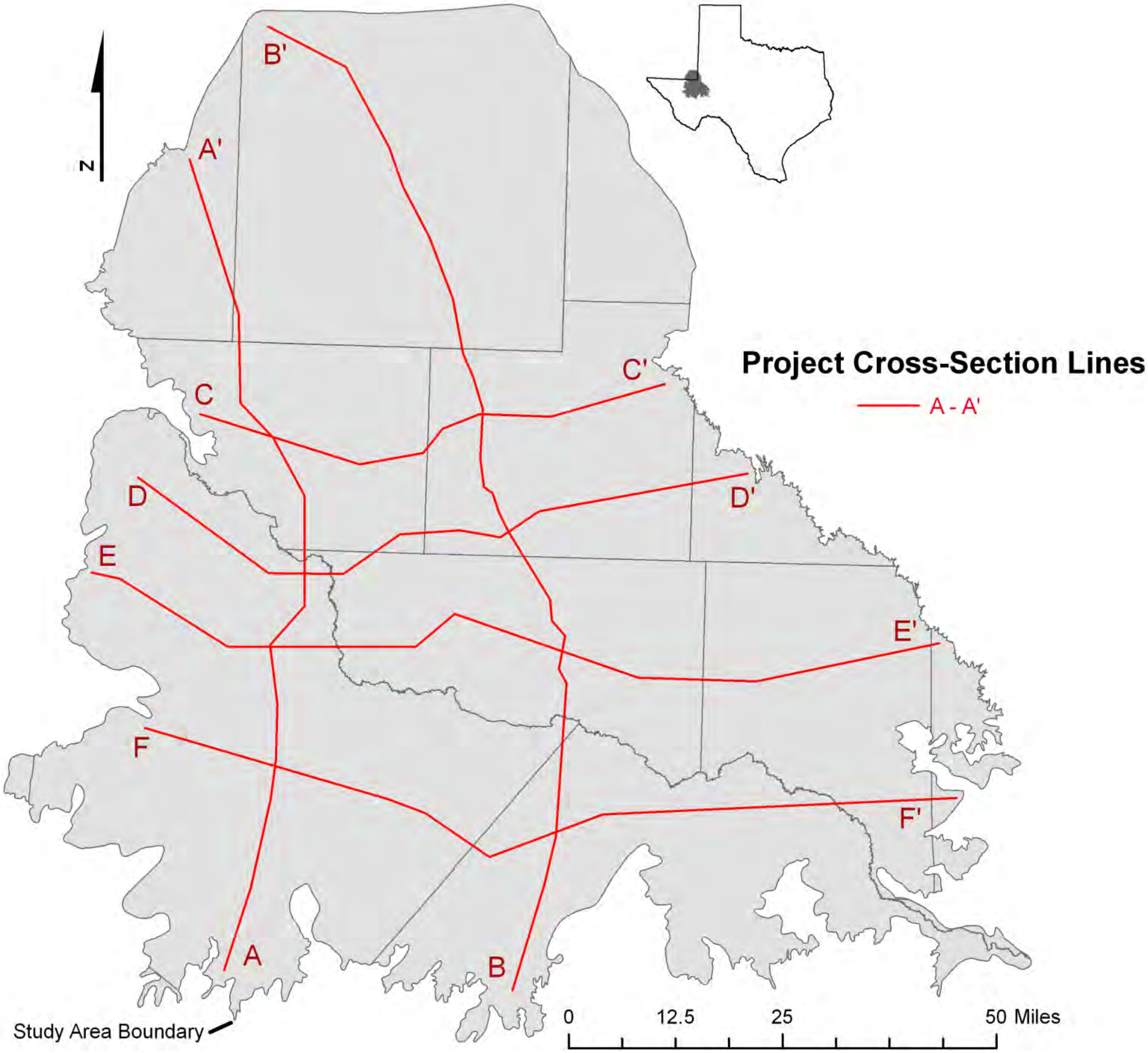

Figure 6-7. **Locations of geologic cross-section lines.**

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), we wrote specific queries to evaluate each of these scenarios and to assign the correct thickness of a lithologic unit to the correct formation. More than 40 separate queries were performed to create a final data set because both the Pecos Valley Alluvium and Dockum Group sediments were evaluated in this project. We loaded these queries into Microsoft Visual Basic for Applications and linked them to a form to systematically process the information. We performed a separate query to assemble the information into a table for export into GIS for spatial display.

6.1.4 Structural geometry

Pecos Valley Aquifer hydrostratigraphic unit structural top and bottom

A significant thickness (up to 1,800 feet) of saturated Pecos Valley Aquifer is present in the solution troughs (Figure 6-5). Regions outside of the troughs generally contain less than 200 feet of alluvial material, thinning to zero where Triassic Dockum Group or Cretaceous strata are exposed at the ground surface. The Pecos Trough is a broad area of significant sediment accumulation that lies directly on the unconformity above the Dewey Lake or Rustler formations. The northeastern extent of the Pecos Trough terminates abruptly against a ridge of Permian Salado and Castile evaporites capped with Dockum Group strata. This faulted margin of the basin juxtaposes Pecos Valley Alluvium against Permian evaporites draped with relatively thin, fractured Dewey Lake and Dockum Group red beds (Figures 6-8 and 6-11).

The Monument Draw Trough consists of a linear system of narrow, elongate, and deep collapse features where the basal part of the Pecos Valley Alluvium is isolated from adjacent alluvial-filled collapse features. The trough broadens in central Ward County and becomes narrow in northwestern Pecos County (Figure 6-14). There is no groundwater flow between the Monument Draw and Pecos troughs mainly because of the intervening structurally high ridge in Loving and eastern Reeves counties (Figure 6-11). The two troughs act like separate groundwater systems (Ashworth, 1990).

A distribution of water wells showing percent penetration into the Pecos Valley Aquifer is shown in Figure 6-15. The Monument Draw Trough in Winkler and south-central Ward counties has very few water wells that penetrate the full thickness of the aquifer. The Pecos Trough in northern Reeves and northwestern Loving counties is similarly underrepresented by water wells. The implication is that there is not enough lithologic and water chemistry data in the thicker sections of the Pecos Valley Alluvium to map water quality. Formation information was based solely on interpretations of gamma ray geophysical well logs.

The complex nature of solution trough development in the Pecos and Monument Draw troughs has led to complex sediment infill patterns and differences in the nature of the sediments in the two troughs. Basal Pecos Valley sediments in the Monument Draw trough typically consist of eroded red Dockum Group sediments or solution collapse material from the Dockum Group. The base of the formation is often difficult, if not impossible, to determine. As the solution troughs deepened and alluvial material started to accumulate, a distinct package of sediments consisting primarily of sand began to form in the depressions. These sediment packages - a few hundred feet thick - are recognizable in wells located in the same general geographic area suggesting that they are not laterally continuous over large distances. Furthermore, the sediment packages are not always present at the same depth, suggesting that sections of the trough may have collapsed at different rates.

It is also not uncommon to encounter a significant accumulation of clay in some wells. However, correlation of individual lithologic units over large distances is, at best, uncertain. This complex pattern of sediment infill has profound implications for groundwater development since the present-day aquifer exhibits anisotropic properties. In summary, it appears that each “sub-basin” within the Monument Draw trough acts somewhat independently of adjacent sub-basins, and wells within a sub-basin record solution collapse at different rates.

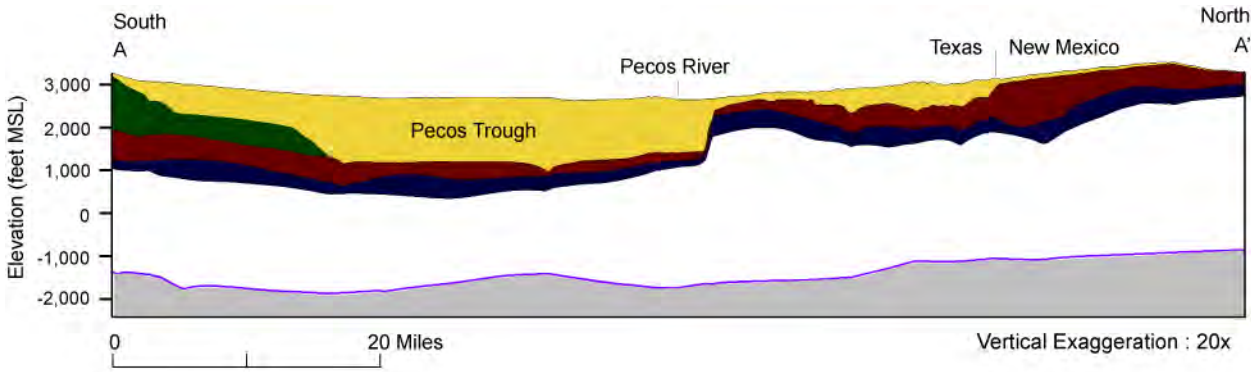

Figure 6-8. **The south to north section crosses the Pecos Trough in Reeves County and solution collapse features in Loving County. Refer to Figure 6-7 for cross-section location. The bottom of the Rustler Formation was determined by data from Jones and others (2011).**

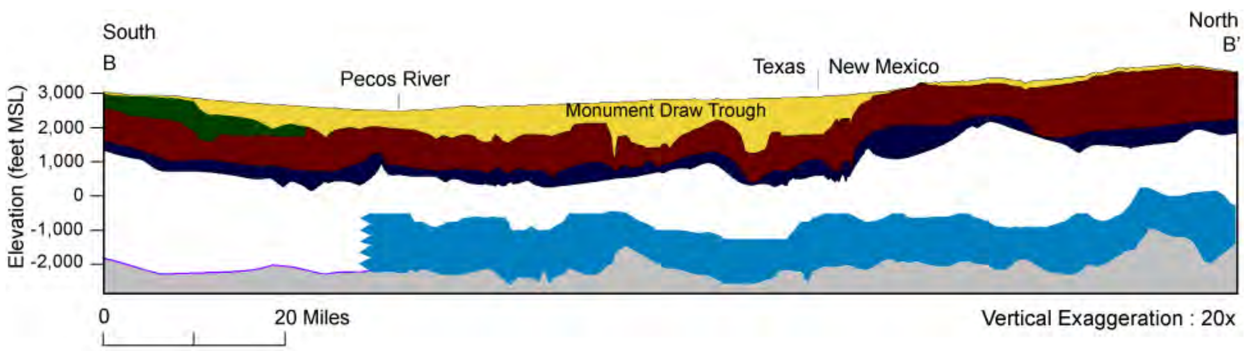

Figure 6-9. **The south to north section crosses the Monument Draw Trough. Note the complexity of the bottom Pecos Valley Alluvium. Refer to Figure 6-7 for cross-section location. The bottom of the Rustler Formation was determined by data from Jones and others (2011). The Capitan Reef Complex top and bottom surfaces are from Standen and others (2009).**

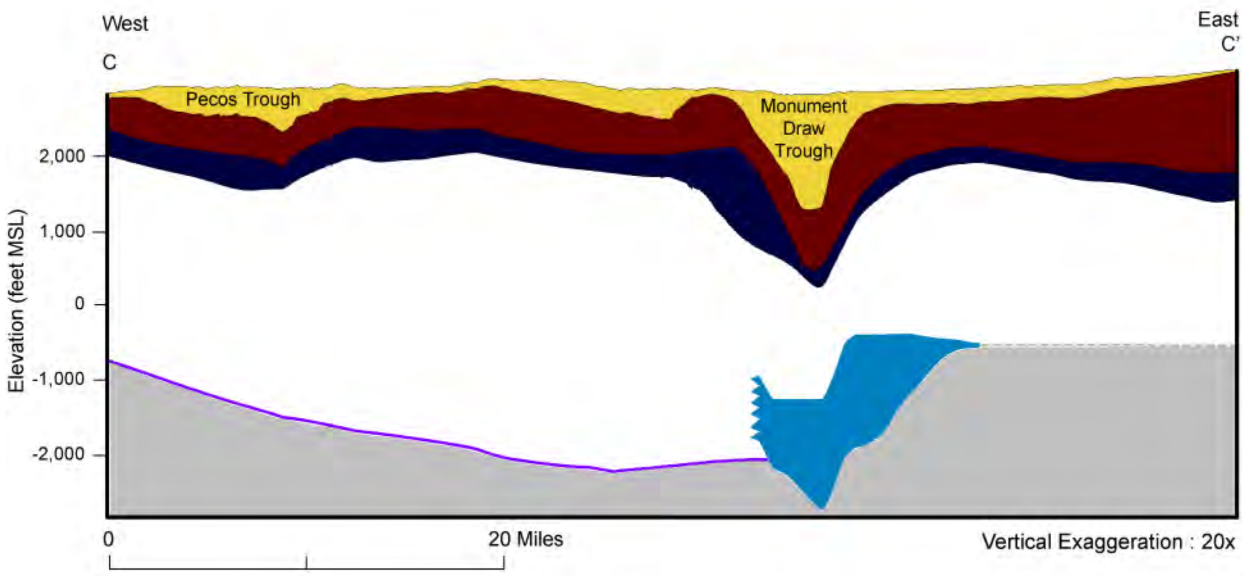

Figure 6-10. The section crosses the solution collapse features in Loving County and the Monument Draw Trough in Winkler County. Refer to Figure 6-7 for cross-section location. The pre-Salado contact east of the Capitan Reef Complex is diagrammatic. The Rustler bottom was calculated from Jones and others (2011). The Capitan Reef Complex top and bottom surfaces are from Standen and others (2009).

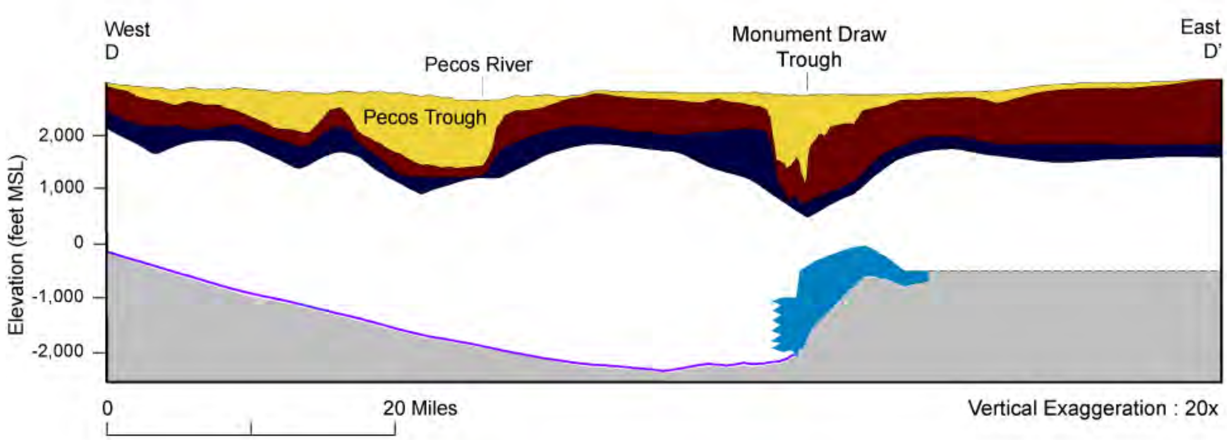

Figure 6-11. The section crosses the Pecos Trough in Reeves County and the Monument Draw Trough in Winkler County. Refer to Figure 6-7 for cross-section location. The pre-Salado contact east of the Capitan Reef Complex, is diagrammatic. The Rustler bottom was calculated from Jones and others (2011). The Capitan Reef Complex top and bottom surfaces are from Standen and others (2009.

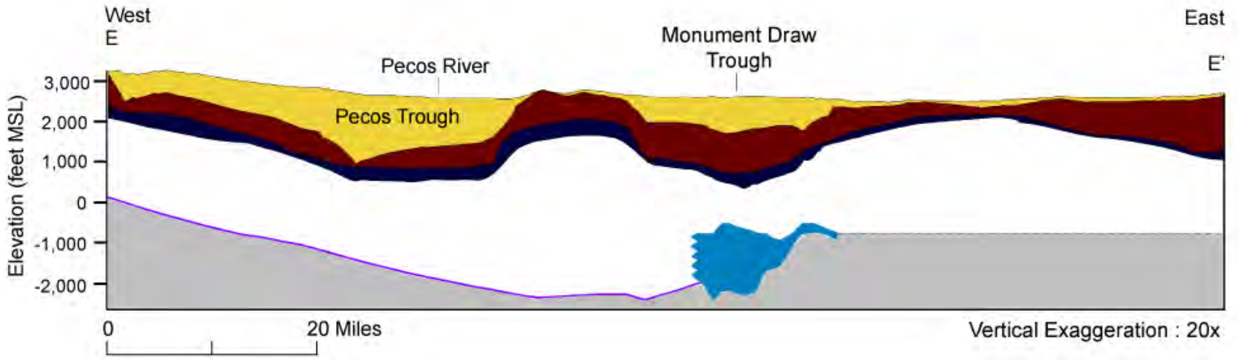

Figure 6-12. The east to west section crosses the Pecos Trough in Reeves County and the Monument Draw Trough in Ward County. Refer to Figure 6-7 for cross-section location. We did not map the pre-Salado contact east of the Capitan Reef Complex, so this boundary is diagrammatic. The bottom of the Rustler Formation was determined by data from Jones and others (2011). The Capitan Reef Complex top and bottom surfaces are from Standen and others (2009).

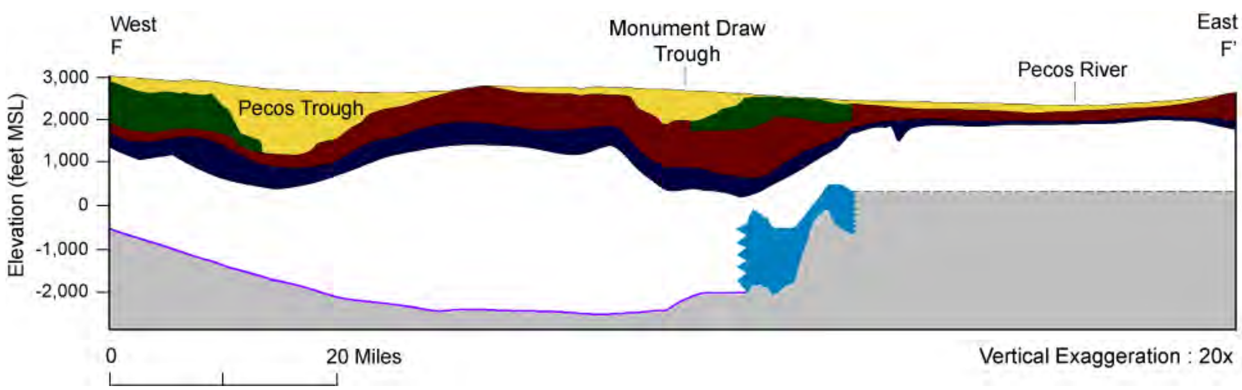

Figure 6-13. The east to west section crosses the Pecos Trough in Reeves County and the Monument Draw Trough in Pecos County. Refer to Figure 6-7 for cross-section location. We did not map the pre-Salado contact east of the Capitan Reef Complex. This boundary is diagrammatic. The bottom of the Rustler Formation was determined by data from Jones and others (2011). The Capitan Reef Complex top and bottom surfaces are from Standen and others (2009).

