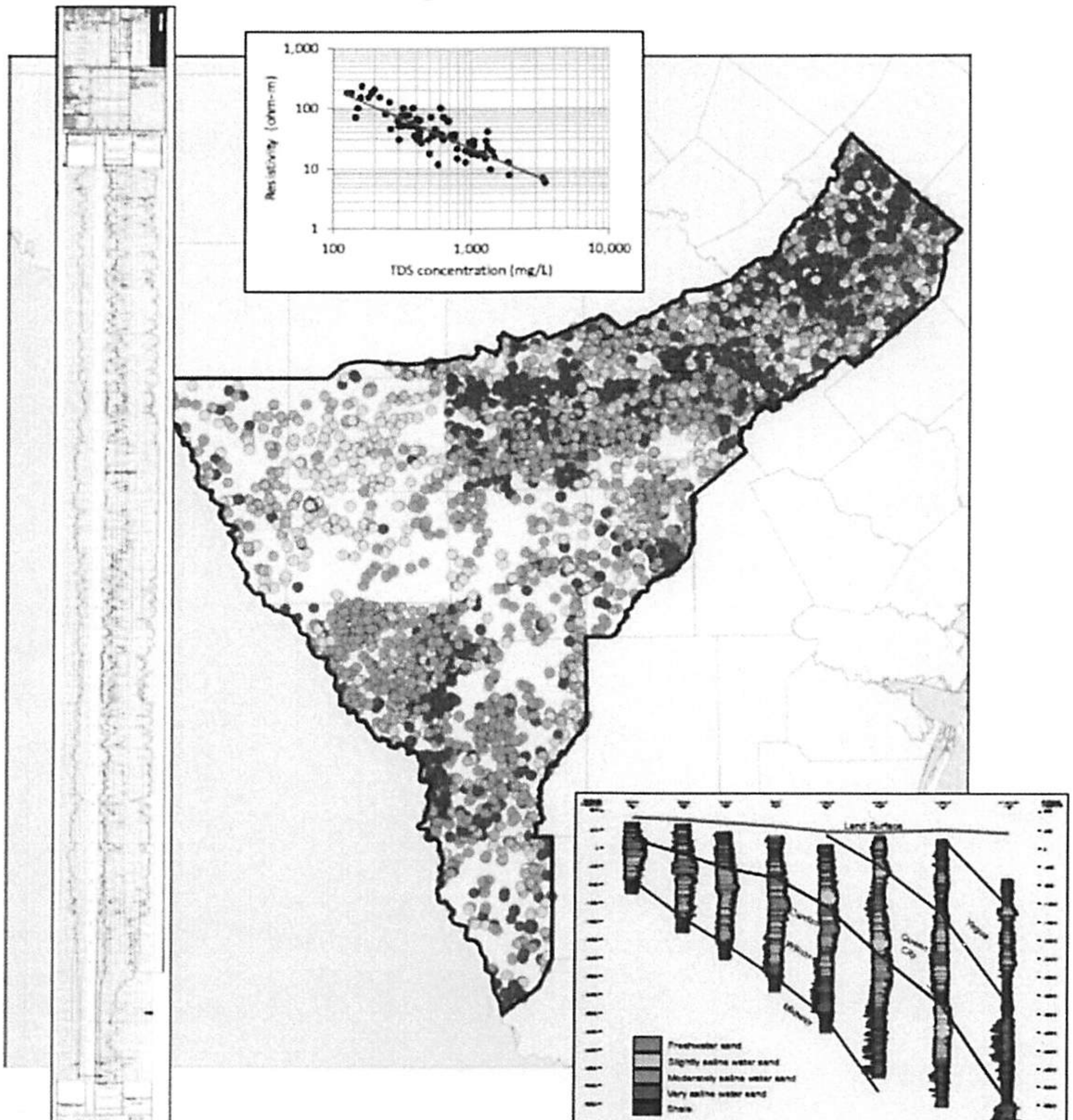
Fresh, Brackish, and Saline Groundwater Resources in the Carrizo-Wilcox, Queen City and Sparta Aquifers in Groundwater Management Area 13—Location, Quantification, Producibility, and Impacts

TWDB Contract Number 1548301855



Submitted to the Texas Water Development Board

April, 2019

by

Bureau of Economic Geology
The University of Texas at Austin
Austin, Texas – 78758

INTERA Incorporated
9600 Great Hills Trail, Suite 300W
Austin, Texas – 78759

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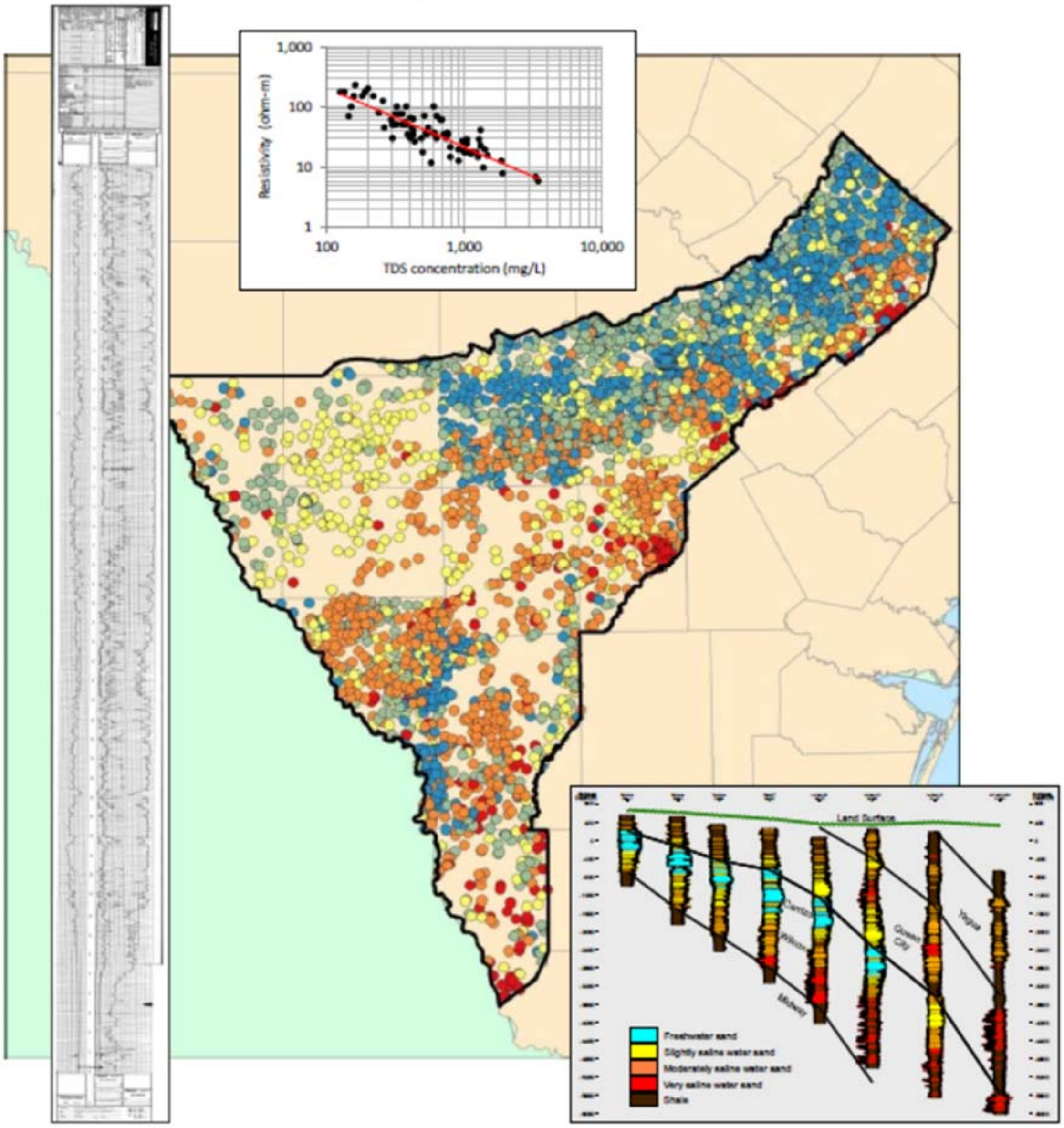

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Contributed to the geologic effort on this project. Revised some of the log analyses. Contributed to the Executive Summary, and Sections 1, 2, 4, 9, and 10 of this report. Edited the final version of the report.

H. Scott Hamlin:

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Bridget R. Scanlon:

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Contributed to the groundwater quality studies, and led the GIS effort on this project. Contributed to Section 3 of this report.

Steven C. Young:

Led the groundwater volume calculation and modeling effort on this project, and contributed to Sections 5, 6, 7, 8, and 9 of this report.

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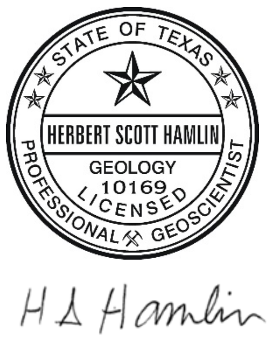
GEOSCIENTIST SEALS

This report documents the work of the following licensed professional geoscientists with the Bureau of Economic Geology at the University of Texas at Austin, and INTERA Incorporated.



Scott Hamlin led the geologic effort on this project, and wrote Sections 1, 2, and 4 for the first version of this report. The seal appearing on this document was authorized by H. Scott Hamlin, P.G. on April 25, 2019.