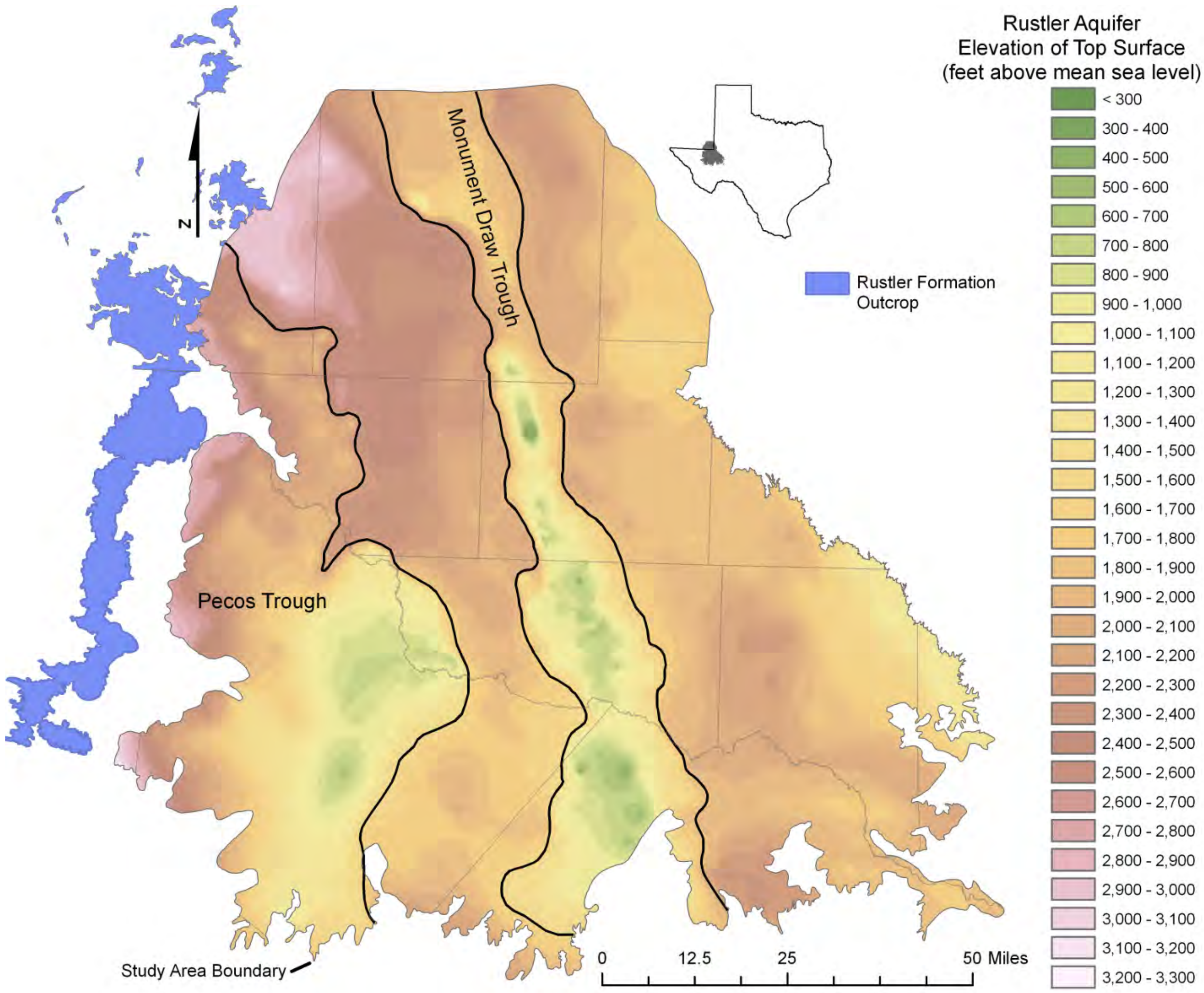

Figure 6-14. **Rustler Aquifer top elevation surface. Solid black lines show approximate boundaries of the Monument Draw and Pecos Troughs.**

The Pecos Trough in Reeves County records a different pattern of infill than the Monument Draw Trough. The base of the Pecos Valley Alluvium in this trough is much easier to distinguish in both water well logs and on geophysical well logs. The presence of eroded volcanic material in basal Pecos Valley sediments (as described in section 6.1.1) provides evidence of source rock to the south of the project area. Drillers have reported boulders in many of the boreholes drilled in this region. An examination of the Pecos Valley thickness map (Figure 6-5) indicates a central north-south trending section of thick sediment with narrower, thicker sediment channels feeding the main trough from all directions. This same pattern is also reflected in the elevation map of the top of the Rustler Formation (Figure 6-14).

Recharge to the Pecos Valley Aquifer occurs through infiltration of rainfall, seepage from ephemeral streams, cross-formational flow, and irrigation return-flow (Ashworth, 1990; LaFave, 1987). Recharge was not evaluated for this project, but Jones (2001, 2004, and 2008) and Anaya and Jones (2009) provide an excellent discussion on this topic.

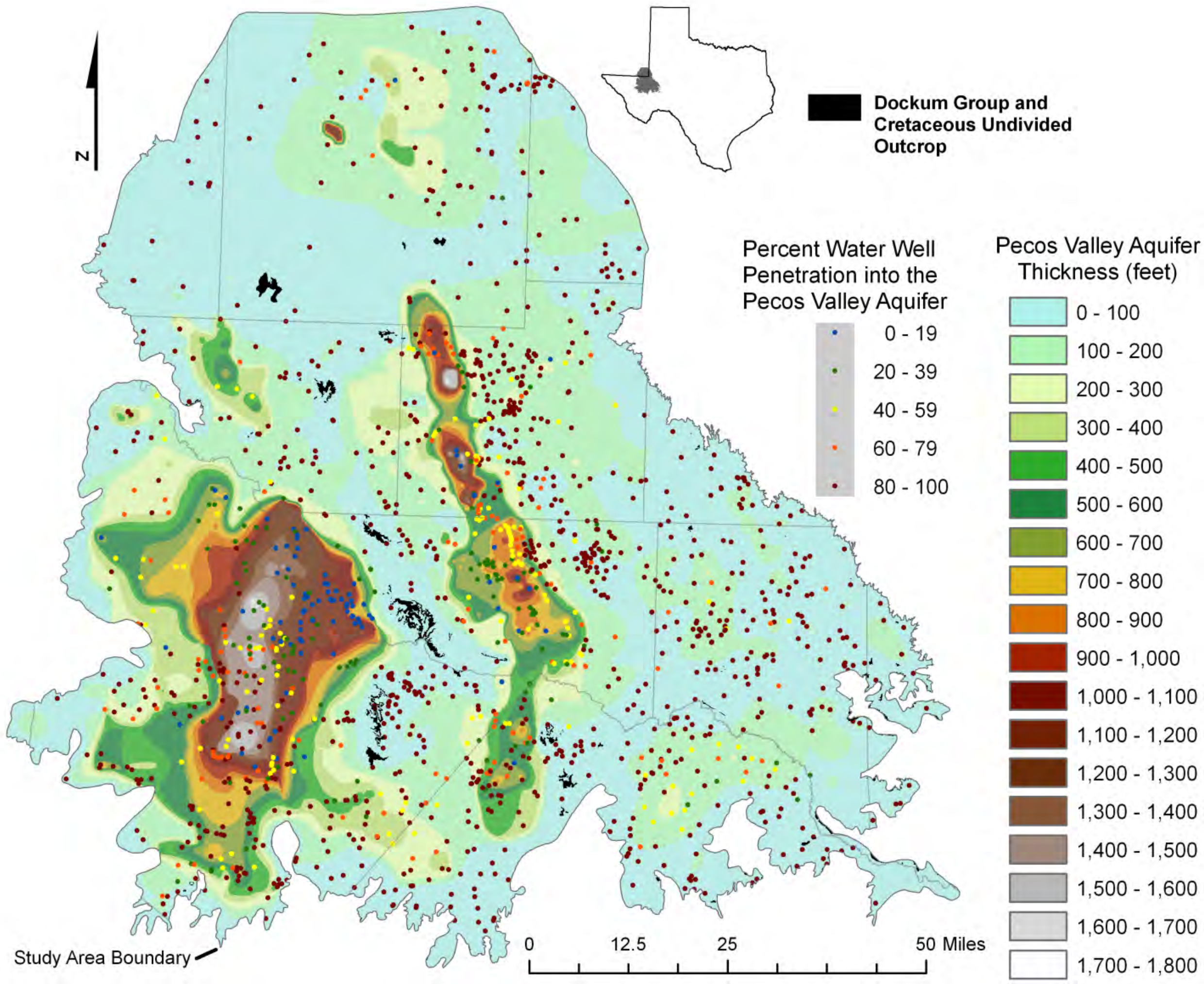

Figure 6-15. **Water wells showing percent of penetration into the Pecos Valley Aquifer. Base map shows Pecos Valley thickness. The water wells in the northern portion of the Pecos Trough in Reeves County penetrate less than half the thickness of the Pecos Valley Aquifer. Deep sections of the Monument Draw Trough in Winkler and Ward counties are also relatively unexplored for water resources.**

Dockum Group–Dewey Lake hydrostratigraphic unit structural top and bottom

Sands within the Dockum Group are an important source of groundwater in parts of the project area. There are many wells specifically drilled into the Dockum Aquifer or into both the Pecos Valley and Dockum aquifers. We performed net sand calculations for both of these aquifers. Figures 6-16 and 6-17 show the locations of wells with Pecos Valley and Dockum net sand results. The net sand data set for the Dockum Group is incomplete because many wells only partially penetrate the Dockum Aquifer. Many more gamma ray logs remain in the project collection that could be correlated for simplified lithology to gain a more complete understanding of the 3-D extent of Dockum Group sands in the project area.

Dockum sands are overlain by fine-grained red beds and shale, especially in the eastern part of the project area where the formation begins to thicken. Figure 6-18 shows well locations where

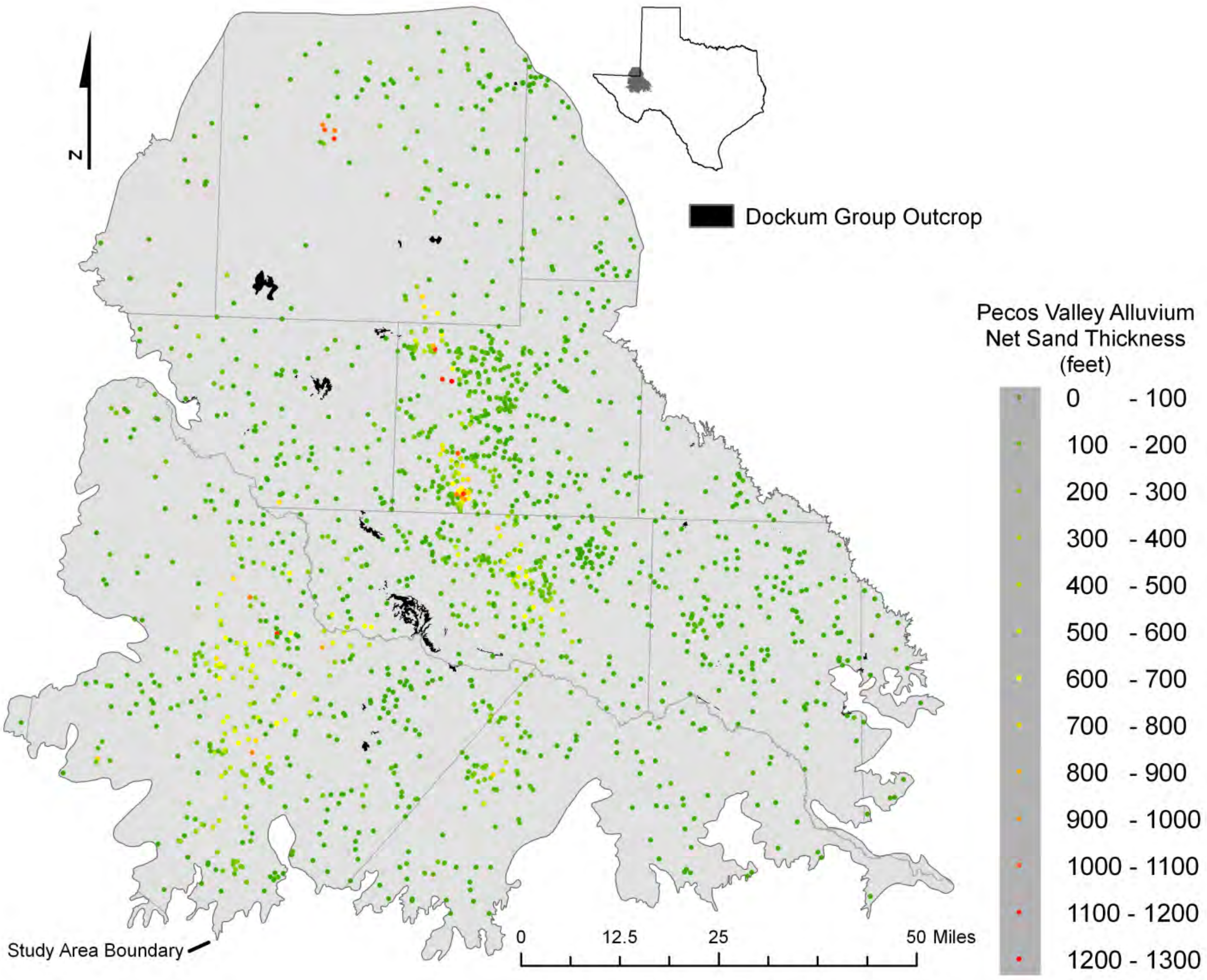

Figure 6-16. Pecos Valley Aquifer net sand map.

erosion has removed the overlying fine-grained red beds in the upper Dockum Group allowing the Pecos Valley Alluvium to be deposited directly above the Dockum sands. In these locations, the two aquifers are interconnected. The Dockum sands are underlain by fine-grained sediments across the entire project area.

Localized fracturing of the Dockum sands allows higher well production in the cities of Kermit (Garza and Wesselman, 1959) and Pecos (Richey and others, 1985) well fields. An examination of the top of the Rustler Formation in the City of Pecos well field indicates slight anticlinal/synclinal folding with maximum downwarp in the well field. Similarly, the Rustler Formation in the area around Kermit shows a synclinal structure with maximum downwarp in the well field. Based on this observation, the top surface of the Rustler Formation in conjunction with Dockum net sand maps can be used to discern areas favorable to the formation of fractured sands.

Cretaceous undivided hydrostratigraphic unit structural top and bottom

The Cretaceous undivided strata in the project area were mapped for the purpose of understanding the relationship with the overlying Pecos Valley Alluvium (Figure 6-19). The Cretaceous units represent a small fraction of the Edwards-Trinity (Plateau) Aquifer in Texas (Anaya and Jones, 2009). The lateral extent of the Cretaceous Undivided sediments in the project area is still problematic.

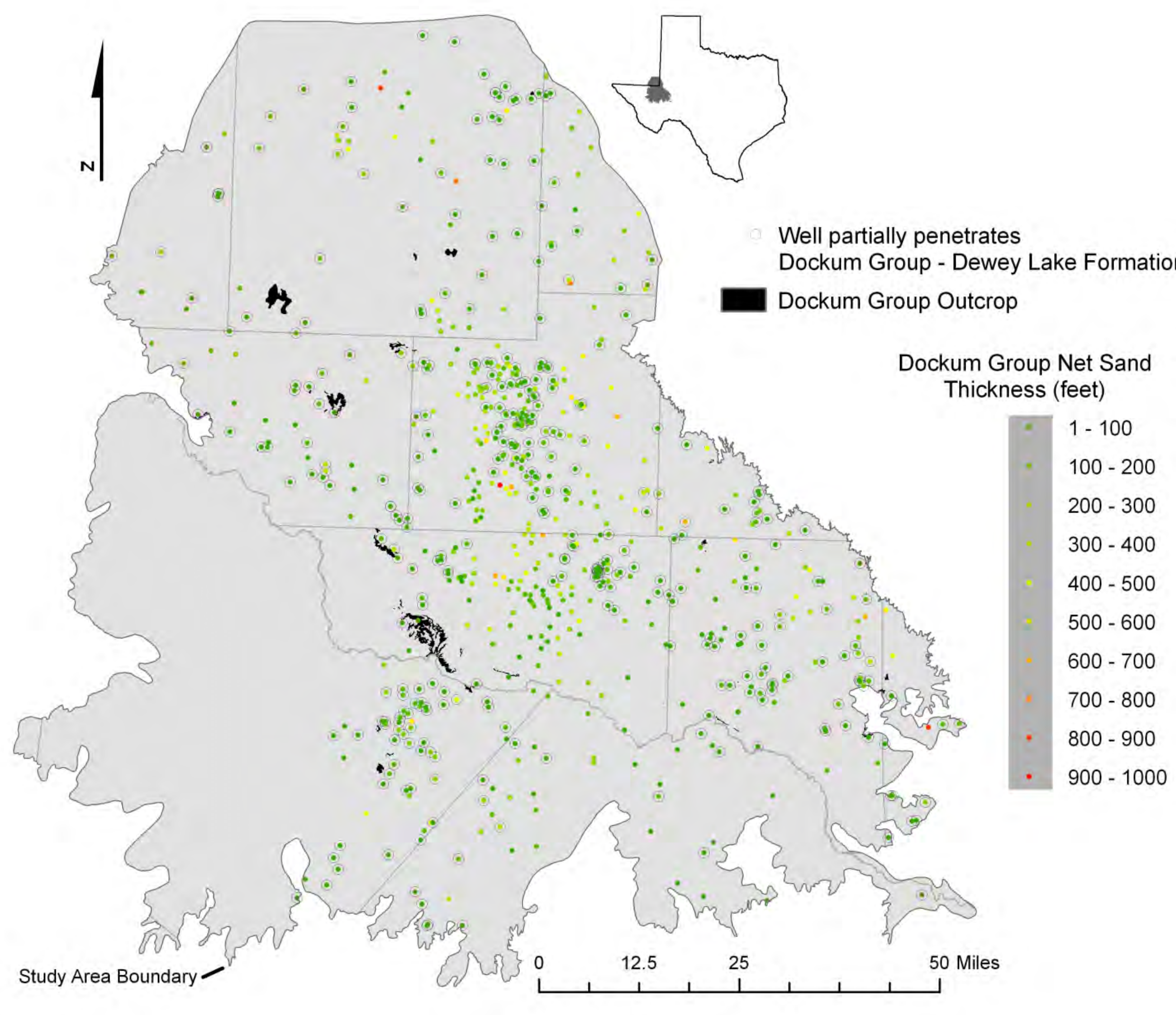

Figure 6-17. Wells with Dockum Group net sand thickness values. Wells with superimposed open circle symbol indicate well did not fully penetrate the Dockum Group–Dewey Lake Formation interval, so net sand values may be less than total.

We mapped the Cretaceous Undivided in Reeves County as an escarpment along its northeastern edge based on limited well control data in the area. Ogilbee and others (1962a; Plate 7) have mapped this as a wedge, but we could not confirm the interpretation because wells in this area do not reach the Cretaceous sediments. Additional work needs to be done to better understand the stratigraphy.

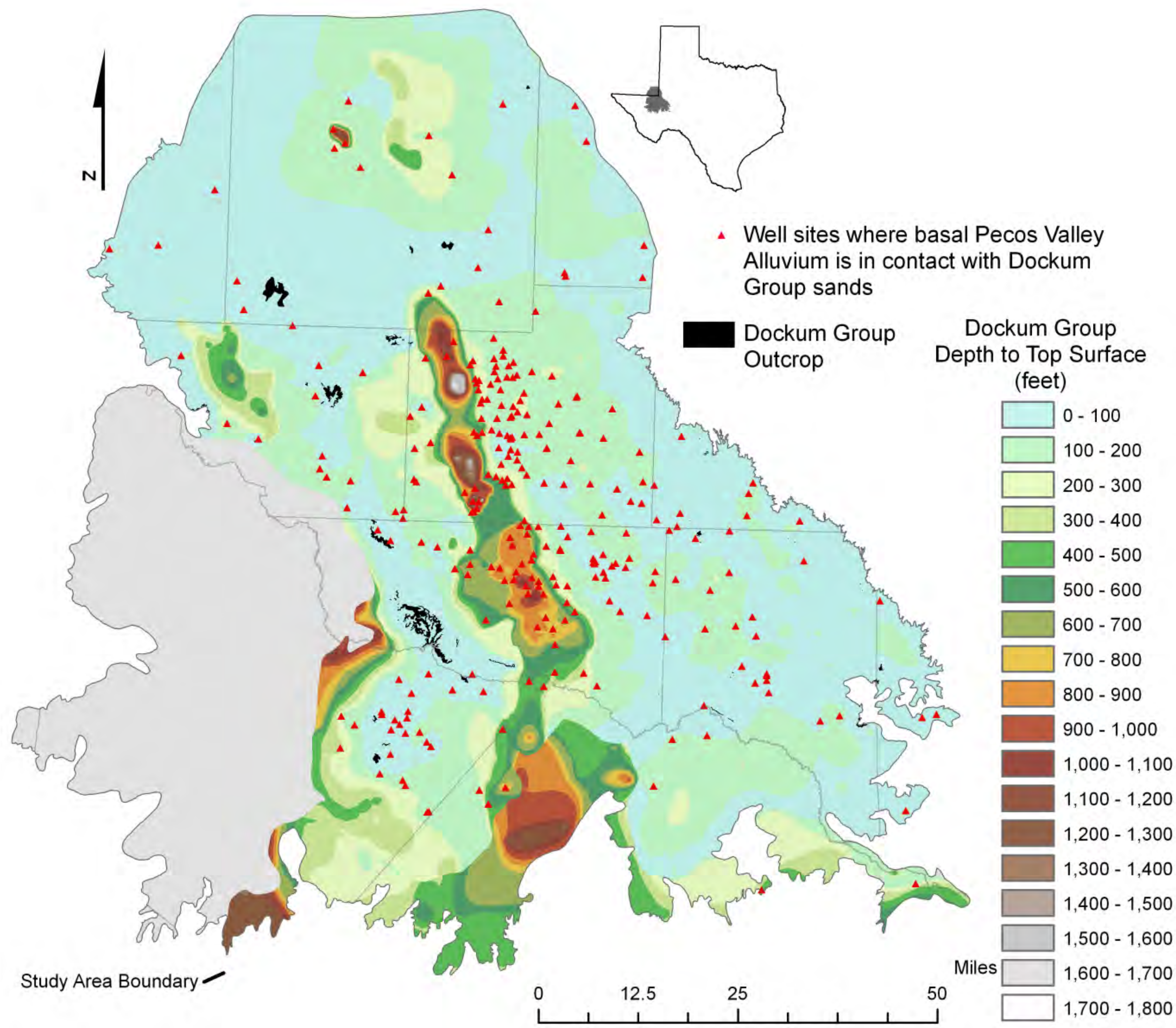

Figure 6-18. **Map showing areas where the basal Pecos Valley Alluvium lies directly over the Dockum Group. The two aquifers are interconnected at these locations. The Dockum Group is missing in the western project area, represented by gray color.**

In the Coyanosa area of northwestern Pecos County, Cretaceous Undivided strata appear to have collapsed into a solution feature (Figures 6-9 and 6-13). The edge of Cretaceous sediments could be bounded by faults in this area, although more work needs to be done to define the relationships.

Cretaceous strata that collapsed into the solution features probably fractured, thereby increasing the transmissivity of the sediments. An examination of the top surface of the Rustler Formation in areas with overlying Cretaceous strata shows areas and magnitudes of collapse (Figure 6-14).

Armstrong and McMillion (1961a) mapped the Pecos Valley and Edwards Trinity (Plateau) aquifers as the Pecos aquifer in Pecos County. They indicate that the individual formations are hydraulically connected in the county.

Rustler hydrostratigraphic unit structural top

An examination of the top surface of the Rustler Formation reveals several prominent features: an east-sloping surface from the Rustler Formation outcrop in Culberson and Eddy counties eastward into the Pecos Trough; a prominent structurally-elevated ridge essentially north-south between the Pecos and Monument Draw troughs; the Monument Draw Trough trending north-northwest; and an eastward sloping surface on the east side of the project area dipping into the Midland Basin (Figure 6-14).

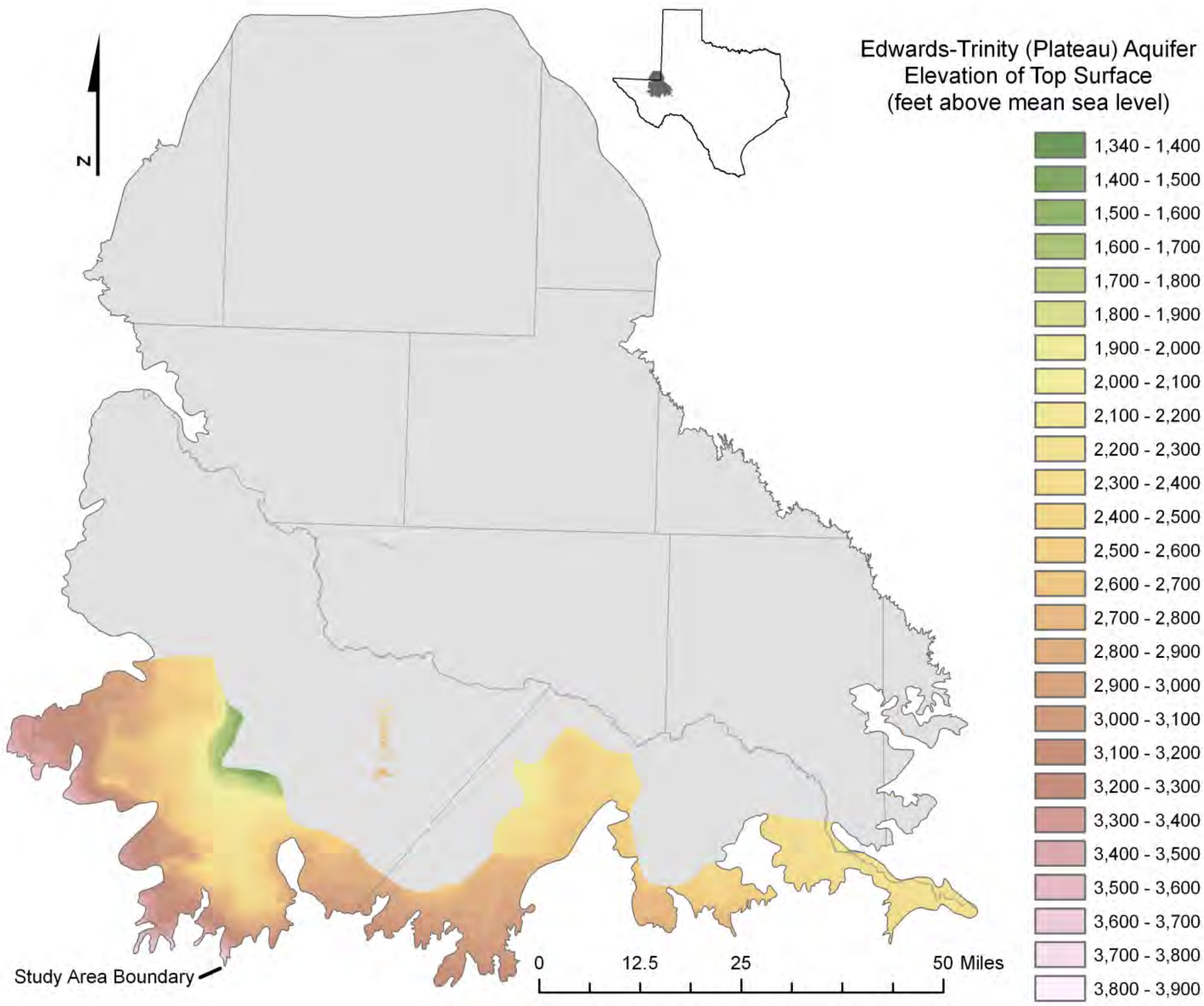

Figure 6-19. Top surface elevation of the Edwards-Trinity (Plateau) Aquifer.

The Pecos Trough is most prominent in Reeves County where the top surface is more than 2,100 feet below ground surface and there is a near-vertical fault margin with over 1,000 feet of displacement along the northeastern edge. The Pecos Trough has a slight topographic expression in the form of a low, broad depression (Figures 6-11 and 6-12). In Reeves County, the trough is a broad collapse structure with an abrupt termination against Permian evaporites in the northeastern part of the county. Dean and Anderson (1982) characterize the Permian evaporite section as having breccia beds (known as blanket solution breccias) in place of halite within the Castile and Salado formations in this area.

The structurally-elevated ridge separating the Pecos and Monument Draw troughs is underlain by the thickest sections of evaporites of the Salado and Castile formations (Figures 6-11 and 6-12) (Dean and Anderson 1982; Maley and Huffington, 1953). The ridge is capped by a thin veneer of Pecos Valley Alluvium underlain by Triassic Dockum Group sediments. This suggests that the Dockum Group sediments played a role in protecting the underlying evaporites from solution. The ridge also restricts groundwater flow between the two solution troughs within the Rustler, Dockum Group, and Pecos Valley aquifers (Ashworth, 1990; Jones and others, 2011).

The Monument Draw Trough consists of a series of coalesced collapse features with the top of the Rustler Formation occurring more than 2,500 feet deep in northwest Winkler County. Cross-section B-B’ along the deepest axis of the Monument Draw Trough (Figure 6-9) shows that the lower portion of the trough consists of separate basins of various geometries. The Monument Draw Trough overlies the western and central extent of the Permian Capitan Reef Complex along the western margin of the Central Basin Platform (Hiss, 1976; Figure 3-3). Several authors have suggested that the Capitan Reef Complex influenced development of the solution collapse (Hiss, 1976; Maley and Huffington, 1953).

Some of the solution collapse features along the Monument Draw Trough are very limited in areal extent, with the deepest part of the collapse represented by only one well (for example, BRACS Well IDs: 2594 and 2612). These features may represent breccias pipes that appear similar in size to features studied in New Mexico (Snyder and Gard, 1982) and to modern features in Winkler County (Baumgardner and others, 1982; Paine and others, 2009). Other features have the appearance of coalesced individual breccia pipes amongst a number of wells in the area, each showing differences of several hundred feet of displacement to the top of the Rustler Formation. Evaluation of the Pecos Valley Alluvium in some of these wells suggests a complex pattern of collapse, timing, deposition, and, in some cases, erosion.

Approximate solution trough boundaries are shown in Figure 6-14. Jones and others (2011) referred to the solution troughs as grabens. We continue to use the term solution trough where the trough boundary is characterized by downwarping of overlying formations in some places and clearly faulted in other areas. A system of concentric ring faults analogous to modern collapse features in the Wink Sink region (Paine and others, 2009) likely surround small diameter, deep, individual breccia pipes and areas where several breccias pipes have coalesced into a larger structure. The nature of the trough boundary is important with respect to fracturing or faulting of overlying, lithified formations and juxtaposition of one formation against another.

Several authors have prepared contour maps for the top of the Rustler Formation for part or all of the project area (Garza and Wesselman, 1959; Hiss, 1976; Johnson, 1993; Jones and others, 2011; Maley and Huffington, 1953; Ogilbee and Wesselman, 1962a; White, 1971). We reviewed these maps but could not use them for stratigraphic picks because the majority of well logs used by those authors could not be obtained for our project. The exception was the project conducted by Jones and others (2011) for which we exchanged data sets for the top surface.

The solution troughs have been referred to by different names in other earlier studies. For example, the Pecos Trough was called as the Balmorhea-Pecos-Loving Trough (Hiss, 1976) and the Toyah Basin (LaFave, 1987) and the Monument Draw Trough as the Belding-San Simon Trough (Hiss, 1976) or the Belding-Coyanosa Trough (Boghici, 1997).

Solution collapse of Permian evaporites has affected the Ogallala Formation in the Texas Panhandle which may be temporally correlative with part of the Pecos Valley Alluvium sediments. Similar styles of solution collapse, spatial relationships of overlying formations, and timing of collapse and sediment input have been documented in this region (Gustavson and others, 1980; Paine, 1995). Shallow geophysical techniques addressing the present solute input to surface water are addressed in Paine and others (1994) and those techniques could be applied to the project area in future studies.

Jones and others (2011) present a comprehensive analysis of the Rustler Formation and its behavior as an aquifer. We added additional well control from their project to the BRACS database, but this was obtained after we had generated our GIS datasets.

Structural cross-sections

We constructed six geologic cross-sections to illustrate the geologic structure and stratigraphic relationships of the Pecos Valley Aquifer and underlying formations in the study area. Cross-section locations are shown in Figure 6-7 and the cross-sections are presented in Figure 6-8 through Figure 6-13. The cross-section lines were positioned to highlight salient features of the Pecos Valley Aquifer and the underlying formations across the study area.

ViewLog, a software package from EarthFX Incorporated, was used to generate the cross-sections. Raster files of stratigraphic surfaces created in GIS were imported into ViewLog to produce the cross-sections. A vertical exaggeration of 20 was applied to all cross-sections to aid in the visual interpretation of each image.

6.2 Aquifer determination analysis

A detailed analysis of each well site, well depth (depth screen top/bottom), and aquifer surface (depth of top/bottom) is necessary to determine which aquifer(s) are being utilized by a well in the project area. 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. Because of the complex stratigraphy and solution trough structures present in the Pecos Valley Aquifer, aquifer codes have been applied inconsistently. In order to create a uniform data set and to be able to compare water quality, static water level, and aquifer test within an individual aquifer or across a group of aquifers, we analyzed the data and compiled it into a table in MS Access. We used GIS data analysis and database queries utilizing many different tables of information for this purpose.

Each aquifer in the project area (the Pecos Valley, Edwards-Trinity Plateau, Dockum, Rustler, and Capitan Reef Complex aquifers) was included in the analysis. The top and bottom surfaces representing the Capitan Reef complex was obtained from the geodatabase created by Standen and others (2009). We received information for the bottom of the Rustler Formation from Jones and others (2011) after the initial aquifer determination was run. For the initial analysis, data for Rustler Formation wells was updated manually. The first step was to extract all TWDB groundwater wells and BRACS project wells that are contained within the project area into one table. There are 5,312 wells in this table: 2,672 with a state well number; 3,132 with a BRACS well number; and 492 of these have both numbers.

The next step was to extract the depth-to-surface value of each formation (for example, Pecos Valley Alluvium bottom depth) at each well site using the ArcGIS® spatial analyst, extraction, extract value to point and then updating the data table in MS Access. The next step was to create a region map (Figure 6-1; Table 6-1) in ArcGIS® showing areas with different stratigraphic relationships. A region code was then assigned to each well record. The combination of spatial intersection of a well screen top, well screen bottom, well depth, or total depth of hole with the top and bottom surfaces of the formation was made for each well site. The intersection precedence was, if present, well screen, well depth, and total depth of hole. Well screens that straddled more than one aquifer had each aquifer assigned to it. If well screen information was not available, the well depth or total depth of the hole was used. In these cases, all aquifers were selected based on the depth and formation top/bottom depths.

Queries were written in Structured Query Language (SQL) and the analysis was organized in Visual Basic for Applications (VBA) in MS Access. All of the wells were processed in one step. Results were checked for consistency and accuracy with the raw data and the queries and the VBA code was corrected accordingly. The selection process recorded the aquifer(s) for each well, the SQL code sequence used for the selection (for quality control) and the aquifer decision with each well record. We did not select aquifers for the oil and gas wells.

We developed a database data entry form to allow staff to review all well information and the automated aquifer selection results. Information for all water wells in which a selection was not made by the software was verified manually. Staff has the ability to overwrite the computer analysis and assign an aquifer decision of "Geologist, best professional judgment". This would, for example, occur if a well had multiple screens – the software only uses the shallowest top screen depth and the deepest bottom screen depth. Thus, all wells with multiple screens were checked manually.

The well information stored in the MS Access database was extracted and geo-referenced in ArcGIS® to spatially display the information. This step was used to verify the SQL logic and to identify and correct errors. The patterns of aquifer usage across the project area can thus be evaluated, although care needs to be exercised when using wells whose aquifer(s) were assigned only on the basis of well depth or total depth of hole.

Wells with aquifer test information were assessed using the aquifer determination results and then compared with the source of the data in published reports. In several cases, the aquifer assigned to a well in the published report was different from the aquifer determination result. After re-examining the water well report lithology, well screen, and formation surface data sets, we concluded that errors in past reports have persisted in more recent studies.

While the analysis tool was written specifically for this project area, the methodology can be applied anywhere in the state. However, each data set and the series of custom queries must be developed for each specific project area.

6.3 Water levels, saturated thickness

We developed a static water level grid map from water wells completed in the Pecos Valley Aquifer. The map was created for the purpose of generating the Pecos Valley Aquifer saturated thickness map and to estimate brackish water volumes (Section 6.5.3).

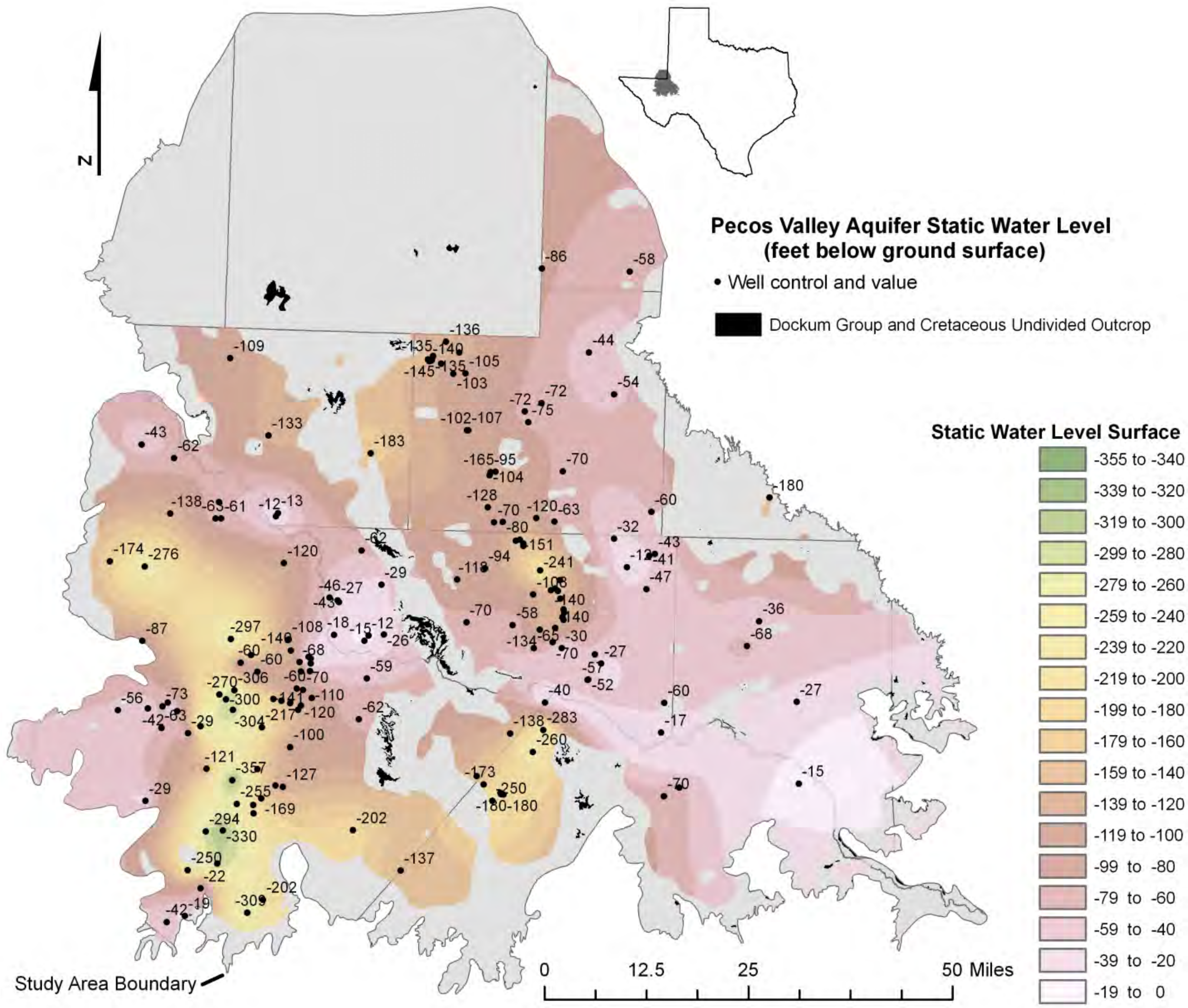

Figure 6-20. **Pecos Valley Aquifer static water level surface and well control. New Mexico was not processed. Gray areas in Texas represent unsaturated Pecos Valley Alluvium. This map was created for the generation of brackish water volume calculations. Static water level measurements compiled from records in 2000 through 2009.**

A significant challenge in creating the static water level map was the spatial distribution and small number of well records. A typical static water level map is created using data from one winter season, producing a water level surface that reflects a minimum influence from seasonal irrigation pumping. While the database contains 15,130 water level records from 2,108 wells, winter-season water levels from wells completed in the Pecos Valley Aquifer are typically less than 80 measurements in any given season during the last 6 years. The spatial distribution of these wells (clustered in small areas) created significant problems for developing a grid map.