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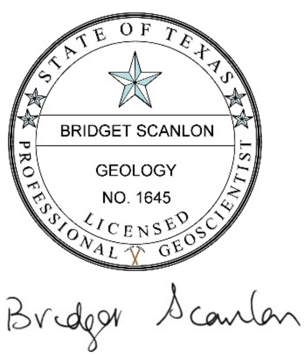

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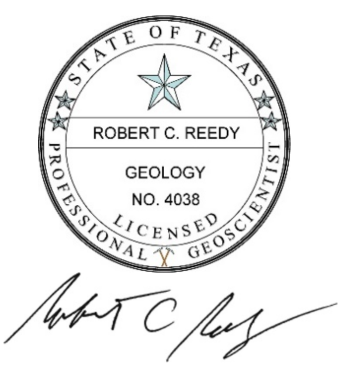
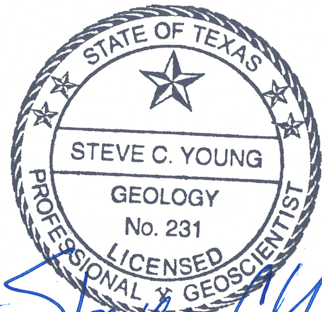
Bridget R. Scanlon, Ph.D., P.G., Senior Research Scientist



Robert Reedy contributed to the groundwater quality and GIS effort on this project, and Section 3 of this report. The seal appearing on this document was authorized by Robert C. Reedy, P.G. on April 25, 2019.



Steve Young led the groundwater volume calculation and modeling effort on this project, and contributed to Sections 5, 6, 7, 8, and 9 of this report. The seal appearing on this document was authorized by Steven C. Young, P.G. on April 25, 2019.

Steven C Young 4/25/2019

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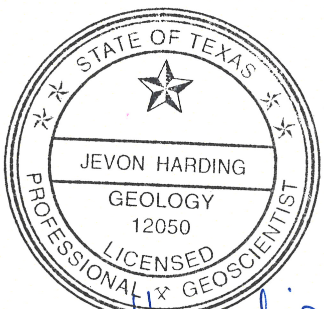

Jevon Harding contributed to the groundwater volume calculation and modeling effort on this project, and Sections 5, 6, 7, and 8 of this report. The seal appearing on this document was authorized by Jevon Harding, P.G. on April 25, 2019.

Jevon Harding 4-25-19

Jevon Harding, P.G., Hydrogeologist

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Abbreviations and Acronyms

°F	degrees Fahrenheit
amsl	above mean sea level
AFY	acre-feet per year
BEG	Bureau of Economic Geology
cm/s	centimeters per second
C_w	specific conductivity
C_t	proportionality constant
ft	feet
ft/day	feet per day
GAM	groundwater availability model
GCD	groundwater conservation district
GHB	general head boundary
GHS	geohydrostratigraphic
GHSM	geohydrostratigraphic model
GMA	groundwater management area
gpm	gallons per minute
Kh	horizontal hydraulic conductivity
Kz	vertical hydraulic conductivity
mg/L	milligrams per liter
µg/L	micro grams per liter
pCi/L	picoCuries per liter
PPA	Potential Production Area
QCSP GAM	Queen City-Sparta Groundwater Availability Model
R	potential recharge
R_t	formation resistivity
R_w	water resistivity
SP	spontaneous potential
Ss	specific storage
TDS	total dissolved solids

TERS	Total Estimated Recoverable Storage
TWDB	Texas Water Development Board
USGS	United States Geological Survey

Executive Summary

In order to reduce the use of fresh groundwater, the 84th Texas Legislative Session passed House Bill 30 in 2015 with an aim to identify brackish groundwater production zones at local and regional scales for parts of Texas that have moderate to high availability of brackish groundwater. The current study was undertaken to identify potential production areas that can provide brackish water over a 30 to 50-year time period using the Carrizo-Wilcox and Queen-City and Sparta Groundwater Availability Models, along with the latest data, scientific approaches and best practices.

Two potential production areas were delineated in the Carrizo-Wilcox Aquifer, and one in the Queen City- Sparta aquifers based on the application of an empirical approach to salinity mapping (total dissolved solids) from geophysical logs, which was in turn rooted in an understanding of the groundwater quality of these aquifers. These three potential production areas were selected based on the criteria listed in House Bill 30, which are as follows:

- These areas are separated by hydrogeologic barriers sufficient to prevent significant impacts to water availability or water quality in any area of the same or other aquifers, subdivisions of aquifers, or geologic strata that have an average total dissolved solids level of 1,000 milligrams per liter or less at the time of designation of the zones.
- Are not located in an area of the Edwards Aquifer subject to the jurisdiction of the Edwards Aquifer Authority, the boundaries of the Barton Springs-Edwards Aquifer Conservation District, the Harris-Galveston Subsidence District, or the Fort Bend Subsidence District.
- Are not located in an aquifer, subdivision of an aquifer, or geologic stratum that has an average total dissolved solids level of more than 1,000 milligrams per liter and is serving as a significant source of water supply for municipal, domestic, or agricultural purposes at the time of designation of the zones, or in an area of a geologic stratum that is designated or used for wastewater injection through the use of injection wells or disposal wells permitted under Chapter 27.

However, our detailed analyses indicated that complete isolation of the potential production areas is not possible because of one or more factors like the presence of freshwater sands in close proximity, the nature of local faults, and the interlayered and interfingered nature of the fresh and brackish groundwater sands in GMA 13. While none of the three delineated areas met all the requirements listed above, potential production area 1 in the Carrizo-Wilcox Aquifer seemed to be more favorable than the other two. This was based on potential production area 1 having better hydrogeologic barriers (such as the local shaly nature of the middle Wilcox), and the lack of associated faults (which, if present, might have increased the possibility of groundwater mixing). In the interest of showing details of our evaluation, and for possible future use of the findings by the TWDB, discussions on all three potential production areas have been included in this report.

Groundwater volumes were estimated for different groundwater quality classifications in the Carrizo-Wilcox, Queen City, and Sparta aquifers. The equations for calculating groundwater volumes require input values of aquifer properties for each aquifer, most of which were obtained from the GMA 13 Groundwater Availability Model for the respective aquifer. The groundwater volumes were calculated for both drainable unconfined storage and in-place unconfined storage – the former based on the specific yield values obtained from the Groundwater Availability Model, and the latter based on porosity values determined as part of this study.

The total Carrizo-Wilcox volume calculated for in-place unconfined storage is 4.9 billion acre-feet, or approximately 2.4 times greater than the total volume calculated using drainable unconfined storage (2.0 billion acre-feet). The total Sparta volume calculated for in-place unconfined storage is 1.5 billion acre-feet, or approximately 2.2 times greater than the total volume calculated using drainable unconfined storage (677 million acre-feet). The total Queen City volume calculated for in-place unconfined storage is 2.2 billion acre-feet, or approximately 2.2 times greater than the total volume calculated using drainable unconfined storage (1 billion acre-feet). The sand fraction (groundwater contained in sand) is about 0.38 in the Carrizo-Wilcox Aquifer, 0.23 in the Sparta Aquifer and 0.33 in the Queen City Aquifer. The sand fraction values vary among the Carrizo-Wilcox aquifer units, ranging from 0.63 in the Carrizo Aquifer to 0.27 in the middle Wilcox Aquifer.

The volumes of fresh (TDS <1,000 mg/L), brackish (TDS = 1,000 – 10,000 mg/L), and very saline (TDS = 10,000 – 35,000 mg/L) groundwater in the Carrizo-Wilcox Aquifer calculated for drainable unconfined storage are 466 million acre-feet, 834 million acre-feet, and 744 million acre-feet, respectively. Of the Carrizo-Wilcox Aquifer units, the lower Wilcox Aquifer contains the most groundwater (35%). However, the majority of groundwater (66%) in this aquifer unit is very saline. Only about 23% of the groundwater in the Carrizo-Wilcox Aquifer is fresh water, and the majority of this fresh water occurs in the Carrizo Aquifer (73%). Brackish water (the sum of slightly saline and moderately saline water) makes up the majority of water in both the Sparta Aquifer (56%) and Queen City Aquifer (71%). Freshwater makes up very little of the remaining Sparta groundwater (9%), whereas very saline accounts for 35% of the total groundwater. The Queen City is fresher, with freshwater accounting for slightly more (15%) of the total groundwater than very saline water (14%).

Groundwater models were developed and applied to simulate changes in groundwater levels caused by pumping from two potential production areas in the Carrizo-Wilcox Aquifer, and one in the Queen City and Sparta aquifers. The primary objective of the modeling was to provide the TWDB with sufficient information to determine the amount of brackish groundwater that a potential production area could produce over a 30 and 50-year period without causing a significant impact to water availability. The groundwater models were used to simulate pumping at 5,000, 15,000, and 30,000 acre-feet per year for 50 years at four hypothetical well fields in two potential production areas in the Carrizo-Wilcox Aquifer. For the Queen City Aquifer, groundwater models simulated pumping at 2,000, 6,000, and 10,000 acre-feet per year for 50 years at two hypothetical well fields in one potential production area; the same simulation was performed for the Sparta Aquifer. For all groundwater model simulations, drawdowns were tabulated after 30 years and 50 years of pumping at hypothetical monitoring wells located in the fresh water zones and/or up dip regions of the pumped aquifer. For most of the monitoring locations, the amount of drawdown is a linear function of the pumping rate at a well field, and once this relationship is established using information provided in the report, it can be used to calculate the pumping rate that would cause a specific drawdown amount at a specific monitoring well location. Besides tabulation of drawdown values, plots of drawdown for elapsed times of 5 years, 10 years, 30 years, and 50 years are shown. Based on our evaluation of groundwater movement inferred from the changes in the water levels, the data are insufficient to rule out potential non-negligible changes to the water quality in the fresh water zone.