Since the water level surface was going to be used to estimate brackish water volume, we decided to average all water levels within the 2000-2009 time period to create one water level per well. This data set consisted of 332 water wells, with 163 completed in the Pecos Valley

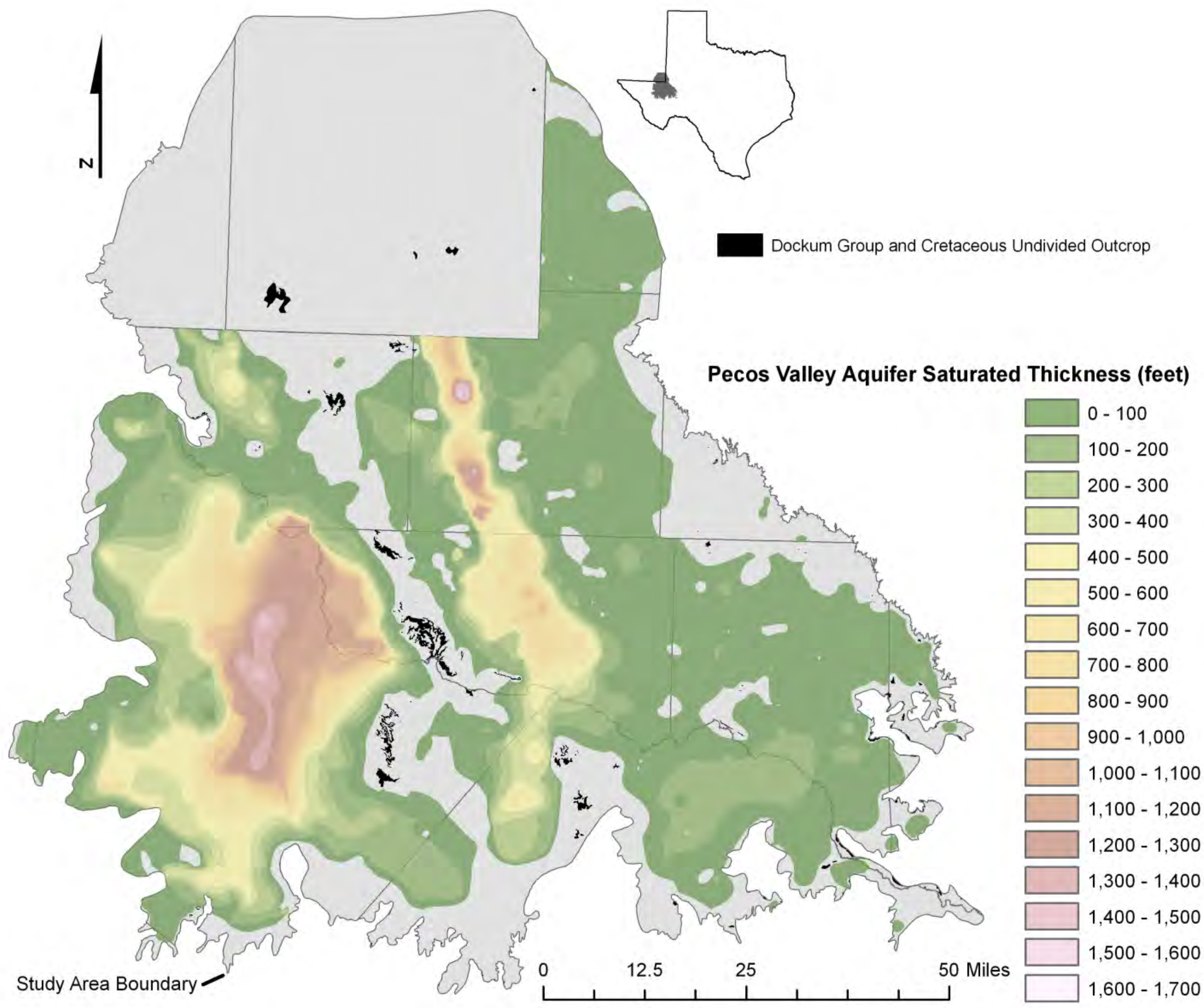

Figure 6-21. **Pecos Valley Aquifer saturated thickness.**

Aquifer with a relatively good spatial distribution. We did not collect and analyze water level data for New Mexico.

The well points were extracted from MS Access and imported into ArcGIS® and georeferenced. The points were interpolated using the ArcGIS® spatial analyst topo to raster tool. The resulting grid map was compared with input points (Figure 6-20). Some counties have few data points, resulting in a rough approximation of the static water table surface. Major pumping centers in central Reeves, northwestern Pecos, north-central Ward, and northwestern Winkler counties are clearly visible on Figure 6-20.

The static water level grid was subtracted from the Pecos Valley thickness map using the ArcGIS® spatial analyst raster calculator tool to produce a saturated thickness grid map (Figure 6-21). The unsaturated regions and all of the New Mexico project area were converted to no-data cells.

6.4 Water quality

A description of water quality in the Pecos Valley Aquifer with an emphasis on parameters that are important to and a concern for desalination is provided below.

6.4.1 Aquifers

The master water quality data and the aquifer determination table were combined into one table and georeferenced in ArcGIS®. Water quality can be spatially displayed for a specific aquifer or combination of aquifers. The ability to discretely select water quality based on an aquifer is an important advancement in the study of brackish aquifers and can be considered an improvement over previous studies such as the report completed by LBG-Guyton (2003). The estimation of brackish water reserves for the Pecos Valley Aquifer depended on the ability to select data using this technique, and is one of the reasons our volumetric estimates are different from those in LBG-Guyton (2003).

6.4.2 Parameters of concern for desalination

If used for potable purposes, brackish groundwater needs to be treated (desalinated). Without treatment, brackish water can cause scaling and corrosion problems in water wells and treatment equipment and cannot be used in many industrial processes. The TCEQ has established a primary standard of 500 mg/L TDS and a secondary standard of 1,000 mg/l TDS for public water supply systems (TCEQ, 2011). Groundwater with TDS concentrations greater than 3,000 mg/l is not usable for irrigation without dilution or desalination and, although considered satisfactory for most poultry and livestock watering, can cause health problems at increasingly higher concentrations (Kalaswad and Arroyo, 2006).

The physical and chemical parameters of concern to desalination facilities using the process of reverse osmosis are listed in Table 6-3. The TWDB Groundwater Database contains sample results in two tables for most of these parameters, however the amount of information available from a well can vary greatly. For example, TWDB does not maintain information on silt density index or turbidity from groundwater samples. If the turbidity or silt density index is high, feedwater pre-treatment is required to avoid plugging membranes in a reverse osmosis treatment system. In Texas, reverse osmosis is the predominant desalination technology.

Table 6-3. Parameters of concern for desalination.

Physical Parameters		**Chemical**	**Parameters**	
	Cations		**Anions**	**Other**
Conductivity	Al^{+3}	K^{+}	Cl^{-}	Alkalinity
pH	As^{+3}	Mg^{+2}	CO_3^{-2}	Boron
Silt Density Index	As^{+5}	Mn^{+2}	F^{-}	Dissolved Oxygen
Temperature	Ba^{+2}	Na^{+}	HCO_3^{-}	H_2S
Turbidity	Ca^{+2}	NH_4^{+}	NO_2^{-}	Hardness
	Cu^{+2}	Ni^{+2}	NO_3^{-}	Pesticides
	Fe^{+2}	Sr^{+2}	OH^{-}	Radionuclides
	Fe^{+3}	Zn^{+2}	SO_4^{-2}	Silica
				TDS

Groundwater quality can vary greatly in an aquifer due to factors such as mineral composition of aquifer materials; recharge rates, spatial distribution, chemical composition of recharge waters, and historical changes with time; geochemical processes; natural and man-made discharge rates and spatial distribution; residence time; and groundwater flow velocity. A review of published literature and comparison with GIS mapping of chemical parameters shows that groundwater geochemistry in the Pecos Valley Aquifer is extremely complex.

Mapping groundwater quality data also depends on the number and spatial distribution of samples, types of samples collected, and dates when samples were collected. We present a series of maps for the Pecos Valley Aquifer showing some of the parameters of concern. The lack of significant numbers of samples in any one recent sampling year meant that we had to extract data from a multi-year period. The most recent sample for a well since 1960 was queried from the database to create the maps. While these maps display the spatial distribution of chemical parameters, they do not necessarily show the current water quality conditions. Users interested in a specific region are encouraged to use the available database, GIS datasets, and GIS software to construct site-specific maps using criteria to meet project needs.

TDS is a measure of the mineral content in groundwater and is an important parameter in designing a reverse osmosis plant. Figure 6-22 shows the spatial distribution of TDS in 527 samples in the study area. The TDS content ranged from 116 to almost 15,000 mg/L TDS, and three wells showed concentrations of 49,295mg/L (probable oil field contamination from produced salt water), 71,118 mg/L (probable contamination from brine mining of Salado Formation halite), and 223,000 mg/L (well adjacent to Ozark Lake in Ward County where groundwater containing sodium sulfate was pumped to the surface and allowed to evaporate (White, 1971). Wells sampled prior to 1960 indicate additional elevated TDS likely associated with oil field contamination (Garza and Wesselman, 1959).

Silica is an important desalination parameter because at elevated concentrations it can foul reverse osmosis membranes. The term silica is widely used to refer to dissolved silicon in natural water but the actual form is hydrated and should be represented as H_4SiO_4 (Hem, 1985). The SiO_4^{4-} tetrahedron is the building block of most igneous and metamorphic rocks and is present in some form in most soils and groundwater.Figure 6-23 shows the spatial distribution of silica in 478 well samples taken from the Pecos Valley Aquifer. Silica content ranged from 1 to 83 mg/L.

Iron in groundwater can become oxidized and will precipitate when it reaches ground surface. To avoid fouling reverse osmosis membranes, water with elevated levels of iron must be pre-treated. Unfortunately, there were not enough analyses of iron samples in the database to adequately map and characterize the element in the majority of the project area. Nevertheless, 69 wells are mapped in Figure 6-24. The concentration of iron in these samples ranged from 0.01 to 4.5 mg/L.

Radionuclide samples from the TWDB groundwater database include 79 wells in the Pecos Valley Aquifer consisting of 188 sample results. Samples include a mixture of uranium, radium, alpha and beta constituents. The gamma ray log was interpreted for high gamma ray response during the process of determining simplified lithology. Elevated gamma ray readings were detected in 46 samples, some with more than one depth interval affected. In the Pecos Valley Alluvium, 22 wells have high gamma ray response, 32 in the Dockum Group-Dewey Lake Formation, and one in the Cretaceous Undivided. Figure 6-25 shows the well locations in which high gamma ray concentrations were recorded. The presence of radionuclides is important when

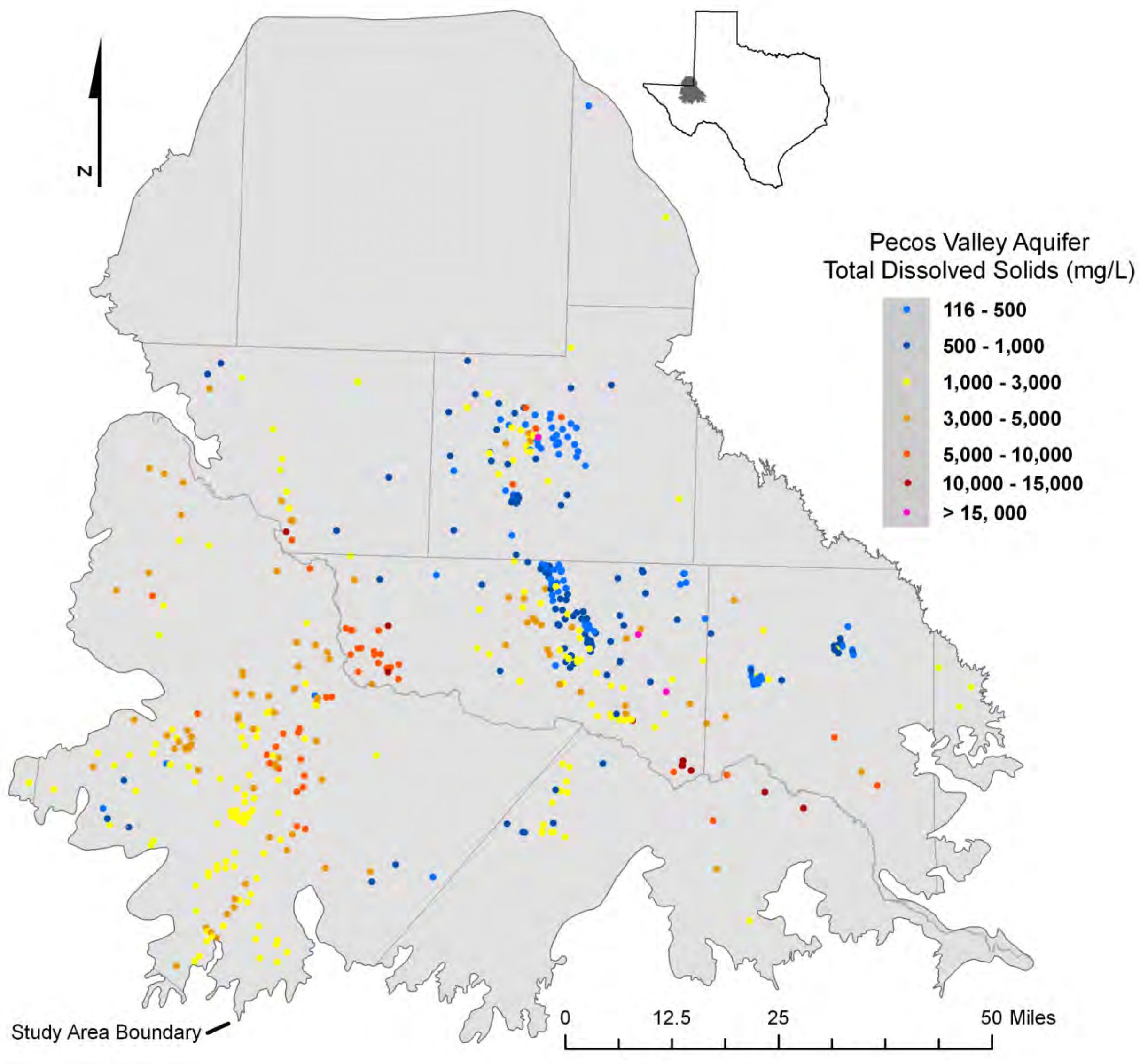

Figure 6-22. TDS concentrations in wells completed in the Pecos Valley Aquifer. Wells are colored based on range of TDS values. The three pink-colored wells exceed 15, 000 mg/L TDS and are probably the result of contamination as explained in the text.

considering disposal of concentrate. Elevated naturally occurring radioactive material (NORM) waste in the concentrate will impact the method of waste disposal and cost.

The source of natural radionuclides was not examined in this study, but McGowen and others (1977) provide a discussion on this subject for the Dockum Group.

Sulfate in groundwater can cause scale and fouling of reverse osmosis membranes and source water may need to be pre-treated. Sulfate concentrations in the Pecos Valley Aquifer range from 2 to 4,208 mg/L with one site in southeastern Ward County recording concentrations as high as 81,700 mg/L. Likely, this site has been impacted by sodium sulfate mining in the area. Figure 6-26 shows the distribution of sulfate samples in the project area.

Chloride concentrations in the Pecos Valley Aquifer range from 3 to 7,280 mg/L with five sites showing elevated chloride concentrations of between 13,000 and 70,000 mg/L. Figure 6-27 shows the distribution of chloride samples in the project area.

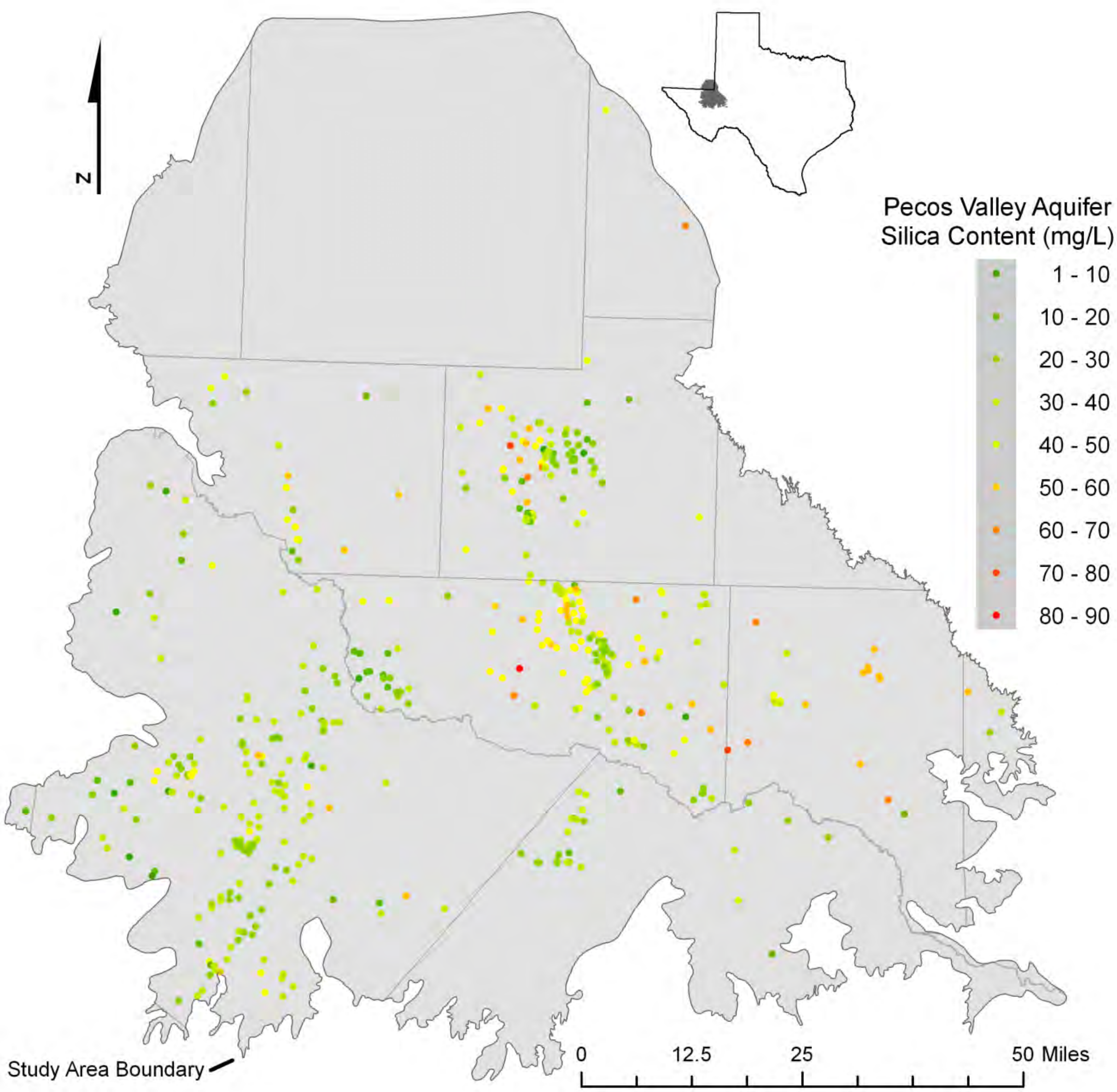

Figure 6-23. **Silica concentrations in wells completed in the Pecos Valley Aquifer.**

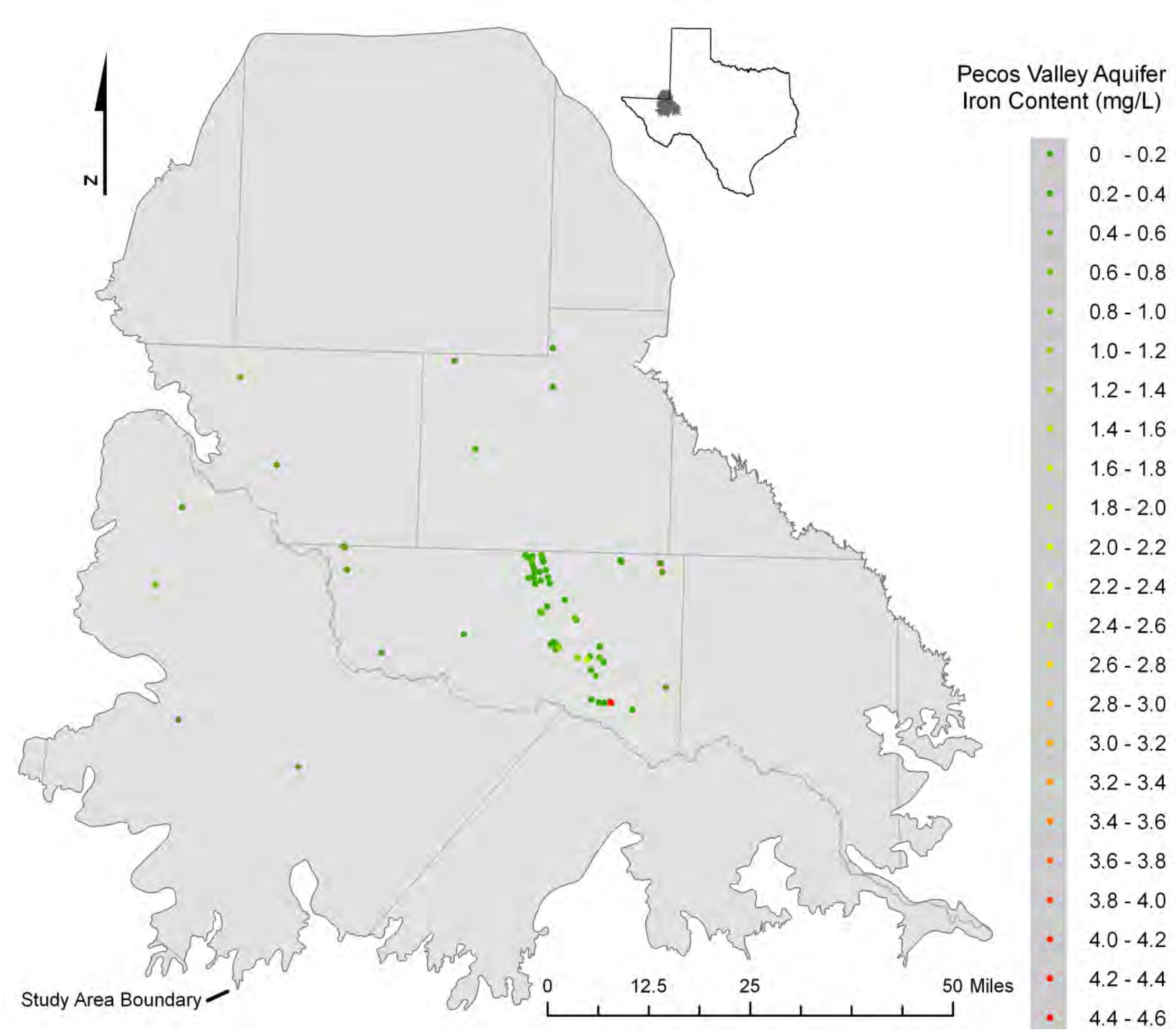

Figure 6-24. Iron concentrations in wells completed in the Pecos Valley Aquifer.