1 Introduction

Brackish groundwater is becoming increasingly important as fresh groundwater resources diminish. Brackish groundwater is defined as water containing between 1,000 and 10,000 milligrams per liter (mg/L) total dissolved solids (TDS) (LBG-Guyton Associates, 2003). Groundwater salinity is divided into five categories: fresh (TDS <1,000 mg/L), slightly saline (TDS = 1,000 – 3,000 mg/L), moderately saline (TDS = 3,000 – 10,000 mg/L), very saline (TDS = 10,000 – 35,000 mg/L), and brine (TDS >35,000 mg/L) (Winslow and Kister, 1956). Reliable maps and models of brackish and saline groundwater resources are needed for planning purposes to meet rising water demands. Brackish groundwater is usable with minimal treatment for many purposes in municipal, agricultural, and oil field operations, and may be better suited than sea water (TDS = 35,000 mg/L) for desalination. For example, in Groundwater Management Area (GMA) 13 in South Texas, brackish groundwater in the Carrizo-Wilcox, Queen City, and Sparta aquifers are potential sources of water for hydraulic fracturing in the Eagle Ford Shale play (Scanlon and others, 2014).

Brackish groundwater is difficult to distinguish and quantify because few direct salinity measurements are available. Most chemical analyses of formation water samples are either from freshwater aquifers or from oil field brines. Geophysical logs can help fill the gap between fresh groundwater and formation brine. Geophysical log interpretation spans the entire groundwater flow regime from outcrop to deep subsurface, and from fresh groundwater to brine. Geophysical logs provide continuous vertical records of the electrical properties of both rocks and fluids in wells, whereas groundwater sample analysis provides only point-sourced data. However, hydrochemistry data from groundwater sampling are needed to calibrate geophysical log interpretations. This study characterizes brackish groundwater distribution and quantification using four integrated approaches: (1) groundwater quality and hydrochemistry as context for salinity mapping and to better understand salinity sources, (2) geophysical log (electric log) interpretation of groundwater salinity to map brackish groundwater, (3) calculation of volumes of fresh, brackish, and saline groundwater to quantify the resource, and (4) groundwater modeling to help predict the impacts of brackish groundwater production. In this study we mapped and quantified brackish groundwater resources in the Carrizo-Wilcox, Queen City, and Sparta aquifers in GMA 13.

2 Hydrogeologic Setting

Cenozoic formations of the Texas Gulf coastal plain form prolific groundwater flow systems, which include the Carrizo-Wilcox, Queen City, Sparta, Yegua-Jackson, and Gulf Coast aquifers (**Figure 2-1**). Each Cenozoic formation comprises a wedge of sand and shale that dips and thickens toward the coast (Galloway and others, 2000). Major aquifers, such as the Carrizo-Wilcox and Gulf Coast, are located in the thickest, most laterally extensive, and sand-rich Cenozoic sediment wedges, whereas minor aquifers, such as the Queen City, Sparta, and Yegua-Jackson, are located in sediment wedges that are less sandy and more limited in lateral (especially downdip) extent (George and others, 2011). In these coastal groundwater flow systems, recharge enters the aquifer at outcrop and flows down the structural dip of the formation, becoming increasingly saline with depth. Larger sand-rich flow systems will contain lower salinity groundwater at greater depths than smaller sand-poor flow systems.

GMA 13 encompasses the Rio Grande Embayment area of the upper coastal plain of South Texas, which extends from the Rio Grande (Zapata County) in the southwest to the San Marcos Arch (Gonzales County) in the northeast (**Figure 2-2**). Most fresh and brackish groundwater resources in GMA 13 are in the Carrizo-Wilcox, Queen City, and Sparta aquifers. Although it does contain a partial Carrizo-Wilcox outcrop, Maverick County is excluded from the study area because shallow electric log coverage is not sufficient to map brackish groundwater resources in that county.

2.1 Wilcox Group

The Wilcox Group is a thick succession of fluvial-deltaic sandstone and shale that was deposited during the Late Paleocene and Early Eocene in the first major Cenozoic progradational episode into the Gulf of Mexico Basin (Fisher and McGowen, 1967; Galloway and others, 2000, 2011). The onshore Texas Wilcox Group is divided into three intervals. Lower and middle Wilcox sandstones are thickest along the upper Texas coast (Houston Embayment), whereas upper Wilcox sandstones are thickest in South Texas (Rio Grande Embayment) (Bebout and others, 1982; Xue and Galloway, 1993, 1995). In South Texas, the Carrizo Formation is the updip equivalent of the upper Wilcox interval (Hargis, 1985, 1986, 2009). Carrizo fluvial facies updip are contiguous with upper Wilcox deltaic facies downdip (Hamlin, 1988). The middle and lower Wilcox intervals were deposited in a variety of coastal plain and marine environments, and are generally less sandy than the Carrizo-upper Wilcox interval. The study area covers the Rio Grande Embayment and the southern flank of the San Marcos Arch. The study area includes most of GMA 13 except Maverick County. The Wilcox Group ranges in thickness from a few hundred feet (ft) at outcrop to 5,000 ft along the southeastern boundary of GMA 13. The Wilcox Group dips gently to the southeast at 50 to 150 ft per mile, and the top of the Carrizo-Wilcox Aquifer is 4,000 to 6,000 ft deep along the southeastern boundary of GMA 13.

Carrizo-Wilcox sands form one of the most extensive and productive aquifers in Texas. In South Texas almost the entire fresh groundwater resource is located in Carrizo-upper Wilcox sands. Fresh groundwater extends as far as 50 miles downdip from the outcrop to as deep as 5,000 ft below sea level (Klemt and others, 1976; Hamlin, 1988). Middle and lower Wilcox sands contain primarily brackish and saline groundwater. The middle Wilcox interval is shale-dominated, and generally forms an aquitard between the lower Wilcox interval and the Carrizo-upper Wilcox interval. The Carrizo-Wilcox aquifer is variably consolidated and includes sands and sandstones, both of which are referred to as sands in this report.

2.2 Queen City and Sparta Formations

The Queen City and Sparta formations include fluvial-deltaic depositional systems similar to the Wilcox Group, but also include abundant mud-rich coastal plain and marine shelf deposits. In contrast to the Wilcox, Queen City and Sparta sand-rich depositional systems are more limited in thickness and lateral extent. Following Wilcox deposition, a marine transgression deposited the Reklaw Shale. Queen City deltaic and strandplain shorelines prograded basinward across the Reklaw Shale but did not extend as far downdip as did the underlying Wilcox (Guevara and Garcia, 1972). Following Queen City deposition, a second marine transgression deposited the Weches

Shale. Sparta shoreline systems prograded basinward across the Weches Shale (Ricoy and Brown, 1977). The Sparta is thinner and less sand-rich than either the Carrizo-Wilcox or the Queen City. Thus, three sandy progradational shoreline systems are separated by two shale-dominated transgressive marine systems, forming an interlayered aquifer/aquitard hydrogeologic system. The Queen City Formation thickens toward the southwest from 400 ft in Gonzales County to 2,000 ft in Zapata County. The Sparta Formation, although thinner, displays similar thickness trends, ranging from less than 100 ft in Gonzales County to about 500 ft in southern Webb County.

The Queen City and Sparta formations form minor aquifers on the Texas coastal plain (George and others, 2011). In GMA 13, fresh groundwater in these aquifers extends as much as 20 miles downdip from outcrop in a few locations but is limited to outcrop or near-outcrop in many locations. Maximum depth to base of fresh groundwater is about 2,500 ft in the Queen City and 1,500 ft in the Sparta, although fresh groundwater at these depths is uncommon (LBG-Guyton Associates, 2003). The composition of the Queen City and Sparta aquifers is similar to that of the Carrizo-Wilcox: mostly unconsolidated sands and muds. Prior to groundwater development in GMA 13, the Queen City aquifer received fresh groundwater recharge by upward leakage from the underlying Carrizo-Wilcox aquifer (Hamlin 1988).

Chronostratigraphy				Age (M.Y.)	Stratigraphic Unit	Dominant Lithology	Hydrogeologic Unit	
Cenozoic	Quaternary		Holocene	0.02	Alluvium	sand	Alluvium/Beaumont aquifer	Gulf Coast aquifer
			Pleistocene		Beaumont	sand		
					Lissie/Alta Loma	sand	Chicot aquifer	
	Tertiary	Neogene	Pliocene	1.8 5.3	Willis	sand		
			Miocene		Goliad	sand	Evangeline aquifer	
					Fleming/Lagarto	mud	Burkeville aquitard	
				23.9	Fleming/Oakville	sand	Jasper aquifer	
		Paleogene	Oligocene		Catahoula/Frio/Anahuac	sand and mud	aquitard	
				33.9	Vicksburg	mud	aquitard	
			Eocene		Jackson	sand and mud	Yegua-Jackson aquifer	
					Yegua	sand and mud		
					Sparta	sand	Queen City-Sparta aquifer	
					Queen City	sand and mud		
					Reklaw	mud	aquitard	
				55.8	Upper Wilcox/Carrizo	sand	Carrizo-Wilcox aquifer	
			Paleocene		Middle Wilcox	mud		
					Lower Wilcox/Simsboro	sand and mud		
				65.5	Midway	mud	aquitard	

Figure 2-1. Stratigraphic and hydrogeologic chart of the South Texas coastal zone (Galloway and others, 1991; Sharp and others, 1991).