Operators of desalination facilities need to dispose the waste (concentrate) produced from their operations. A Class I underground injection well general permit issued by TCEQ, Underground Injection Control Program can be used for disposal of nonhazardous concentrate from desalination of groundwater and seawater, and for nonhazardous drinking-water treatment residuals. A Class II underground injection well (regulated by the RRC) for oil and gas-related use can also be dual-permitted as a Class I well under the general permit and used for disposal of these wastes. Mace and others (2006) have discussed the use of Class II injection wells to dispose of concentrate in oil fields. Figure 3-1 shows the location of over 4,500 Class II injection wells in the project area.

Class V injection wells can also be used for waste disposal if the fluids are non-hazardous. Owners of injection wells are not permitted to inject a waste if the movement of fluids into an underground source of drinking water contains contaminants that can cause a violation of any primary drinking water regulation or may adversely affect public health (Mace and others, 2006).

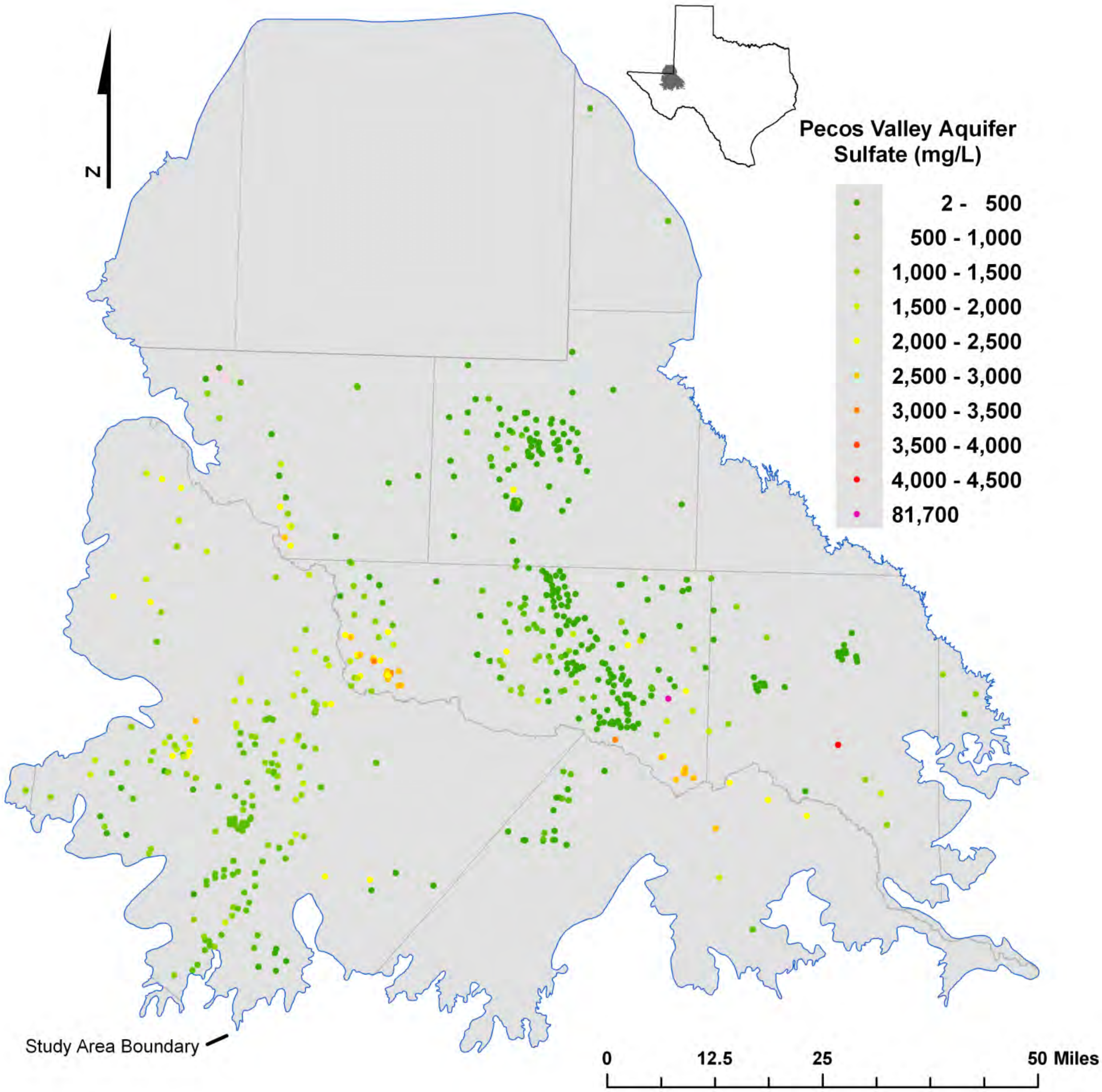

Figure 6-25. Sulfate concentrations in wells completed in the Pecos Valley Aquifer. The one pink-colored well has a value of 81,700 mg/L.

The City of El Paso's, Kay Bailey Hutchison Brackish Groundwater Desalination Plant uses three deep Class V injection wells for concentrate disposal

Most of the desalination facilities in Texas do not treat concentrate prior to disposal. They use one or more methods for concentrate disposal. These methods include discharge to a sanitary sewer or to a surface water body, evaporation, land application, deep well injection, and zero discharge desalination. While most of the desalination facilities in Texas use only one method of disposal, some use more than one (Shirazi and Arroyo, 2011).

A majority of the desalination facilities in Texas discharge their concentrate either to a sanitary sewer or to a surface water body. Thirteen facilities use desalination concentrate for land application, seven use evaporation ponds to treat desalination concentrate, and one uses zero discharge desalination. The City of El Paso uses Class V wells (Shirazi and Arroyo, 2011).

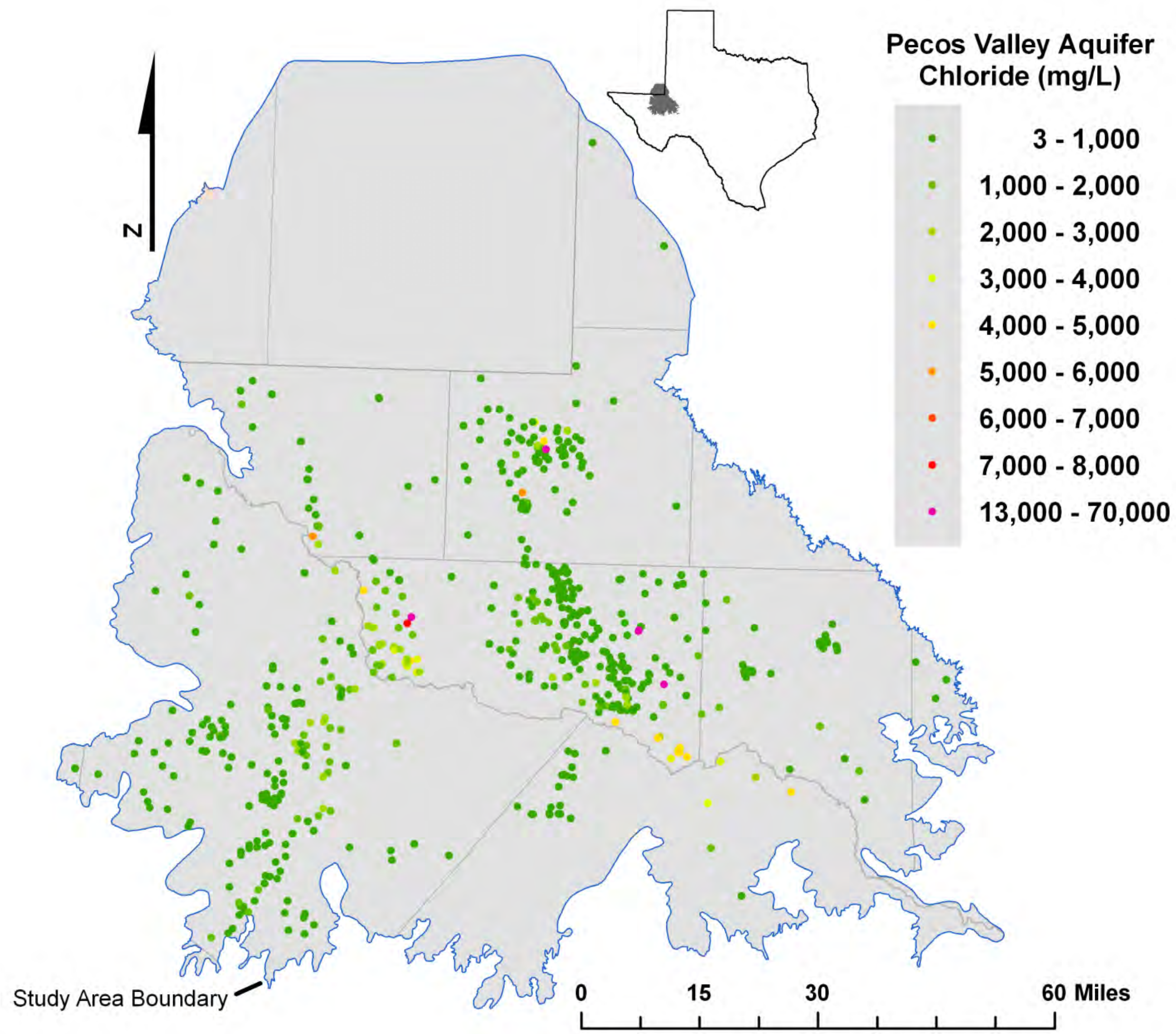

Figure 6-26. Chloride concentrations in wells completed in the Pecos Valley Aquifer. The five pink-colored wells have values ranging from 13,000 to 70,000 mg/L.

6.4.3 Brackish water volume estimates

The TWDB has defined water quality in terms of TDS. Water quality based on TDS has been divided into five categories: fresh (0-999 mg/L); slightly saline (1,000- 2,999 mg/L); moderately saline (3,000- 9,999 g/L); very saline (10,000-35,000 mg/L); and brine (> 35,000 mg/L) (Winslow and Kister, 1956). Brackish water encompasses slightly to moderately saline waters (1,000- 9,999 mg/L).

Brackish groundwater in the Pecos Valley Aquifer was mapped according to TWDB's classification system with the exception that all water with TDS concentrations more than 10,000 mg/L are grouped into one category. This is consistent with the system used by LBG-Guyton (2003). The most recent TDS analysis available for all water wells completed in the Pecos Valley Aquifer was queried from the BRACS database. This resulted in 929 water wells that spanned the years from 1930 to 2008. Since this information was used to estimate brackish water volumes, the most complete data set possible was necessary for analysis. Use of more recent TDS data severely decreased the number of well sites available, leading to additional uncertainty during the interpolation steps.

The TDS concentration data was loaded into ArcGIS® as a point shapefile and georeferenced. The water quality data contains a field with an integer value representing each TDS range listed above. This value was interpolated using the ArcGIS® spatial analyst inverse-distance weighted tool. A number of trials were performed to fine-tune the tool parameters with the input data set. The final grid was processed with the saturated thickness map created for this purpose (see section 6.3) to produce a map showing gridded TDS range values for only the saturated thickness of the Pecos Valley Aquifer (Figure 6-28). The equivalent aquifer in New Mexico was not processed because static water level and water quality data from that area were not obtained for this project.

A separate saturated thickness grid file was created for each range of TDS concentration. Data outside of the TDS range were converted to no-data cells. Volumes were calculated using the ArcGIS® spatial analyst/surface analysis/cut/fill tool. The data table from each cut/fill grid file was imported into MS Excel and the volume field of each individual record was summed and converted into acre-feet.

The storage term for unconfined aquifers is known as specific yield. It measures the volume of water that is released as drainage under gravity from aquifer storage per unit volume of aquifer sediments per unit decline in water level. Not all water in the saturated zone can be removed by drainage or pumping. Retained water is that portion which adheres to the aquifer matrix by surface tension in the void spaces and is known as specific retention. As reported by Anaya and Jones (2009), specific yield data for the Pecos Valley Aquifer is not available. Accordingly, for their study, they used an average range of 0.02 to 0.27, representative of alluvial sediments (Johnson, 1967). As comparison, LBG-Guyton (2003) used a value of 0.12 for the Pecos Valley Aquifer.

We used a value of 0.12 for specific yield to determine the volume of water. We did not attempt to use different specific yield values in the vertical dimension, although it is reasonable to assume that the value may decrease with depth. Table 6-4 shows the results of the calculations. Our estimates indicate that about 85 million acre-feet of brackish water is contained in the Pecos Valley Aquifer. In their regional analysis of the aquifer, LBG-Guyton (2003; Table 5, p. 144) reported about 116 million acre-feet of brackish water.

Limitations in the amount of available information used to determine volume estimates create a level of uncertainty, hence the use of the term estimates. Some of the limitations of the volume estimates (depth stratification, well density, water quality data, static water level data, and specific yield values) are discussed below. The latter three limitations were previously discussed.

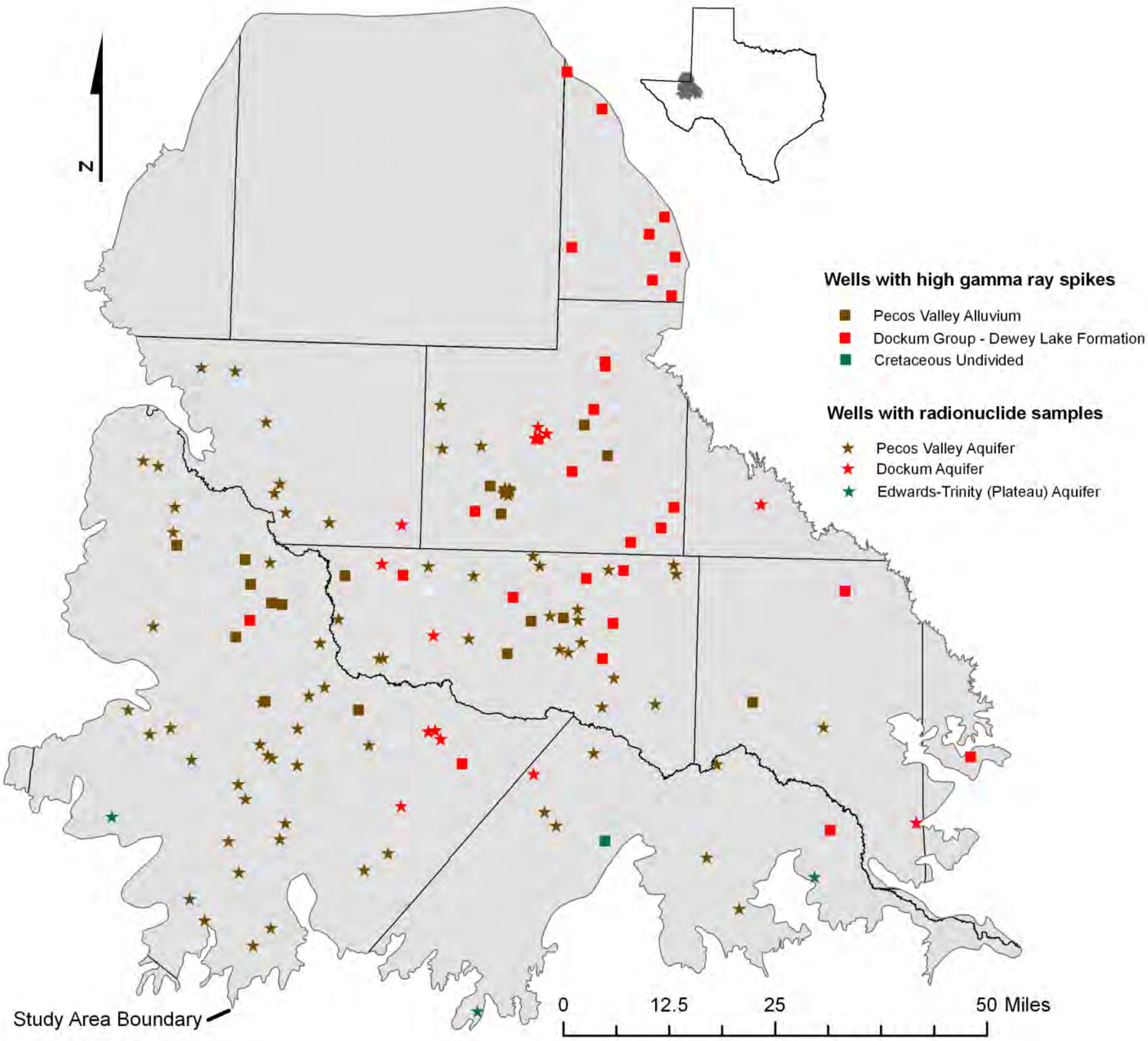

Figure 6-27. **Wells with high gamma ray spikes interpreted from geophysical well logs indicating a possible radionuclide source in the sediments. Wells sampled for radionuclide constituents.**

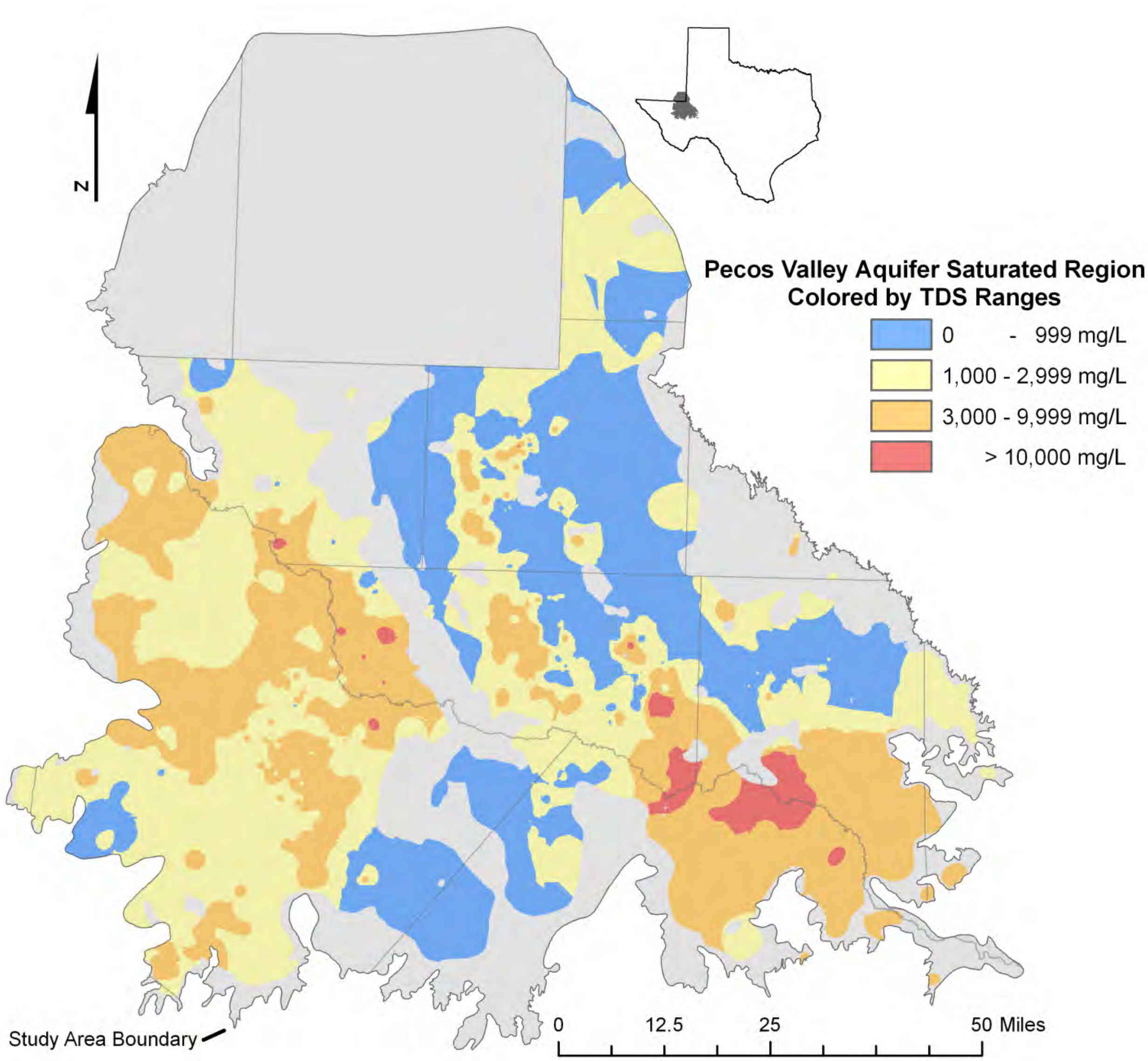

Figure 6-28. **Pecos Valley Aquifer saturated thickness colored according to range of TDS concentrations. This gridded map was created for the generation of brackish water volume calculations using ArcGIS®.**

The volume estimate was derived from a simple 2-dimensional mapping of TDS distribution. No attempt was made to define stratification of waters in the vertical dimension. This is primarily because we lack sufficient depth-based water quality data from water wells. Also, there is an insufficient number of resistivity or SP geophysical well logs in the project area to prepare interpreted TDS concentrations vs. depth profiles. It is also possible that there is no clear or consistent layering of waters of differing salinity in the project area. An indication of this is available in BRACS well 994 in central Reeves County and wells 46-32-206 and 46-40-203 in Ward County (White, 1971). Using the SP log, we estimated an interpreted TDS concentration of 3,275 mg/L at 665 feet below ground surface. At the same location, the TDS progressively increased to an interpreted concentration of 7,400 mg/L at a depth of 1,295 feet below ground surface. The shallow interpreted TDS concentration is similar to water quality samples from wells of equivalent depths within two miles of well 994.

Another limitation of the volume estimates is a lack of water quality data in several areas of the project area. Lack of sufficient well density and use of the inverse-distance weighted interpolation technique created extrapolations into areas of low well density and, in some cases (Andrews County), processing artifacts.

Table 6-4. Pecos Valley aquifer brackish water volumes.

Water Classification	**Volume Aquifer Matrix (Units: cubic feet)**	**Volume Groundwater (Units: acre-feet)**
Fresh Water (0 – 999 mg/L)	5,345,270,000,000	14,725,000
Brackish Water (1,000 – 2,999 mg/L) (3,000 – 9,999 mg/L) Total: (1,000 – 9,999 mg/L)	 16,784,642,000,000 14,151,901,000,000 30,936,543,000,000	 46,239,000 38,986,000 85,225,000
Very Saline Water (> 10,000 mg/L)	331,737,000,000	914,000
Total Volume Pecos Valley (Saturated Thickness)	36,613,551,000,000	100,864,000

6.4.4 Sources of salinity

Salinity within the Pecos Valley Aquifer is derived from both natural and anthropogenic sources. Ashworth (1990) provides a detailed description of the anthropogenic sources of contamination that have occurred or could occur in the project area.

Natural sources of salinity include the dissolution of Permian evaporites (primarily halite, anhydrite- gypsum) and evaporative concentration of water. Anthropogenic sources include past disposal practices of oil and gas-related salt water; spills and leaks from oil fields; abandoned water, oil, and gas wells; irrigation return-flow; and well pumping allowing recharge from higher salinity water.

Garza and Wesselman (1959) and White (1971) provide a compelling description of oil-field salt water disposal practices and contamination in Winkler and Ward counties, respectively. Salt water produced from oil wells contains TDS ranging from 5,400 to 180,000 mg/L. An area in west-central Winkler County (west of Kermit and north of Wink) shows elevated TDS values that can be attributed to oil field salt water disposal (Figure 6-22). Improper placement of surface casing in oil and gas wells, corroded well casings, improper plugging and abandonment of oil and gas wells, brine injection well operation, and leaking oil field pipelines may also lead to high salinity contamination in the Pecos Valley Aquifer.

Cross-formation flow between the Pecos Valley Aquifer and the underlying Edwards-Trinity Plateau, Dockum, and Rustler aquifers has been proposed in many previous investigations (Ashworth, 1990; Jones, 2004; LaFave, 1987; Ogilbee and others, 1962). Water quality changes with time have also been documented in the literature (Armstrong and McMillion, 1961a; Jones, 2004; TWDB groundwater database).

Irrigation return flow in western Ward County has led to a large increase of TDS concentration, primarily sodium and chloride, from irrigation practices using Pecos River water. Declining water levels in the Pecos Valley Aquifer have, over time, changed the groundwater gradient so that the Pecos River is losing water along its reach between Red Bluff Reservoir and Girvin (Ashworth, 1990; LaFave, 1987; White, 1971).

Sodium sulfate mining in southeastern Ward County at Ozark Lake is reflected in TDS values of over 300,000 mg/L in the surrounding Pecos Valley Aquifer (White, 1971).

7. Resistivity analysis of geophysical well logs

Use of geophysical well logs to interpret TDS concentration is a technique that has been used in Texas for decades to select the depth of surface casing required in oil and gas wells. Before the start of the project, we had planned to use the technique to interpret TDS concentrations in the aquifer. Unfortunately, adequate relevant data for the project area is lacking and we could not use the technique. Thus, the method will have to be tested in other areas of the state where the data is available.

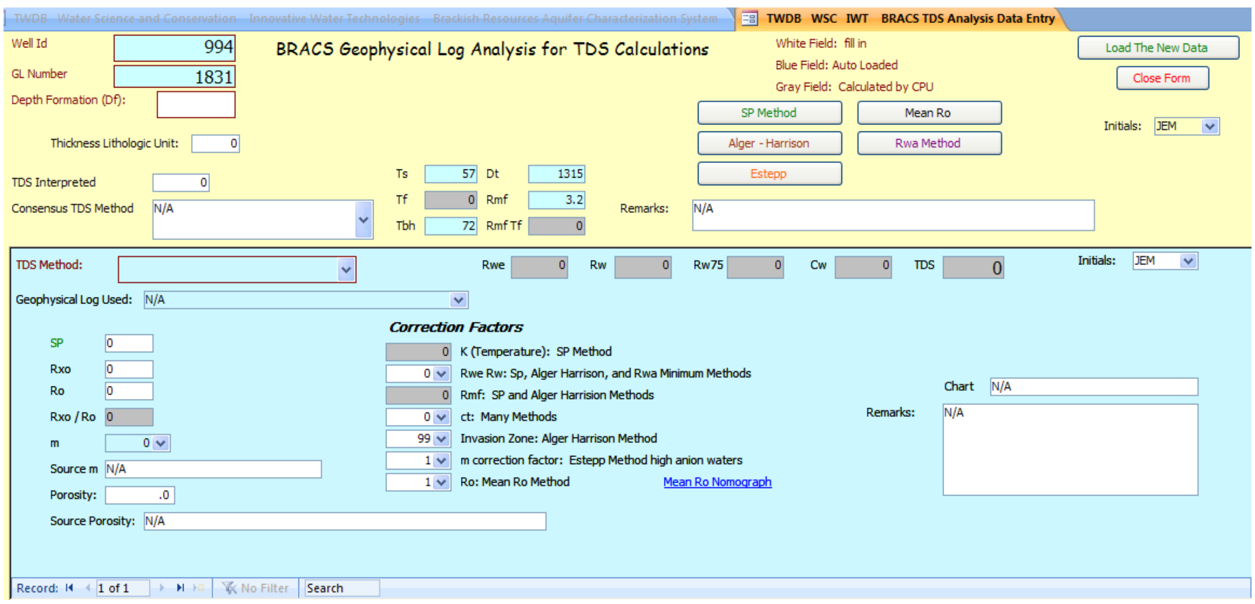

Figure 7-1. **BRACS database primary form for TDS analysis using geophysical well logs. Completed analysis for BRACS well 994 at depth 665 is shown on this screen-shot.**

The interpretation of geophysical well logs began in the oil and gas industry but the application of these tools to water analysis poses significant challenges. Resistivity recorded on geophysical well logs is a combination of the resistivity of the rock formation and the water contained in the pores combined with borehole effects and the resistivity of the mud and mud filtrate. In traditional oil field interpretation, the dominant ions are sodium and chloride. In fresher waters, other cations and anions may dominant the groundwater and the traditional oil field interpretation techniques must be modified (Alger, 1966). The correction factors that must be applied to tool interpretation vary with the techniques used, the aquifer being studied, and the tools used to record resistivity. Estepp (1998, 2010) provides an excellent review and treatment of six different techniques that can be applied. Collier (1993a, 1993b) and Keys (1990) provide discussions on tools and limitations in assessment.

In the early stages of the project we made a decision to automate the mathematical calculations for five of the techniques described by Estepp (1998). Automation reduces the amount of time spent, which can be considerable, and errors that may result from manual calculations. We decided that logs should be evaluated at multiple depth intervals using one or more methods per interval. Each method was reviewed, formulas with consistent terms were written, and tables designed to contain raw, intermediate, and finished computation results (Figures 7-1 and 7-2). Visual Basic for Applications (VBA) code was prepared and tested against the case studies presented by Estepp (2010). The VBA code was written in BRACS database modules and embedded in data entry forms linked to the primary tables. This work will be presented in a future TWDB report once testing for the different methods is completed. The work described in the next section should be considered a prototype of the Spontaneous Potential method.

Each TDS interpretation method is applicable within a specific range of TDS values and requires correction factors (Table 7-1). Table 7-2 summarizes the parameters for each method and can be used to select a method based on the types of geophysical well log tools and header information available.

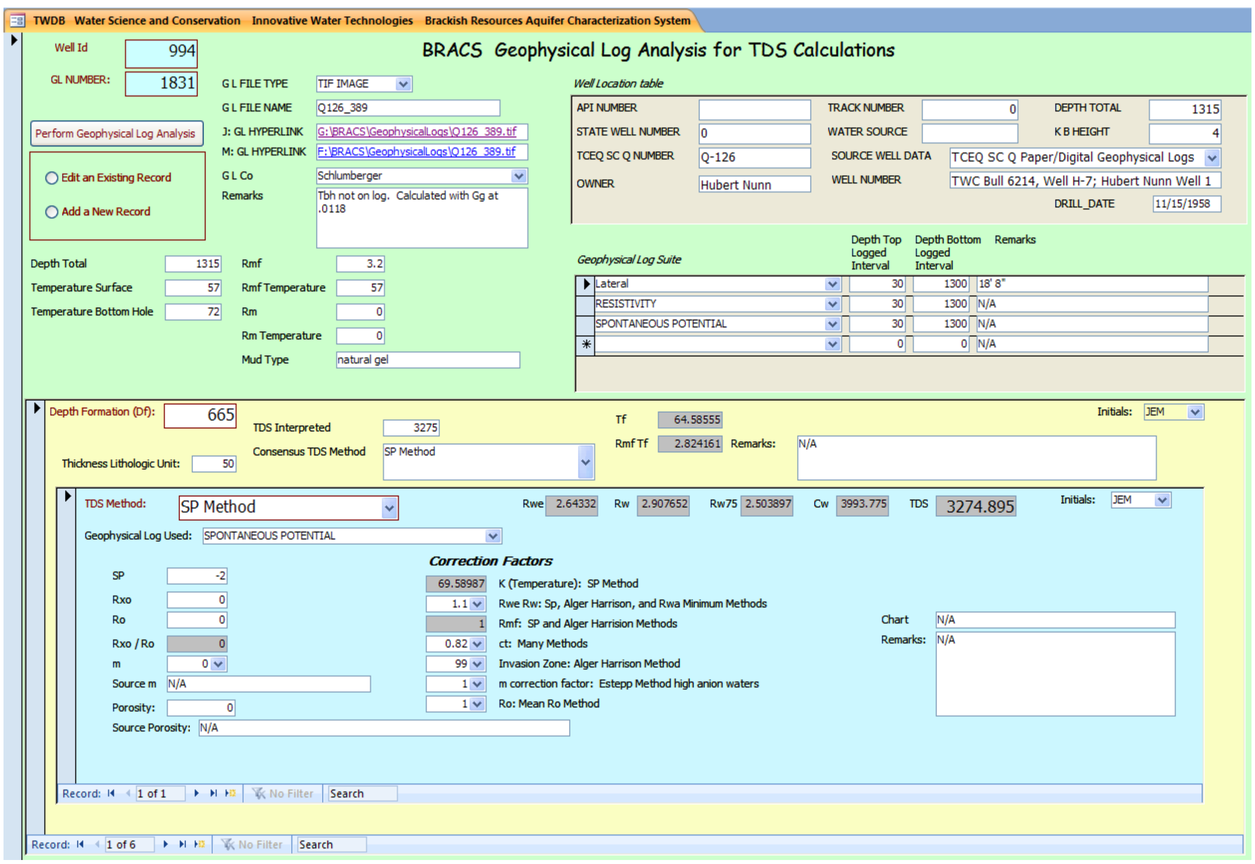

Figure 7-2. **BRACS database secondary data entry form for TDS analysis using geophysical well logs. Beginning of data entry for BRACS Well 994 is shown on this screen-shot.**

Table 7-1. **Working ranges of TDS for five interpretations methods (after Estepp, 2010).**

TDS Method	TDS Range			
	100 – 1,000	1,000 – 3,000	3,000 – 10,000	10,000 – 100,000
SP	freshwater correction required		working range	
Alger-Harrison	freshwater correction required		working range	
Rwa Minimum	freshwater correction required		working range	
Estepp	working range		possible use	not applicable
Mean Ro	working range			

Note: Rwa = apparent formation water resistivity
Ro = deep resistivity

7.1 Interpretive techniques

Only a handful of geophysical well logs in the project area contained SP or resistivity tools within the depth range of the drinking water aquifers. Of these wells, many logs were unsuitable for analysis of Pecos Valley Aquifer water because of the depth range, log quality, adequate input parameters, and tool type. Two example geophysical well logs analyzed for TDS are discussed below. Interpretation of the SP tool worked the best, and a brief discussion of this tool is also presented.

The SP log is a record of the direct current reading between a fixed electrode at the ground surface and a movable electrode in the well bore (SP tool). The tool must be run in an open borehole with a conductive mud. SP is measured in millivolts. The electrochemical factors which create the SP response are based on the differences in salinity between the mud filtrate in the borehole (Rmf) and the formation water resistivity (Rw) within permeable beds (Asquith, 1982). A negative deflection of the SP response occurs when Rmf > Rw and a positive deflection occurs when Rmf < Rw. When Rmf = Rw there is no deflection from the shale baseline. The SP response of shale is relatively constant and is referred to as the shale baseline. The permeable bed boundaries are detected at the point of inflection of SP response. The magnitude of deflection of the SP response is due to the difference in resistivity between Rmf and Rw, not permeability.

SP is most affected by cation species, and oil-field analysis equations assume the formation water is dominated by sodium and chloride. Divalent cations in dilute formation water have a larger impact on SP response than sodium (Alger, 1966). The SP response of high calcium or magnesium waters indicates the water is more saline than an analysis using resistivity tools. Alger (1966) described a method for correcting this effect, however a complete water quality analysis is needed to apply the correction. He indicated that once a well is calibrated, the analysis can be extrapolated from one well to others assuming the water quality remains relatively constant.

The SP response is affected by bed thickness; thin beds do not allow a full SP response and must be corrected (Asquith, 1982; Estepp, 1998; Schlumberger, 1972). If a sand unit is less than 10 feet thick, the response curve tends to be pointed, and requires a thickness correction. SP response is also affected by bed resistivity, borehole invasion of drilling fluid, hydrocarbons, and shale content. Shale content reduces the SP response. SP tools run in freshwater water wells commonly use native mud when, prior to logging, the borehole fluid is essentially formation water. In this situation, the resistivity of formation water and borehole fluid is almost equal and the SP tool cannot be used for TDS interpretation (Keys, 1990).

7.1.1 BRACS well 1376

BRACS well 1376 lateral log was analyzed at 530 feet below ground surface using the 2/3 rule correction technique (Estepp, 1998) and the Alger-Harrison Method. It produced an interpreted TDS concentration of 1,992 mg/L. The SP method when used at the same depth produced an interpreted TDS concentration of 3,150 mg/L. When applied at a depth of 815 feet, the SP method produced an interpreted TDS concentration of 2,603 mg/L. The decrease in TDS with depth could be caused by naturally occurring higher salinity water over lower salinity water, or by an increase in clay content in a sand layer at this depth which creates a lower SP response with a concomitant higher calculated TDS.

Seven water wells located within about a mile of BRACS well-1376 contained TDS at an average concentration of 2,860 mg/L (Table 7-3 and Figure 7-3). The range in percent sodium divided by the sum of cations ranged from 42 to 93 % in wells nearby (Table 7-3). Well screens varied above and slightly below the interpreted depths of 530 and 815 feet sands in BRACS well 1376. TDS also varied with depth, some wells showing higher salinity above lower salinity and vice versa. The contributions of water to, and the mixing relationships within, the well bore among the sampled wells is unknown. The data suggest that water chemistry in the region may be highly variable.

The concentration of TDS estimated by the SP method are well within the upper and lower range recorded in samples collected from wells installed within the same depth zone in this part of Reeves County. The SP was not corrected for cations in this analysis. The concentration of TDS estimated using the Alger-Harrison method using the Lateral tool was below the TDS range. This may be due to the tool idiosyncrasy (described below) or because of the presence of high concentrations of sulfate anions that have a large effect on the resistivity tool response.

Resistivity tools using the lateral log were determined to be inadequate for our study because the tool response needs corrections for asymmetrical curves and anomalous signals created by adjacent bed thickness and resistivity differences (Schlumberger, 1972).

7.1.2 BRACS well 994

BRACS well 994 was assessed at six different depths (Table 7-4). The SP response and interpreted TDS concentrations increased progressively with depth. The well-screen for this well was installed at depths of between 457 and 1,005 feet, but the well itself was logged to a total depth of 1,315 below ground surface. Existing lab analysis of water samples collected from the well show TDS concentration of 3,660 mg/L. The average interpreted TDS for the three depth zones (665 to1,055 feet) was 3,567 mg/L, matching the lab measurement very closely.