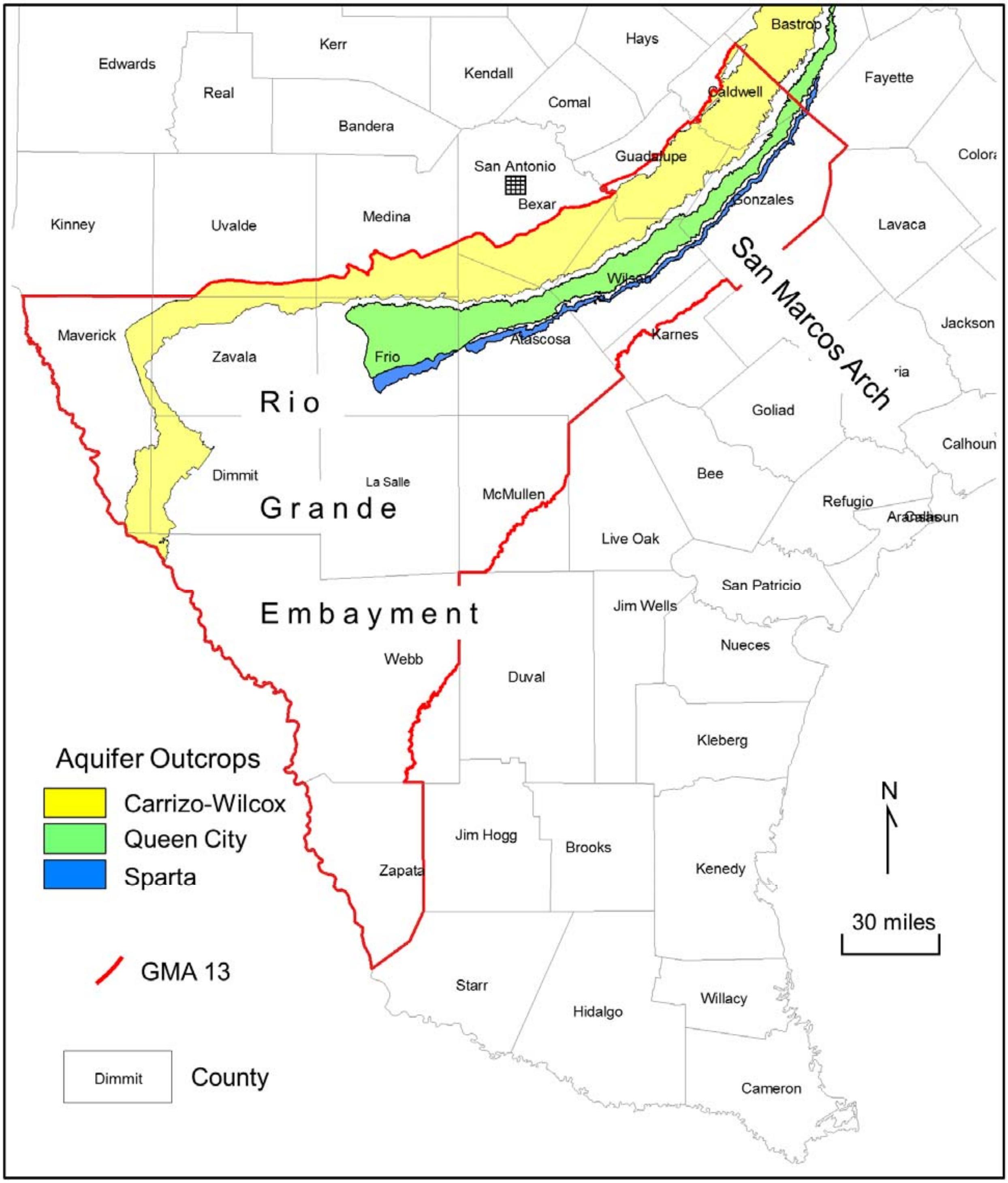


Figure 2-2. Map of GMA 13 showing outcrops of aquifers covered in this report and major Gulf Coast Basin structural elements (Rio Grande Embayment and San Marcos Arch).

3 Groundwater Quality

3.1 Previous Studies

Understanding groundwater quality is important for interpreting geophysical logs and understanding the evolution of the groundwater chemistry to assess potential sources of salinity. Many factors may influence groundwater quality, including recharge rates (current and paleo-recharge rates), composition of recharge water, lithology, interconnectedness of different lithologies, mineralogy, geochemical processes (mixing, cation exchange), residence time of groundwater, cross-formational flow, faulting, and relationship between geopressure and hydropressure systems. We quantified spatial variability in recharge rates for the Carrizo-Wilcox aquifer for the GAM study (Reedy and others, 2009). Previous studies have noted a distinct band of relatively dilute, low chloride, sodium, and sulfate water downdip from the outcrop zone that has been attributed to paleo-recharge of Pleistocene water (Green and others, 2008). Hamlin (1988) characterized the regional hydrochemistry of this region, describing the evolution of water from predominantly calcium-bicarbonate to sodium-bicarbonate water, attributed to cation exchange. Kreitler and others (2013) noted the evolution of groundwater from mixed cation mixed anion (chloride, sulfate) type water near the outcrop zone to sodium bicarbonate water further down dip, confirming the findings of Hamlin (1988). Increases in down dip salinity were attributed mostly to increases in bicarbonate concentrations, rather than large increases in chloride concentrations. The importance of open and closed systems relative to carbon dioxide, and down dip coalification of organic material forming methane and carbon dioxide, are considered important in controlling bicarbonate concentrations. Hamlin and others (1988) also noted a relationship between bicarbonate and pH up to pH of 8.6 with increases with distance along flow paths. Carbonic acid is believed to be derived from methane fermentation at depth (Hamlin, 1988). Studies by Kreitler and others (2013) suggested limited cross formational flow impacting water quality. Large variations in water quality were identified in some regions where faults are mapped. Two vertical cross sections with detailed sampling and analyses along with data from multiple depths in wells from the San Antonio Water Systems provide valuable data in assessing vertical stratification of groundwater quality. Isotopic age dating from many studies can help determine variations in groundwater residence time and relationship to groundwater chemistry (Pearson and White, 1967; Castro and Goblet, 2003; Kreitler and others, 2013). This proposed study builds on a previous study conducted by the Bureau to assess the availability of fresh and brackish groundwater to support hydraulic fracturing in the region where we mapped groundwater TDS in the various aquifer units in the study region (Scanlon and others, 2014).

Previous studies of groundwater quality in the Queen City and Sparta aquifers are reviewed by Kelley and others (2004). Brown (1997) examined regional trends in groundwater quality in the Queen City Aquifer and Biri (1997) conducted similar studies in the Sparta Aquifer. The main finding of these studies is that salinity generally increases regionally towards the south in both aquifers, although neither study covered Webb or Zapata counties. High levels of sodium were also noted as a problem for irrigation water. Payne (1968) subdivided water chemistry in the Sparta aquifer into bicarbonate type water in the north, sulfate type water in the south, and chloride type water in the downdip confined zone. TDS was also found to be inversely related to sand thickness (Payne, 1968). Subsurface bacteria have been found to affect dissolved sulfate and methane concentrations in the Sparta Aquifer (Grossman and others, 1986; Zhang and others, 1988). Kelley and others (2004) identified the dominant processes impacting groundwater chemistry, including ion exchange, with calcium exchanging for adsorbed sodium on clays, increasing the sodium to calcium ratio downdip in these aquifers; oxidation of dissolved or solid organic carbon and methane by bacteria, increasing bicarbonate concentrations, and chloride diffusion from clay beds to higher permeability zones in the aquifers.

3.2 Groundwater Quality Data Sources

We developed a geochemical database that includes groundwater quality data within ±5% charge balance. The primary source of groundwater quality data was the TWDB Groundwater Database. Our study includes 1,462 groundwater samples from the Carrizo-Wilcox Aquifer (**Table 3-1**, **Figure 3-1**), 140 samples from the Queen City Aquifer, and 118 samples from the Sparta Aquifer (**Table 3-1, Figure 3-2**). All samples from the Carrizo-Wilcox Aquifer were analyzed for major ions; analyses of silica are available in 1,345 samples, iron in 634 samples, radium-226 in 81 samples, uranium in 154 samples, barium in 408 samples, and boron in 570 samples. All samples from the Queen City and Sparta aquifers were analyzed for major ions and silica; analyses of iron are available in 143 samples, barium in 87 samples, and boron in 83 samples. The most recent analysis was used in cases where multiple samples were reported. Data on produced water (water co-produced with oil and gas) quality were obtained from the United States Geological Survey (USGS) produced water quality database (205 wells) (https://energy.usgs.gov/EnvironmentalAspects/EnvironmentalAspectsofEnergyProductionandUse/ProducedWaters.aspx#3822349-data). Operators in the Eagle Ford play report drilling and using brackish water with TDS up to 36,000 mg/L in Dewitt County (6,000 ft deep wells) (Scanlon and others, 2014). Although groundwater chemistry data are limited in the Queen City and Sparta aquifers, it was judged sufficient to map regional trends in water quality.