The interpreted TDS concentration did not include a cation correction even though the percent sodium concentration divided by the sum of cations was 40 percent for well-994 and ranged from 39 to 48 percent for nearby wells (Table 7-5). Water quality measured in six nearby wells (Table 7-5 and Figure 7-4) averaged 3,759 mg/L, also comparing well with the interpreted TDS in this zone. An examination of Table 7-4 shows an increase in TDS concentration to 7,400 mg/L in the lowest sand encountered during drilling. This suggests that there is stratification of saline

Table 7-2. **Parameters and correction factors required for geophysical well log interpretation of TDS.**

Parameters			TDS Methods				
Name	**Symbol**	**Units**	**SP**	**Alger-Harrison**	**Rwa Minimum**	**Estepp**	**Mean Ro**
Depth Well	Dt	Feet	Yes	Yes	Yes	Yes	Yes
Depth Formation	Df	Feet	Yes	Yes	Yes	Yes	Yes
Temperature Surface	Ts	Degrees Fahrenheit	Yes	Yes			
Temperature Bottom Hole	Tbh	Degrees Fahrenheit	Yes	Yes			
Resistivity Mud Filtrate	Rmf	Ohm-meters	Yes	Yes			
Rmf Temperature	n/a	Degrees Fahrenheit	Yes	Yes			
Spontaneous Potential	SP	+ / - millivolts	Yes				
Deep Resistivity	Ro	Ohm-meters		Yes	Yes	Yes	Yes
Shallow Resistivity	Rxo	Ohm-meters		Yes		Yes	
Porosity		Percent			Yes		Yes
	Correction Factors						
TDS : Specific Conductivity	ct	n/a	Yes	Yes	Yes		
High anions: Rwe to Rw	Rwe Rw	n/a	Yes	Yes	Yes		
Resistivity: Invasion Zone		n/a		Yes			
Cementation Factor	m	n/a			Yes	Yes	
High anions: m correction	m cor	n/a				Yes	
High anions: Mean Ro		n/a					Yes
Mean Ro Nomograph							Yes

water in the Pecos Valley Aquifer in the Pecos Trough. Because most water wells, including all the nearby wells, do not fully penetrate the aquifer (Figure 6-10) in this region, a thorough examination of this phenomenon is not possible without additional well control or SP logs.

Table 7-3. **Water quality samples surrounding BRACS well 1376. Refer to Figure 7-3 for well locations. Asterisk in TDS field indicates an average from multiple samples.**

State Well Number	Well ID	TDS (mg/L)	% Sodium in Summed Cations	Well Screen (ft below ground surface)	Well Depth (ft below ground surface)
4635906	925	2261	93	480 - 910	910
	3116	2540	49	200 - 885	885
	3132	2880	49		400
4635902		3352*	74	200 - 585	585
4635905		2868*	74		850
4635907		2706*	63		839
4636707		3415*	42	295 - 815	871

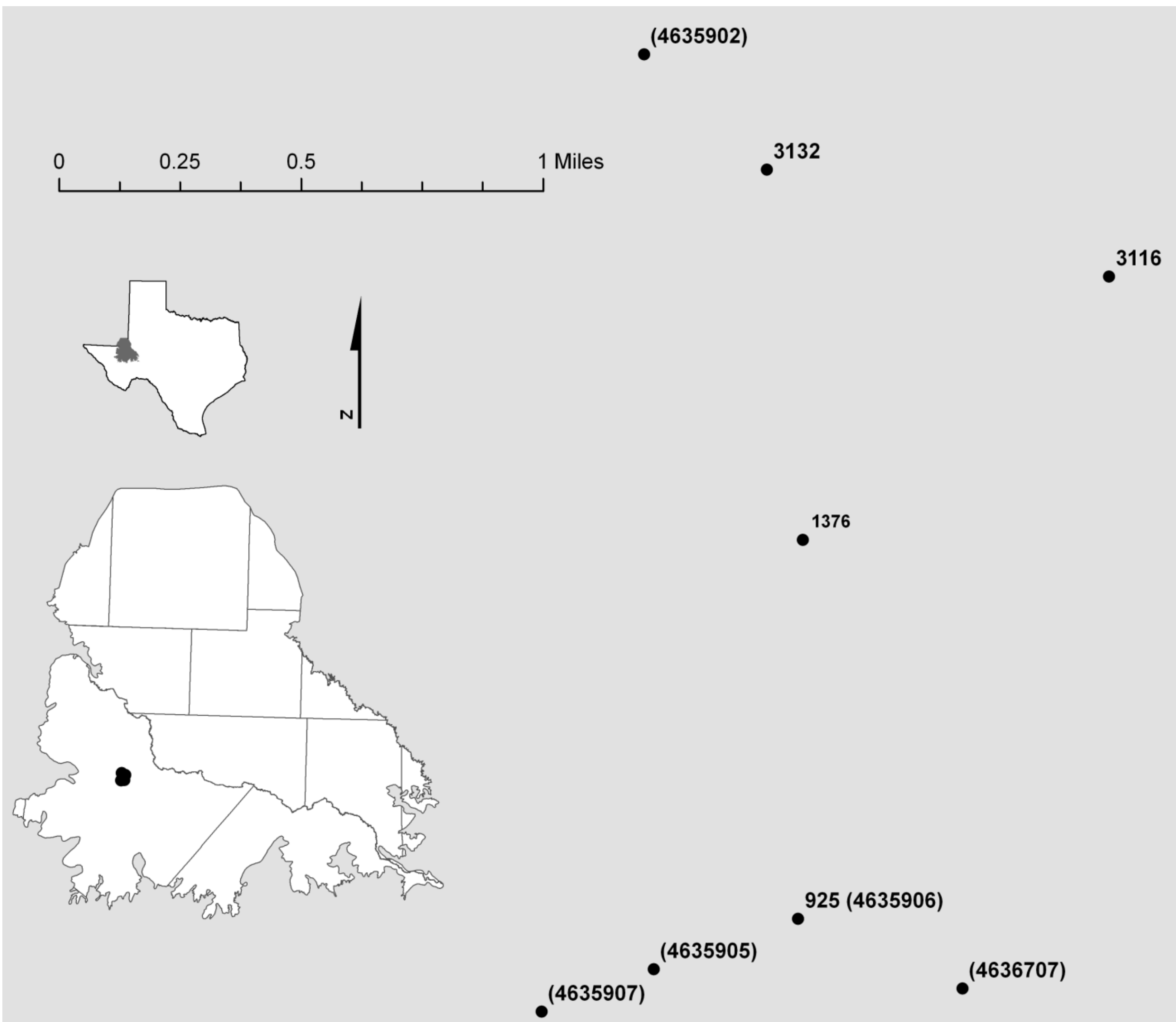

Figure 7-3. **Locations of wells used for interpreted TDS from geophysical well log 1376 and wells with water quality data. Numbers refer to BRACS well id and state well number (in parenthesis). See Table 7-3 for TDS information.**

7.2 Results

The lack of appropriate geophysical well logs at shallow depths within the project area precluded a thorough assessment of the techniques to interpret the TDS content of groundwater. Additional work needs to be done in other areas of Texas to better test the application and understand its limitations. The principal requirement for using this technique is the availability of data and control on the correction factors necessary to interpret the logs.

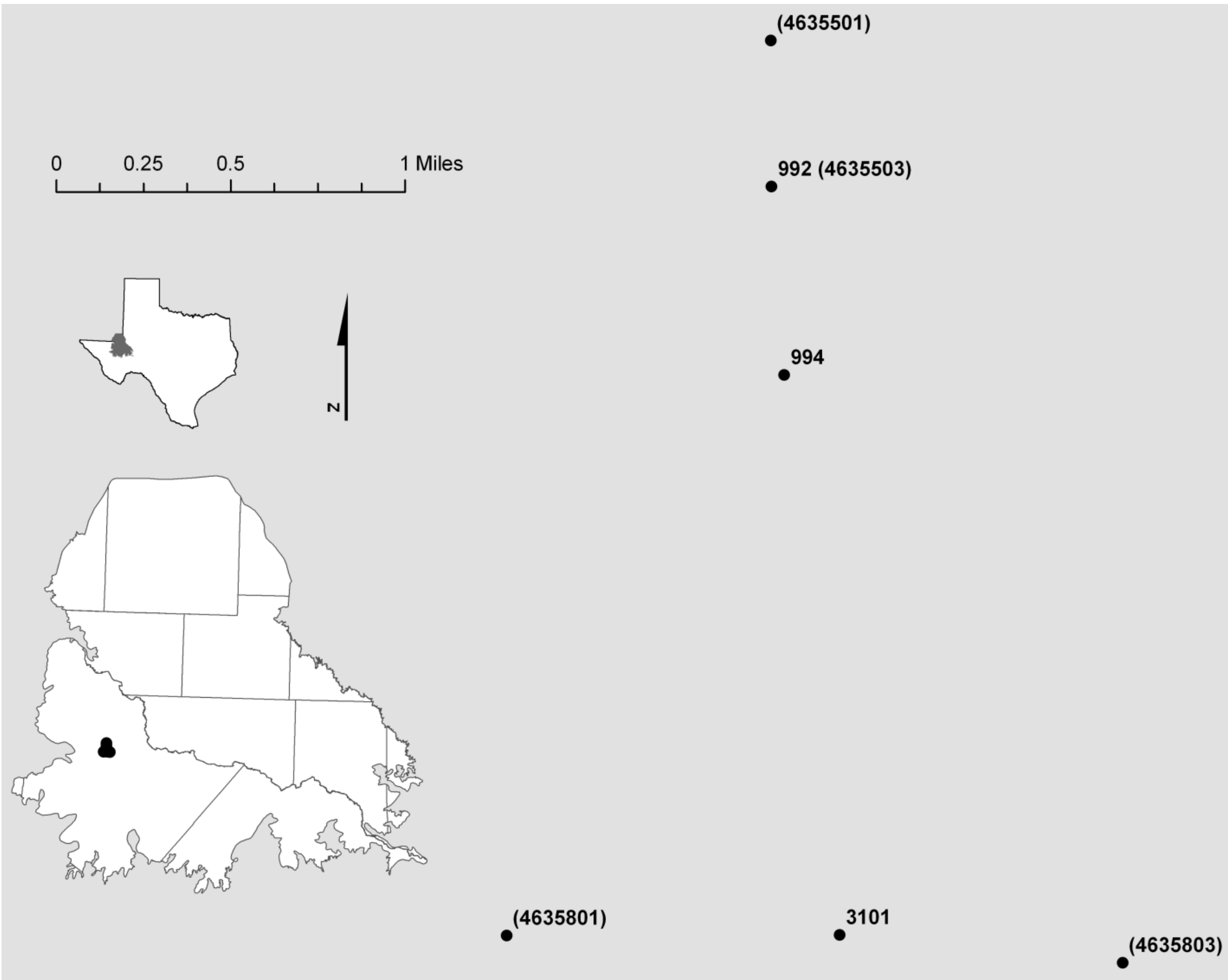

Figure 7-4. Locations of wells used for interpreted TDS from geophysical well log 994 and wells with water quality data. Numbers refer to BRACS well id and state well number (in parenthesis). See Table 7-5 for TDS information.

The interpretation of TDS using the SP tool in the Pecos Valley Aquifer project area appears promising, despite the limited amount of logs available. Additional work will need to be done to incorporate a cation-correction process for this method. Professionals interested in this project area should continue to look for shallow geophysical well logs that may exist in other collections.

Table 7-4. **The SP log from BRACS well 994 located in Reeves County was assessed at six depth intervals for interpreted total dissolved solids (TDS). The well was also screened and sampled for TDS. This table shows the vertical relationships of this assessment.**

<table>
<tr><th>Depth
(feet below ground)</th><th>Interpreted TDS
(mg/L)</th><th>Average TDS
(mg/L)</th><th>Well Screen
(feet below ground)</th><th>Lab TDS
(mg/L)</th></tr>
<tr><td>457</td><td></td><td></td><td rowspan="4">457 – 1,005</td><td rowspan="4">3,660</td></tr>
<tr><td>665</td><td>3,275</td><td rowspan="4">3,567</td></tr>
<tr><td>820</td><td>3,441</td></tr>
<tr><td>1005</td><td></td></tr>
<tr><td>1055</td><td>3,985</td><td></td><td></td></tr>
<tr><td>1145</td><td>4,253</td><td></td><td></td><td></td></tr>
<tr><td>1245</td><td>6,499</td><td></td><td></td><td></td></tr>
<tr><td>1295</td><td>7,400</td><td></td><td></td><td></td></tr>
</table>

Table 7-5. **Water quality samples surrounding BRACS well id 994. Refer to Figure 7-4 for well locations. Asterisk in TDS field indicates an average from multiple samples.**

State Well Number	Well ID	TDS (mg/L)	% Sodium in Summed Cations	Well Screen (ft below ground)	Well Depth (ft below ground)
4635503	992	3941*	45	344 - 1053	1053
	994	3660	40	457 - 1005	1005
	3101	3630	39		800
4635501		3966	48	300 - 865	865
4635801		3638*	40	125 - 780	780
4635803		3718	45		550

8. Database description

The TWDB Groundwater Database which has been in use for over 25 years is in the process of being redesigned to meet future requirements. The redesign project is expected to be completed within a few years. In the initial stages of the BRACS project, we determined that the existing TWDB Groundwater Database was not capable of managing all of the new information and storing the procedures that are needed to analyze the data to meet the project objectives. To meet these objectives and deadlines, staff selected Microsoft (MS) Access 2007 as the BRACS database software with the long-term objective of merging BRACS tables with the future Groundwater Database. MS Access has proved to be excellent software for managing project information and testing new table and analysis designs.

All well information and supporting databases for the Pecos Valley Aquifer project are managed in MS Access. When spatial analysis is required, copies of information are exported into ArcGIS®. Information developed in ArcGIS® is then exported back into MS Access and the tables are updated accordingly. Although this approach may be cumbersome, it takes advantages of the strengths of each software. The project also relied on other software for specific tasks, including Microsoft Excel, Schlumberger Blueview (for geophysical well log analysis), and ViewLog from EarthFX (for developing geologic cross-sections).

For the project, we assembled information from external agencies and updated these databases frequently. All of these databases are maintained in MS Access and GIS files developed for spatial analysis and well selection. Many of the databases were built from scratch or were redesigned to meet project objectives. Data from external agencies or projects was available in many different data designs, so establishing a common design structure proved beneficial in leveraging information compiled by other groups. For example, well location attributes available in the RRC oil and gas well database could be easily copied to the BRACS table. This saved us a tremendous amount of time and helped reduce errors during data entry.

The BRACS and supporting databases are fully relational. Data fields common to multiple data sets 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 MS Access and all code was written at the Microsoft ActiveX Data Objects (ADO) level with full code annotation. The code for geophysical well log resistivity analysis was specifically written with class objects to support a rapid analysis of information with the benefit of only having data appended when the user approved the results.

The BRACS database is documented in a data dictionary which is available from the TWDB Web site (http://www.twdb.state.tx.us/innovativewater/bracs/). The following two sections will briefly describe the BRACS database table relationships and the supporting databases developed to date.

8.1 Table relationships

The BRACS database contains 16 primary tables of information (Table 8-1), 35 lookup tables, nine tables designed for GIS export, and many supporting tables for analysis purposes. A brief description of each of the primary tables is provided in this section. Lookup tables provide control on data entry codes or values for specific data fields (for example, a county lookup table with all 254 county names in Texas). The tables for GIS export are copies of information obtained from one or more tables and in some cases reformatted to meet GIS analysis needs. These tables can be custom tailored to meet project needs and will not be discussed further.

A fully relational database design has information organized into tables based on a common theme. Information must be segregated into separate tables for each one-to-many data relationship. For example, one well may have many well screens with unique top and bottom depth values; each well screen constitutes one record. Tables are linked by key fields. For each one-to-many relationship at least one additional key field is required. The field well_id is the primary key field for every table in the BRACS database.

8.1.1 Well Locations

The table tblWell_Location contains one record for each well record in the BRACS database and is assigned a unique well_id as the key field. The well_id field links all the tables together. This table contains information such as well owner, well depth(s), location attributes (such as latitude, longitude, and elevation), source of well information, county name, and date drilled.

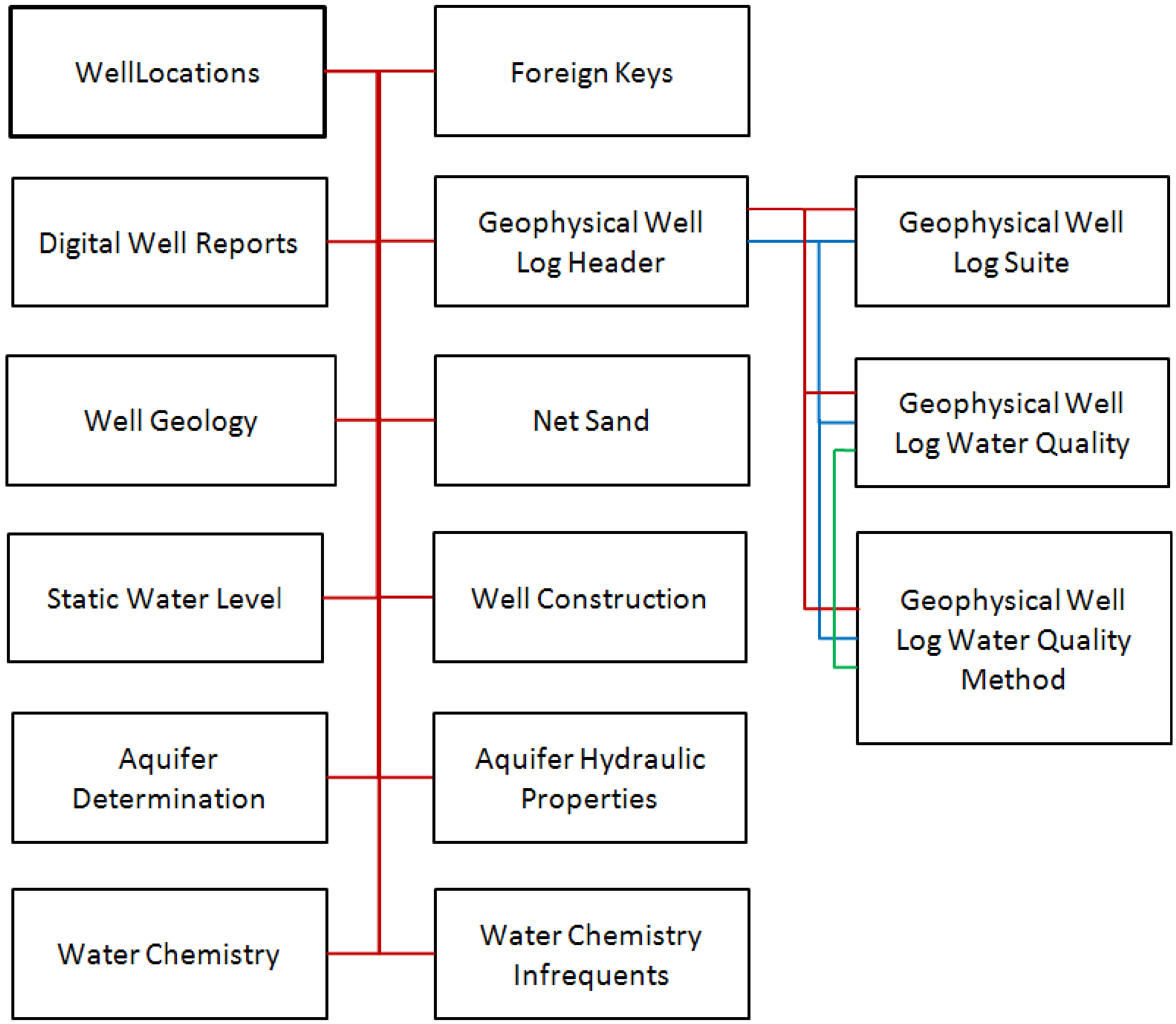

Figure 8-1. BRACS database table relationships. Each rectangle represents a primary data table. The lines connecting the tables represent key fields: red represents the primary key well_id; blue represents the second key; green represents the third key. New well records must be appended to the well locations table to set the unique well_id.

8.1.2 Foreign Keys

The table tblBracs_ForeignKey contains zero to many unique well identification names or numbers assigned to it (for example, state well number, and API number). These identifiers, also known as foreign keys, permit database linkage to the supporting databases developed from external agencies and other TWDB project databases with geophysical well logs and stratigraphic pick information.

8.1.3 Digital Well Reports

The table tblBracsWaterWellReports contains zero to many records for digital copies of water-well reports and miscellaneous records including oil and gas well scout tickets. The purpose of this table is to track the digital file names, file types, and hyperlinks to the documents.

8.1.4 Geophysical Well Logs

Information on the digital geophysical well logs is recorded in the table tblGeophysicalLog_Header. This includes the type of digital file, digital file name, data hyperlink to the log image, and well log parameters such as depth, temperature of the bottom hole, and resistivity of the mud filtrate. The well log parameters were only recorded if the well log was to be used for resistivity analysis for TDS.

Each geophysical well log may have one or more tools used to record subsurface parameters. This information is recorded in the table tblGeophysicalLog_Suite. Each tool name and its start and bottom depth values in feet below ground surface were recorded in this table.

The results from resistivity analysis for TDS are recorded in two tables. Evaluation of more than one depth interval per well necessitated designing one table, tblGeophysicalLog_WQ, to hold the depth of formation, temperature, and resistivity of the mud filtrate values for that interval. Evaluation of more than one resistivity technique per depth interval dictated designing one table, tblGeophysicalLog_WQ_Method, to hold the analysis results including interpreted TDS, log correction values, method used, geophysical well log used, and a multitude of intermediate values.

8.1.5 Well Geology

The descriptions of rock types reported on a drillers' well logs, simplified lithologic descriptions, stratigraphic picks, and hydrogeologic names are all contained in the table tblWell_Geology. Each record contains a top and bottom depth, thickness of the unit, top and bottom elevations, source of data, and a value for type of geologic pick (for example, lithologic, stratigraphic, or hydrogeologic). The latter field permits the storage of all this information in one table and the ability to view the information in one form.

The analysis of net sand, maximum sand thickness, and sand percent for each well record is contained in the table tblWell_Geology_NetSand. The table is custom-designed for this project because the analysis is for the Pecos Valley Alluvium and Dockum Group.

8.1.6 Well construction

Well casing and screen information is contained in the table tblBracs_Casing. This table design is similar to the well-casing table in the TWDB Groundwater Database and contains top and bottom depths for casing and screen.

8.1.7 Water Quality

Two tables contain the results of water quality analyses recorded for wells that are not in the TWDB Groundwater Database: tblBracsWaterQuality and tblBracsInfrequentConstituents. The table designs are similar to those in the TWDB Groundwater Database. The analogous table designs will be helpful when the BRACS and TWDB Groundwater databases are merged in the future.

All water quality records for wells in the project area were appended to the table tblBRACS_PV_MasterWaterQuality. These include records obtained from the TWDB Groundwater Database and records obtained from research for wells in the BRACS database.

8.1.8 Static Water Level

Static water level information is contained in the table tblBRACS_SWL. The table is similar to its equivalent in the TWDB Groundwater Database. Information on dates, water levels, and source of measurement are recorded in the table.

8.1.9 Aquifer Hydraulic Properties

Information from existing aquifer tests conducted in the Pecos Valley and Dockum aquifers is contained in the table tblBRACS_AquiferTestInformation. The table contains fields for hydraulic conductivity, transmissivity, specific yield, storage coefficient, drawdown, pumping rate, specific capacity, the types of units for each measurement, date of analysis, source of information, and remarks. If an analysis included the top and bottom depths of the screen, well depth, and static water level, it was captured in this table in case the values differed from what is presented in the casing table (test may have been performed before total depth of the well was reached). The length of aquifer tests, values for drawdown versus recovery, pumping and static water levels, and two analysis remarks fields complete the table design. Since many results are from Myers (1969), a page reference to that report for each test is recorded and references to other published reports and table numbers are also included.

8.1.10 Aquifer Determination

The results of the aquifer determination for well records described in Section 6.2 are presented in table tblAquiferDetermination. This table includes fields for the project region, new aquifer decision, TWDB Groundwater Database aquifer code assigned to the well (if any), well and screen depths, whether the well has multiple screens, aquifer decision codes, well owner, and latitude/longitude coordinates. Fields for formation top and bottom depths of the Pecos Valley Alluvium, Cretaceous Undivided, Dockum Group-Dewey Lake Formation, Rustler Formation, and Capitan Reef Complex are listed.

8.2 Supporting data sets

Many geographic information system (GIS) data sets were created during the course of this project. The GIS techniques used to build the files are explained in the following sections. Each GIS file contains metadata.

8.2.1 GIS data set development

The raster grid files are limited to 12 characters, necessitating the development of a file naming scheme for all GIS files. This scheme was also applied to table field names and Visual Basic Coding within the MS Access database for consistency among data sets. A list of the file naming conventions and GIS files organized by formation is presented in Appendix 13.1.

8.2.2 Processes to create data sets

ArcGIS® and the Spatial Analyst extension software by Environmental Systems Research Institute, Inc., (ESRI) was a critical component of the geographic information system (GIS) creation and analysis of spatial data for the project. Files created and managed in GIS consist of point, polyline, and polygon shapefiles and grid files.

All well records were managed in MS Access databases. Well records were queried from the databases and imported into ArcGIS® for spatial analysis. When new attributes were added to a well using ArcGIS®, the information was imported into MS Access and the well records updated.

Every well record in each database used for this project contained latitude and longitude coordinates in the format of decimal degrees with a North American Datum of 1983. All of these well records were imported into ArcGIS® and georeferenced in a geographic coordinate system, North America, North American Datum 1983 projection. A point shapefile was then saved in a working directory. Every well record then had an elevation assigned from the USGS seamless 30 meter digital elevation model using the ArcGIS® toolbox/extraction/extract value to point tool. The dbase file from each shapefile was then imported into MS Access and the elevation data updated to each well record, along with date, method, vertical datum, and agency attributes. Each well record also recorded the kelly bushing height when available. GIS point files subsequently created for each formation were corrected for kelly bushing height and elevation.

In many cases new wells were plotted in ArcGIS® and the latitude, longitude, and elevation were determined and appended to the database tables manually. The Original Texas Land Survey obtained from RRC was the principal base map used to plot well locations; county highway maps and topographic maps were used on occasion.

All formation surfaces (top, bottom, and thickness) began with a finished point file that was interpolated with ArcGIS® spatial analyst. Formation surfaces were prepared using the ESRI integer grid format, used for storing raster information. Every grid created used a reference grid with 250-foot cell size for coordinate system, grid extent, and snap raster.

As an example, the Pecos Valley Alluvium bottom depth surface was interpolated with the topo to raster tool, where sinks were not enforced. The next step was to create a contour map using the spatial analyst/surface/contour tool. The contour map was manually edited to fit the data points and conform to the geology of the area. Data points were reviewed and in many cases new data was collected and interpreted to fill in problematic areas. When the final contour map was completed, the polylines of the contour map were converted to points using the ArcGIS® tool data management/features/feature vertices to points. Latitude and longitude coordinates were assigned to each point. All contour points and well points were appended to one file and then georeferenced. This new point file was then interpolated with the natural neighbor tool. Although the natural neighbor tool did a reasonable job with point interpolation, it did not create a surface that extended beyond point control. In some cases, points had to be added along the edge of the project area to “force” the tool to extend a surface to cover the entire project area.

Areas representing outcrops of the Dockum Group and Cretaceous formations were extracted from the Geologic Atlas of Texas geodatabase and converted into shapefiles and grid files. The outcrop areas were converted to no-data cells in the Pecos Valley bottom depth surface. Data cells extending beyond the extent of the Pecos Valley Alluvium were also converted to no-data cells. Finally, a grid of each well data point was created and this cell value was used to replace the cell value in the master surface grid so that the stratigraphic value at each well was accurately reflected on the surface map. This step was critical to accurately represent the solution collapse sinks.

The depth surfaces for the Pecos Valley Alluvium, Cretaceous Undivided, and Rustler Formation top were all processed with the above techniques. Intervening formation surfaces were created by processing the adjacent surface: for example, the Dewey Lake Formation bottom surface equals the Rustler Formation top surface.

A project elevation surface matching the snap raster was created from the USGS seamless 30 meter digital elevation model. The elevation surfaces of geological formations were created by subtracting the depth to the surface from the project elevation (DEM) surface. These surfaces were then contoured using the ArcGIS® contour tool.

8.2.3 Map projection parameters

Map projection parameters are contained in the metadata associated with each GIS file.

Each point shapefile in GIS was georeferenced using latitude and longitude in a decimal degree format using the ArcGIS® geographic coordinate system projection, North America, North American Datum (NAD) 1983.

Polyline and polygon shapefiles and grid files are in a Lambert Conformal Conic projection, NAD 1983, known as the Texas State Mapping System (TSMS) that covers the entire state of Texas. Grid files used the TSMS system with a linear unit of a foot because this file format was required as an input to the ViewLog software for cross-section creation and analysis.

Supporting GIS files may be in a variety of projections with a NAD 1983 horizontal datum.

The project snap raster was created to synchronize every grid file in terms of extent, coordinate system projection, and especially grid cell size and registration. Grid files must be “snapped” to a standard grid so that the corners of each grid are registered exactly ensuring that subsequent grid calculations will be accurate.

9. Future improvements

The technique of applying geophysical well log analysis to estimate TDS concentrations could not be fully examined in the study because of the paucity of geophysical well logs containing the requisite information. This will have to be to be investigated in future studies where the data is available. The SP analysis will require a correction process for cations added to the Visual Basic Code and database table design that must be developed and tested. After these techniques are thoroughly tested and approved, a user manual can be written to document the methodology and data entry processes.

During the course of this project we became aware of consultant reports prepared for some of the well field exploration and development in the region. Unfortunately, we were not able to procure these reports. This will always be a challenge even in future projects, especially when the reports are several decades old and in some cases may still be considered proprietary. A greater effort must be made to identify and procure this valuable information.

The TWDB will need to identify methods of providing the digital geophysical well logs to the public via the World Wide Web. The TWDB will also need to scan the paper geophysical well logs in its collection and convert them into electronic files.

Collecting enough hydraulic parameter information (for example, transmissivity and hydraulic conductivity) to produce detailed GIS maps is and will always be a challenge. The productivity of proposed wells is crucial to evaluating a brackish resource for desalination. Although well data from regional projects will never be as good as site-specific well testing in a proposed field, we will continue to collect this valuable information and append it into the BRACS database even after a study has been completed. We need to evaluate techniques to interpret geophysical well logs to determine if we can gain additional knowledge about these parameters.

The BRACS database will continue to evolve as new projects are undertaken, new methods of data analysis used, and additional data sets generated. In the future, the BRACS database will be integrated with the TWDB Groundwater Database to produce one comprehensive data set.

BRACS will move into new study areas across the state and the program will need to be flexible to handle the challenges of data availability and geology, and changing priorities for the brackish groundwater resources of the state. Forging partnerships with organizations, agencies, and other interested entities will be key to the success of the program.

10. Conclusions

We estimate that the Pecos Valley Aquifer contains about 15 million acre-feet of fresh water (0 to 1,000 mg/L), 85 million acre-feet of brackish groundwater (1,000 to 10,000 mg/L), and 1 million acre-feet of very saline water (>10,000 mg/L). The brackish water is present almost everywhere in the aquifer but appears to be more prevalent in the central and western parts. These are also areas where the saturated thickness of the aquifer is the greatest.

The 2010 approved Region F water plan projects water shortages of about 28,887 acre-feet in 2010 increasing to 35,342 acre-feet in 2060. Desalination of brackish groundwater present in the Pecos Valley Aquifer may be one option to meet these projected shortages.

Using the detailed data sets compiled for and generated during the study, water planners can begin to more closely focus on areas of specific interest and evaluate potential well field locations. The information presented in the report, and that available in the data sets, cannot however replace a detailed site investigation that involves test well drilling, aquifer testing, and water quality analysis.

The pilot study has helped lay the foundation for future BRACS projects by developing a database management system in which a variety of data can be stored and processed.

11. Acknowledgments

We wish to thank all the members of the BRACS Technical Resource Panel for their helpful suggestions, comments, recommendations, and support. Their feedback helped improve the quality of the report and their guidance has been invaluable in strengthening the BRACS program. A special thank-you to Norman Gearhart and John Estepp, Texas Commission on Environmental Quality, for the training that they provided us in the early stages of the project, and for scanning and digitizing the geophysical well logs available in their Surface Casing library. Finally, this work could not have been undertaken or completed without the generous support of Jorge A. Arroyo and Robert E. Mace.

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13. Appendices

13.1 GIS Data Sets

Table of GIS file naming conventions

Each code will be separated from the next code with an underscore character. For example, the code pv_b_d_snm refers to the Pecos Valley Alluvium bottom depth surface created by the natural neighbor surface technique, masked.

Code Position	Code Type	Code	Code Description
1	Stratigraphic	bc	Bell Canyon Formation
1	Stratigraphic	cr	Capitan Reef Complex
1	Stratigraphic	dd	Dockum Group- Dewey Lake formation Interval
1	Stratigraphic	dl	Dewey Lake Formation
1	Stratigraphic	do	Dockum Group
1	Stratigraphic	ku	Cretaceous Undivided (Edwards-Trinity Plateau)
1	Stratigraphic	o	Ogallala Aquifer
1	Stratigraphic	pkd	Pecos - Cretaceous - Dockum - Dewey Lake Grouped Interval
1	Stratigraphic	pv	Pecos Valley Alluvium
1	Stratigraphic	rsc	Rustler - Salado - Castile Interval
1	Stratigraphic	ru	Rustler Formation
2	Outcrop	otc	dataset represents the extent of formation outcrop
2	Surface Position	b	Bottom surface
2	Surface Position	t	Top surface
3	Value	d	Depth (feet below ground surface)
3	Value	e	Elevation (feet above mean sea level)
3	Value	sat	saturated
3	Value	tds	Total Dissolved Solids
3	Value	thk	Thickness (feet)
3	Value	vbw	volume brackish water
3	Value	wq	Water Quality Analysis of well
4	Data Type	c,con,cwb	Contour
4	Data Type	conpts	Point file containing contour vertex points and well point stratigraphic picks. Used to generate a grid surface
4	Data Type	p	polygon
4	Data Type	pl	polyline
4	Data Type	pt	Point (generally stratigraphic pick values)
4	Data Type	s,sur	Surface
4	Data Type	st	Stratigraphic Pick, Point
4	Value	swl	static water level
5	Surface Data Value	fp	floating point
5	Surface Data Value	i	integer value
5	Surface Method	id	inverse distance weighted
5	Surface Method	k	kriging
5	Surface Method	n	natural neighbor
5	Surface Method	s	spline
5	Surface Method	swb	spline with barrier(fault; escarpment)
5	Surface Method	tr	topo to raster
6	Contour Interval	100	100 foot contour interval
6	Contour Interval	250	250 foot contour interval
6	Contour Method	wb	Contouring perform with barrier (fault; escarpment)
7	Mask	m	mask (set at the project boundaries)
9	Elevation	elev	elevation data extracted to snap grid
10	Snap Raster	snap	Snap raster file used to snap all project cells into conformable alignment
11	Snap Raster Cell Size	250	Square Cell size in feet (cell size in meters will be followed by m)
11	Snap Raster Cell Size	500	Square Cell size in feet (cell size in meters will be followed by m)

Table field definitions:

Point file: all point files are shapefiles.

Surface file: all surface files are raster integer grid files.

Contour file: all contour files are polyline shapefiles.

Outcrop correction (Yes/No): Were outcrops of other formations used to correct the formation surfaces.

Well Point Correction (Yes/No): Were well point stratigraphic values used to replace surface cell values after the formation surface was prepared. This step allows well points database and GIS files to match exactly.

Elevation Correction (Yes/No): Were formation surfaces compared with project elevation surfaces for “porpoising”, where an interpolated surface projects above a the known elevation of a cell site.

Pecos Valley Alluvium

Formation Surface	Point file	Surface File	Contour File	Outcrop Correction	Well Point Correction	Elevation Correction
Bottom Depth	pv_b_d_pt o_b_d_pt	pv_b_d_snm	pv_b_d_cwb	Yes	Yes	No
Top Elevation		pv_t_e_s		Yes		Yes
Bottom Elevation	pv_b_e_pt o_b_e_pt	pv_b_e_snm	pv_b_e_cwb	Yes	Yes	Yes
Thickness	pv_b_d_pt o_b_d_pt	pv_b_d_snm	pv_b_d_cwb	Yes	Yes	Yes
Saturated Thickness		pv_sat_thk		Yes		
Static Water Level	pv_swl_pt_00-09	pv_swl_00-09		Yes		
Brackish Volumes		pv_vbw_1 pv_vbw_2 pv_vbw_3 pv_vbw_4		Yes		

Notes:

Ogallala points extracted for Texas and New Mexico in areas within and adjoining the project area to develop the Pecos datasets.

Pecos Valley Alluvium top elevation surface based on USGS 30 meter elevation grid re-sampled to project 250 ft cell size.

File pv_con_barrier.shp was used to construct contours in Reeves County along the Cretaceous escarpment.

Brackish Volumes: pv_vbw_1 contains the volume of the 0-999 mg/L range of TDS.

pv_vbw_2 contains the volume of the 1,000-2,999 mg/L range of TDS.

pv_vbw_3 contains the volume of the 3,000-9,999 mg/L range of TDS.

pv_vbw_4 contains the volume of the > 10,000 mg/L range of TDS.

Cretaceous Undivided

Formation Surface	Point File	Surface File	Contour File	Outcrop Correction	Well Point Correction	Elevation Correction
Top Depth	ku_t_d_pt	ku_t_d_snm		Yes	Yes	No
Bottom Depth	ku_b_d_pt	ku_b_d_snm	ku_b_d_con	Yes	Yes	No
Top Elevation	ku_t_e_pt	ku_t_e_snm		Yes	Yes	Yes
Bottom Elevation	ku_b_e_pt	ku_b_e_snm	ku_b_e_con	Yes	Yes	Yes

Notes:

The mapped surfaces in the outcrop areas in northwest Ward and northeast Reeves counties used 25 feet bottom depth as a default value and zero contour thickness surrounding the outcrops.

Cretaceous Undivided top depth/elevation is based on the Pecos Valley Alluvium base in regions 3 and 4.

Dockum Group

Formation Surface	Point File	Surface File	Contour File	Outcrop Correction	Well Point Correction	Elevation Correction
Top Depth		do_t_d_snm		Yes	Yes	No
Top Elevation		do_t_e_snm		Yes	Yes	Yes

Notes:

For most of the project area the Dockum Group and Dewey Lake formation are mapped as one group. There is an area in Reeves County where the Dockum Group is missing, and the Dewey Lake formation does have a top surface mapped. The Dockum Group bottom surfaces (depth,elevation) not prepared.

Individual formations within the Dockum Group were not mapped, however the sandy part of the Dockum Group (commonly referred to as the Santa Rosa where it occurs) can be identified based on lithology determined from water wells and geophysical well log, gamma ray interpretations.

Dewey Lake Formation

Formation Surface	Point File	Surface File	Contour File	Outcrop Correction	Well Point Correction	Elevation Correction
Top Depth	dl_t_d_pt	dl_t_d_snm		No	Yes	No
Bottom Depth	dl_b_d_pt	dl_b_d_snm	dl_b_d_con	No	Yes	No
Top Elevation	dl_t_e_pt	dl_t_e_snm		No	Yes	No
Bottom Elevation	dl_b_e_pt	dl_b_e_snm	dl_b_e_con	No	Yes	No

Notes:

For most of the project area the Dockum Group and Dewey Lake Formation are mapped as one group. There is an area in Reeves County where the Dockum Group is missing, and the Dewey Lake Formation does have a top surface mapped (equals base of Pecos Valley Alluvium or base of Cretaceous Undivided where present).

The Dewey Lake bottom depth/elevation is based on the Rustler top. Dewey Lake Formation bottom depth/elevation contours based on Rustler formation top contours.

Rustler Formation

Formation Surface	**Point File**	**Surface File**	**Contour File**	**Outcrop Correction**	**Well Point Correction**	**Elevation Correction**
Top Depth	ru_t_d_pt	ru_t_d_snm	ru_t_d_con	No	Yes	No
Bottom Depth						
Top Elevation	ru_t_e_pt	ru_t_e_snm	ru_t_e_con	No	Yes	No

Notes:

The Rustler Formation bottom information can be found in the report and data sets of Jones and others, 2011.

Support Files

File Type	**Surface File**	**Description**
Elevation Statewide	Texas30m.img	Texas 30 meter digital elevation model statewide
Elevation Masked	Elev_snap250	Re-sampled 30 meter DEM in a 250 ft cell snapped to project files
Snap Grid	Snap_250ft	Snap grid for project, 250 ft cell, with project extent and coordinate system. Every raster grid snapped to this file. Cell values are random numbers to visualize cell boundaries when checking project grids.
Project Boundary	Bracs_PVA_ProjectBoundary_Simple	Project boundary, polygon, used as mask file.
Aquifer Regions	Bracs_AquiferRegions_pv_project BAR_S (raster grid file)	Project area mapped as regions with different stratigraphic profile of the principle aquifers. Polygon file and raster grid file prepared.
BRACS Well Point Files	BRACS_ST BRACS_AD BRACS_WQ BRACS_WL BRACS_AT	Each well record containing the stratigraphic picks. Each well record containing the aquifer selected for each well and the well id and state well number. Well records with water quality data. Well records with static water level data. Well records with aquifer test data.
Cross Sections	Cross_Section_Points Cross_Section_Lines	Published Cross Section Point Locations Published Cross Section Line Locations