3.3 Characterization of Groundwater Quality

The primary purpose of this characterization effort was to map hydrochemical facies to delineate areas of relatively uniform chemical composition for application of the empirical approach to TDS mapping from electric logs. Future development of brackish groundwater will also be aided by a deeper understanding of salinity sources and distributions that our mapping provides.

We evaluated the distribution of TDS and assessed variations in TDS in the Carrizo-Wilcox aquifer using groundwater data predominantly from the TWDB. TDS in and adjacent to the outcrop zone in the Carrizo-Wilcox aquifer mostly ranges from 500 – 3,000 mg/L (**Figure 3-3**). There is generally a band of lower TDS water (mostly ≤500 mg/L) further downdip. This zone of fresher groundwater has been attributed to paleo-recharge of Pleistocene age water (Green and others, 2008). Slightly higher TDS (500 – 3,000 mg/L) is found further downdip, mostly in the southwest region (Webb, McMullen, and LaSalle counties). The generally higher TDS in the southwest relative to the northeast was attributed to finer grained sediments in the southwest in a previous analysis (Hamlin and others, 1988).

TDS exceeding 3,000 mg/L is found in localized areas throughout the aquifer. Chloride concentrations are also shown, with highest concentrations near the outcrop zone (250 – 7,500 mg/L), and fresher water downdip, with chloride ranging mostly from 25 – 50 mg/L. There are six wells with TDS >3000 mg/L in Zavala County. Four of these wells are shallower (<300 ft) compared with nearby wells (>900 ft) that have low TDS and may be incorrectly categorized as

Carrizo Sand wells. The remaining two wells have depths consistent with neighboring low TDS wells. There does not appear to be a consistent pattern with similar isolated higher TDS in 12 wells throughout Dimmit, La Salle, and Webb counties where the depths of higher TDS wells are generally consistent with those of nearby lower TDS wells.

The vast majority (80%) of TWDB database Carrizo-Wilcox wells in GMA13 indicate a completion in the Carrizo Sand (code 124CRRZ) hydrostratigraphic horizon. These wells are almost entirely located in the confined regions of the aquifer. Most of the remaining wells (16%) indicate that the hydrostratigraphic horizon is the Wilcox formation (code 124WLCX) and are almost entirely located in the outcrop area and mostly in the northern half of the outcrop area starting in Medina County. The band of fresh water down-dip of less fresh water is wider and more well defined in Zavala-Frio-Atascosa counties and is narrower and less well define toward the north. High chloride concentrations are also found further downdip (100 – 7,500 mg/L), particularly in the southwest region, consistent with the TDS distribution.

In the Queen City and Sparta aquifers, wells used for groundwater quality evaluation have sample depths ranging from 20 to 3,500 ft. Groundwater chemistries in the Queen City and Sparta Aquifers are similar, but average TDS is about two times higher in the Sparta Aquifer (2,307 mg/L) than in the Queen City Aquifer (1,249 mg/L). The TDS ranges are 227 – 8,856 mg/L in the Queen City, and 117 – 11,242 mg/L in the Sparta Aquifer. TDS generally exceeds 1,000 mg/L southwest of the Frio River and is quite variable northeast of the Frio River with no evident systematic variation (**Figure 3-4**). High TDS is found in the outcrop of the Queen City in Frio County. The highest TDS (11,249 mg/L) is found in a 1200 ft deep well in Gonzales County. There is no systematic variation in TDS with well depth. For example, some shallow wells have high salinity (e.g. 100 ft deep well in the Sparta Aquifer with 4,400 mg/L TDS; 75 ft public supply well with 2,700 mg/L TDS). Some of these apparent patterns of TDS variability may result from sampling bias. Salinity mapping from geophysical logs (Section 4) reveals more systematic TDS variations and significant fresh groundwater southwest of the Frio River.

TDS of produced waters from oil and gas wells provide an upper bound on TDS in groundwater in the region. Sampling of produced waters is limited with clusters of wells in different regions, e.g. Karnes, Atascosa, and Frio counties (**Figure 3-5**). The limited data suggest that the TDS of produced waters generally increases downdip, from 10,000 – 30,000 furthest updip to 30,000 – 320,000 furthest downdip. These produced waters are based on analyses from conventional oil wells, mostly sampled prior to 1980. The USGS recently collected samples of produced water from unconventional Eagle Ford shale wells; however, the results are not yet available in the USGS website.

The distribution and depths of injection wells used for disposal of produced water (Underground Injection Control Class II wells) were mapped in case water disposal impacts groundwater quality in the vicinity of these wells (**Figure 3-6**). Disposal wells near the outcrop zone range from < 1,000 ft to 4,000 ft. The depths of disposal wells generally increase downdip with wells ranging from 4,000 – 8,000 ft, and some exceeding 8,000 ft (particularly in the southwest in Webb and Zapata counties).

Because of the importance of ionic composition of groundwater on the relationship between resistivity from electric logs and TDS (Estepp, 1998, 2010), we examined the ionic makeup of the water and characterized the dominant composition of the water in the Carrizo-Wilcox, Queen City, and Sparta aquifers. Hydrochemical facies in the Carrizo-Wilcox aquifer vary from predominantly calcium bicarbonate and calcium chloride near the outcrop zone, to mostly sodium bicarbonate and sodium chloride downdip. In the central region of the aquifer, mostly in Atascosa and Frio counties, calcium bicarbonate water is generally further downdip than calcium chloride and sodium chloride rich water. High TDS downdip in the Carrizo-Wilcox aquifer is generally associated with sodium bicarbonate type water, rather than sodium chloride type water (**Figure 3-7**). Localized zones of sodium bicarbonate and sodium chloride water are found mostly in Dimmit County and scattered throughout the aquifer. Major cation and anion water types that make up the water types are also shown (**Figures 3-8** and **3-9**).

Hydrochemical facies in the Queen City and Sparta aquifers range from calcium bicarbonate in the outcrop through sodium calcium bicarbonate and ultimately to sodium potassium bicarbonate chloride type water (**Figure 3-10**). Cation facies vary from predominantly calcium near the outcrop zone to sodium-calcium and sodium-potassium downdip (**Figure 3-11**). Average cation concentrations are dominated by sodium which ranges from 343 mg/L (Queen City Aquifer) to 698 mg/L (Sparta Aquifer). Average calcium concentrations are much lower, and similar in the two aquifers (76 – 85 mg/L). Major anions in the water range from bicarbonate-chloride to chloride-sulfate (**Figure 3-12**). There is no general trend in water type with depth. The main process is cation exchange with waters changing from calcium to sodium.

3.4 Water Quality Relative to Suitability for Desalination or Hydraulic Fracturing

The suitability of the brackish groundwater for desalination and hydraulic fracturing was examined by evaluating the distribution of relevant elements. Parameters of concern for desalination using reverse osmosis (RO) are described in Greenlee and others (2009) and Meyer and others (2012). High concentrations of hydrated silica can foul RO membranes. In the Carrizo-Wilcox aquifer, hydrated silica concentrations are mostly low (≤30 mg/L) (**Figure 3-13**) in wells completed in the up dip confined regions of the Carrizo Sand. Highest silica concentrations in the Carrizo-Wilcox Aquifer are found in the outcrop zone in the central and northern portions of the aquifer in wells that are completed in Wilcox Group units. Isolated zones of high silica are also found in western Dimmit County and furthest downdip in McMullen, Atascosa and Karnes counties (30 – 50 mg/L) that are generally in wells completed in the Carrizo Sand. Hydrated silica concentrations are generally low in the Queen City and Sparta aquifers, mostly ≤20 mg/L; however, some high concentrations (≥50 mg/L) are found near the outcrop **(Figure 3-14**).

High iron levels and subsequent iron precipitation can also foul RO membranes; thus, necessitating pretreatment. For the Carrizo-Wilcox aquifer, the outcrop zone in the central and northern parts usually have the highest iron concentrations (0.5 – 68 mg/L), and coincide with high TDS areas (**Figure 3-15**). The rest of the aquifer has generally low iron levels, mostly ≤0.5 mg/L. Iron concentrations are much higher in the Queen City Aquifer (mean 2,066 g/L) than in the Sparta Aquifer (mean 0.655 mg/L) (**Figure 3-16**), similar to their differences in TDS concentrations; however, the highest levels (34 mg/L) are still much lower relative to the Carrizo-Wilcox Aquifer (68 mg/L). Iron concentrations are generally highest near the Queen City and Sparta outcrop zone, and much lower downdip.

Radionuclides are important because the presence of high levels of Naturally Occurring Radioactive Materials (NORMs) is a problem for disposal of concentrate derived from desalination. The limited number of radionuclide analyses available for the Carrizo-Wilcox Aquifer reveal overall low (mostly ≤5 pCi/L) levels of radium-226. In the central region near the border between Frio and Medina counties, slightly higher concentrations of radium-226 occur, but seem localized (**Figure 3-17**). Uranium concentrations in the Carrizo-Wilcox Aquifer are also generally low (mostly < 2 μg/L), with slightly higher concentrations (3 – 43 μg/L) occurring locally in Zavala County in the southwest (**Figure 3-18**). For the Queen City and Sparta aquifers, there are no reported data on radionuclides or uranium concentrations.

Hydraulic fracturing technologies are evolving to facilitate the use of more brackish and saline groundwater (LeBas and others, 2013); however, this remains an ongoing process as certain constituents in water may still interfere with hydraulic fracturing fluids. Microbial reduction can cause sulfates to interfere with hydraulic fracturing fluids; thus, requiring higher levels of biocides for pretreatment. Other constituents, such as barium sulfate and hard water (containing calcium and/or magnesium) can cause scaling, and also interfere with hydraulic fracturing. Boron can pose problems when cross link gels containing boron are used in hydraulic fracturing fluids. To determine the suitability of brackish groundwater from the Carrizo-Wilcox, Queen City and Sparta aquifers for hydraulic fracturing, we developed areal maps showing the spatial distribution of these ionic concentrations within the aquifers.

The highest concentrations of sulfate, mostly 100 – 1,900 mg/L, occur within or near the outcrop zone of the Carrizo-Wilcox Aquifer (**Figure 3-19**). Sulfate concentrations generally decrease further downdip, with the Zavala, Frio, and La Salle counties in the southwest having sulfate levels of 50 – 100 mg/L. Further north, the downdip decrease in sulfate concentrations is more abrupt, with sulfate concentrations ranging from < 25 – 50 mg/L. Map of the Queen City and Sparta aquifers shows variable sulfate concentrations to the east, with generally no systematic variation (range: < 25 to 585 mg/L). Low levels of sulfate are generally found where bicarbonate levels are high (**Figure 3-20**). Elevated levels of sulfate are generally found west of the Frio River (250 – 585 mg/L).

Systemic trends in barium concentrations is not evident in the analyses for the Carrizo-Wilcox, Queen City or Sparta aquifers, as all had limited analyses of barium (**Figure 3-21**). In the Carrizo-Wilcox Aquifer, high barium concentrations of mostly 100 – 200 μg/L occur in Dimmit, Zavala, Frio, Atascosa and Wilson counties, with a lower barium zone (≤75 μg/L) usually further downdip. Barium concentrations are low (≤50 μg/L) within most of the Queen City and Sparta aquifers, with some localized hotspots where barium ranges from 200 – 500 μg/L) (**Figure 3-22**).

Boron concentrations in most of the Carrizo-Wilcox Aquifer are in the low to moderate range of 100-500 μg/L. Localized spots of higher concentrations occur throughout the aquifer (500 – 26,500 μg/L), and occur widely in the Dimmit, La Salle, and Webb counties (**Figure 3-23**). In the Queen City and Sparta aquifers, boron concentrations range from 200 – 500 μg/L throughout much of the aquifer, with higher concentrations in the confined zone (1,000 –1,500 μg/L) (**Figure 3-24**).

In summary, the water chemistry is generally considered suitable for desalination with generally low silica and iron concentrations. Limited radionuclide analyses restrict our ability to assess its potential impact on concentrate disposal from desalination. Water quality issues related to use for hydraulic fracturing may be problematic near the outcrop zone where sulfate and barium concentrations are high with lower levels further downdip. Limited sampling of boron underscores the need for more intensive sampling to increase the reliability of the areal maps.

Table 3-1. Well depth ranges and numbers of analyses for various water constituents from the Carrizo-Wilcox, Queen City, and Sparta aquifers (TWDB), and from producing oil and gas wells (USGS) in the study area.

Source of Sample	Data Source	Depth Range (ft)	Total Dissolved Solids	Major Ions	Silica	Iron	Radium-226	Uranium	Barium	Boron
Carrizo-Wilcox Aquifer	TWDB	18 – 6,211	1,462	1,462	1,345	634	81	154	408	570
Queen City Aquifer	TWDB	20 – 3,500	140	140	140	143			87	83
Sparta Aquifer	TWDB	20 – 3,500	118	118	118	143			87	83
Produced Waters	USGS	1,494 – 12,388	205							

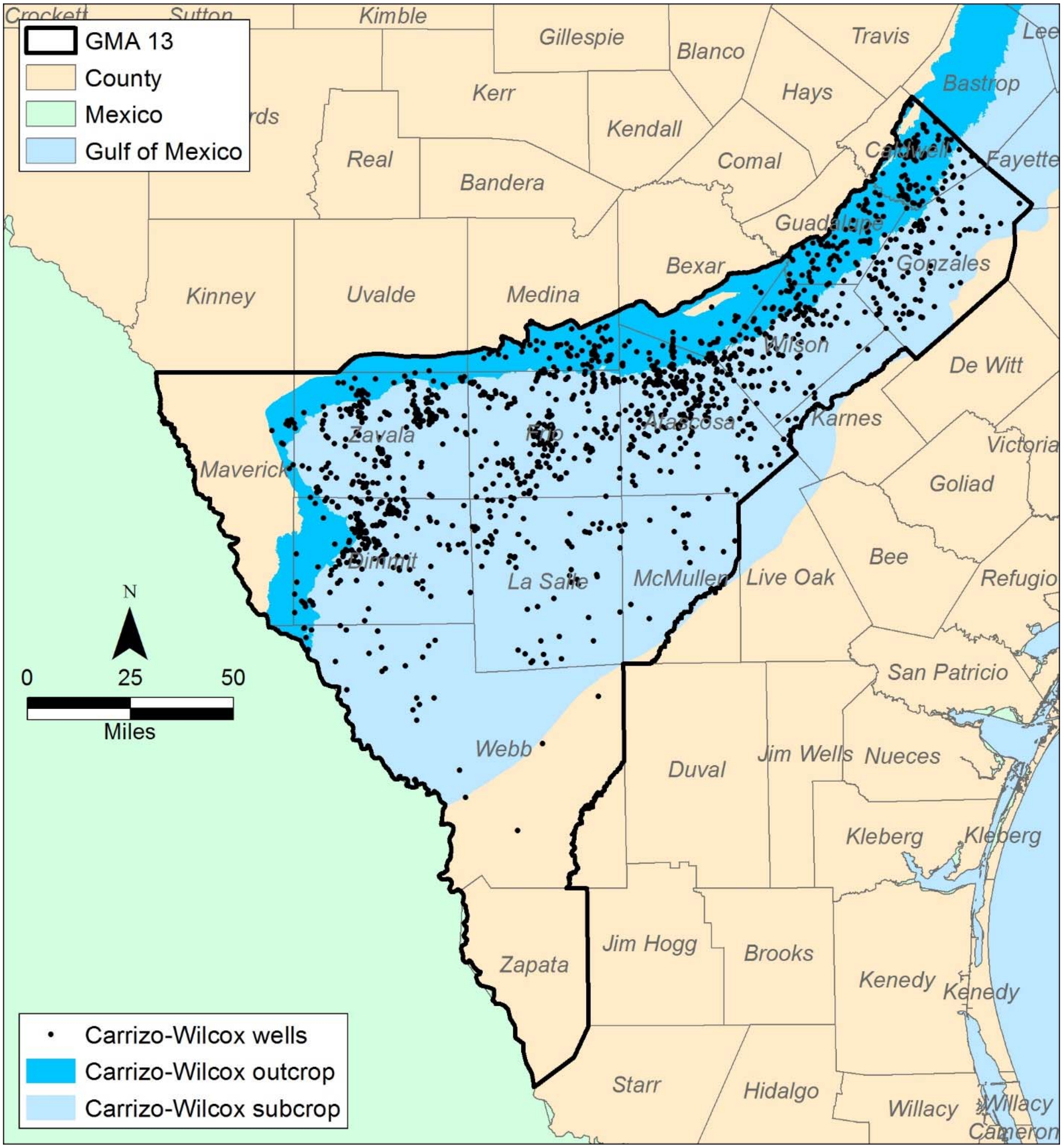


Figure 3-1. Location of wells with groundwater chemical analyses in the Carrizo-Wilcox aquifer from the TWDB database.

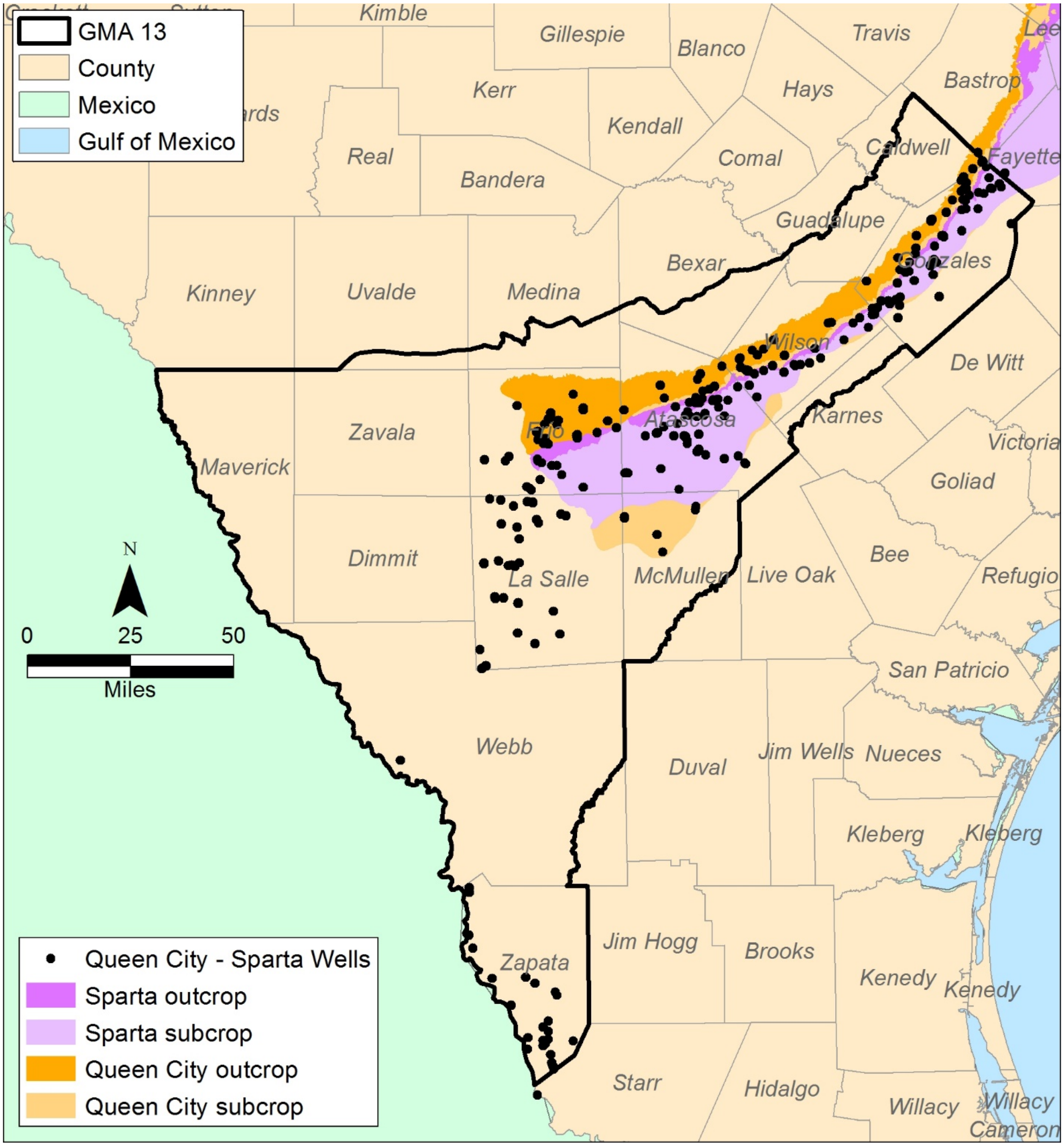


Figure 3-2. **Location of wells with groundwater chemical analyses in the Queen City and Sparta aquifers from the TWDB database. Well locations outside the official aquifer boundaries were completed in Queen City/Sparta-equivalent strata (Bigford, Laredo) in South Texas.**

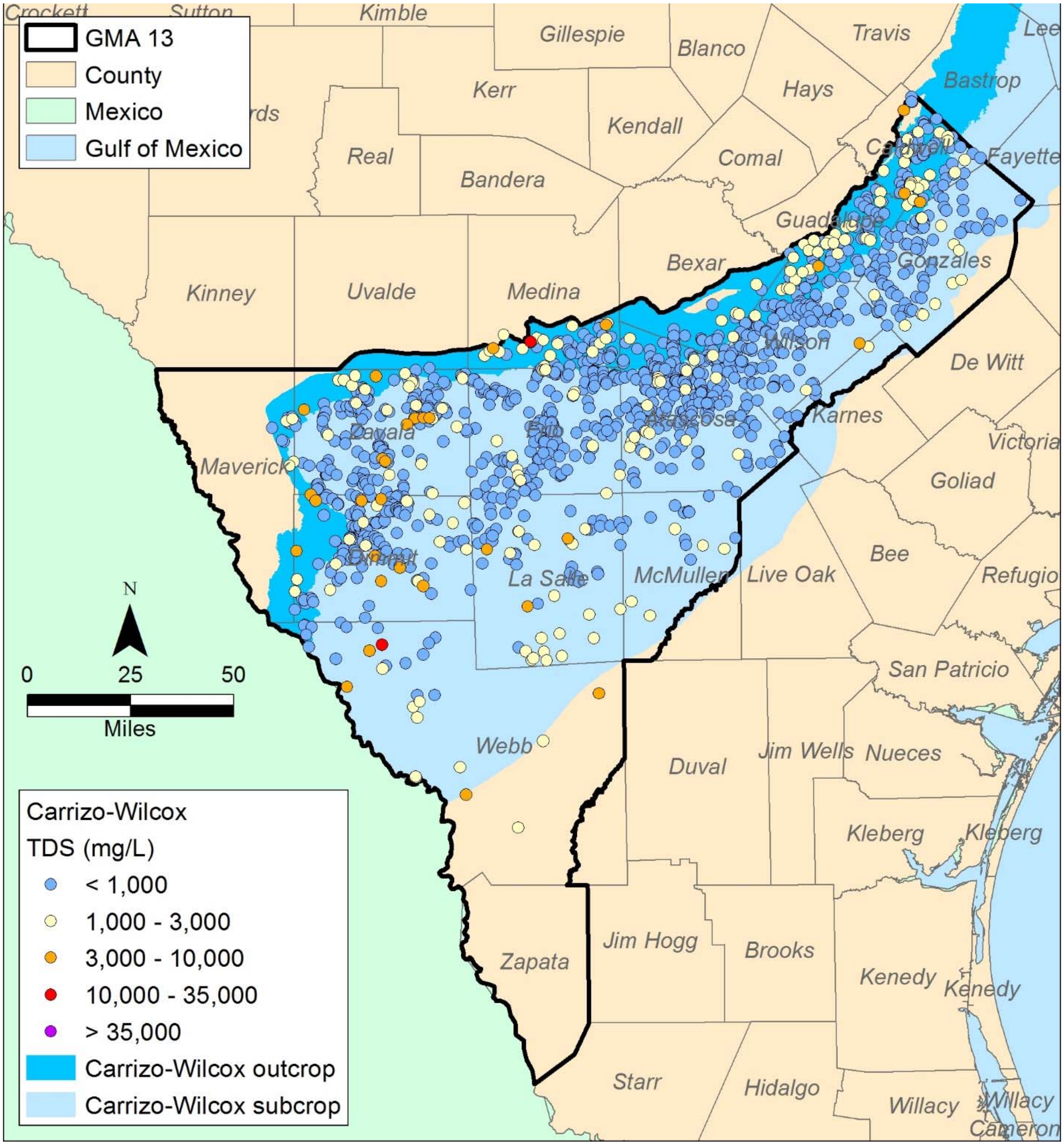


Figure 3-3. **Distribution of groundwater total dissolved solids (TDS) concentrations in the Carrizo-Wilcox aquifer based on the most recent chemical analyses.**

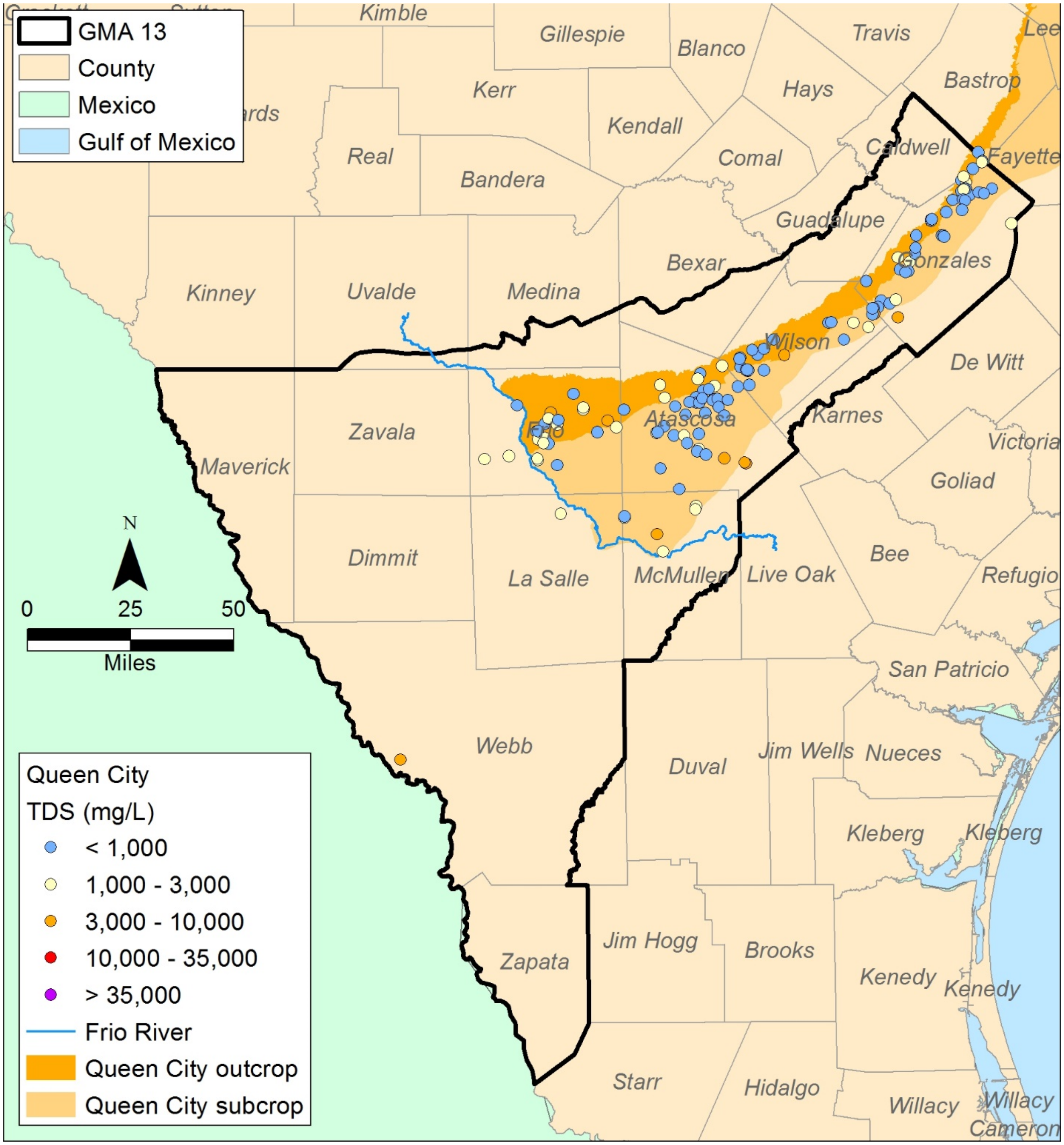


Figure 3-4a. **Distribution of groundwater total dissolved solids (TDS) concentrations in the Queen City aquifer based on the most recent chemical analyses.**

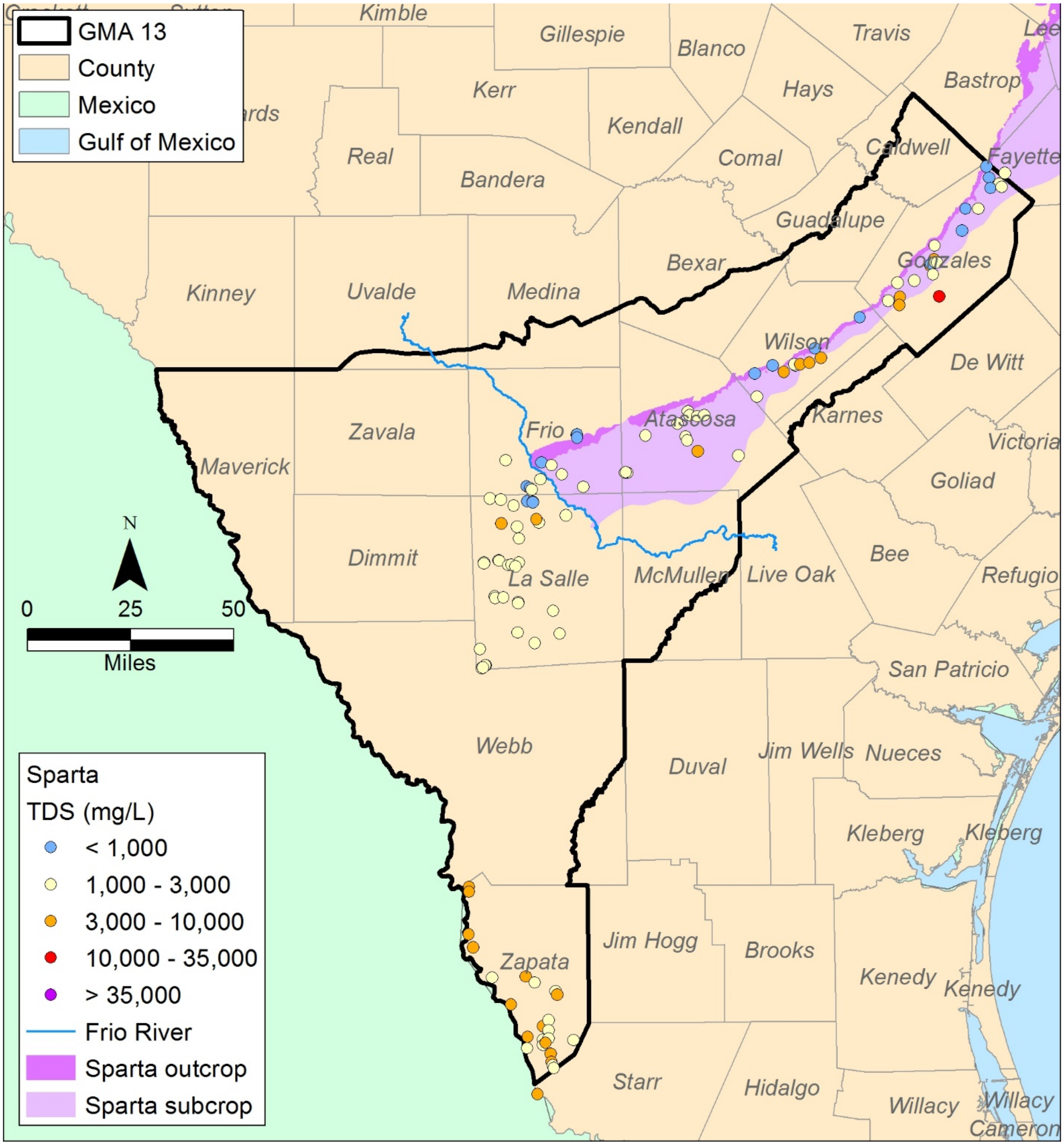


Figure 3-4b. **Distribution of groundwater total dissolved solids (TDS) concentrations in the Sparta aquifer based on the most recent chemical analyses.**

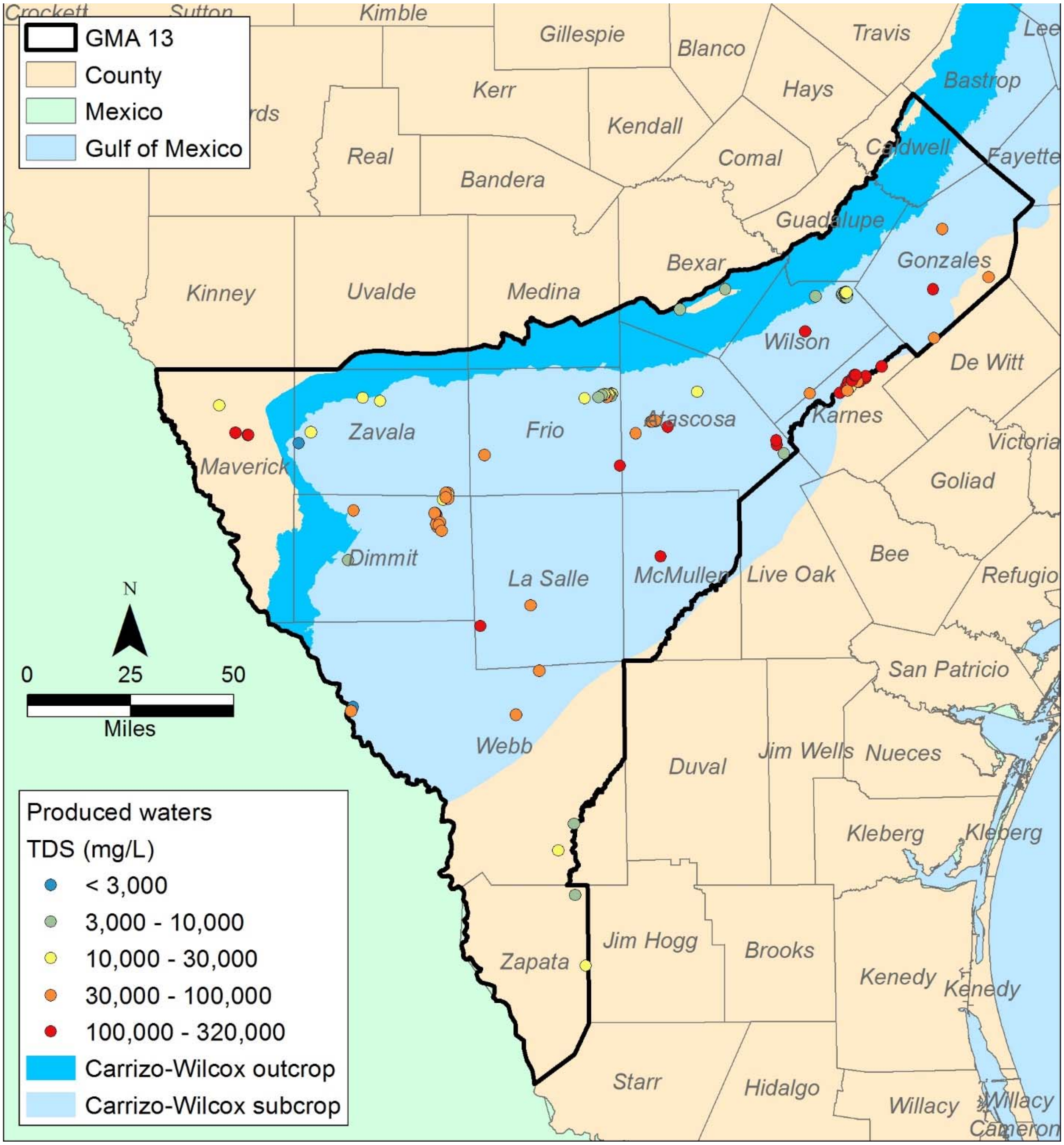


Figure 3-5. **Location and TDS concentrations of wells with water samples from the USGS Produced Waters database (http://energy.usgs.gov/EnvironmentalAspects/EnvironmentalAspectsofEnergyProductionandUse/ProducedWaters.aspx#3822349-data)**

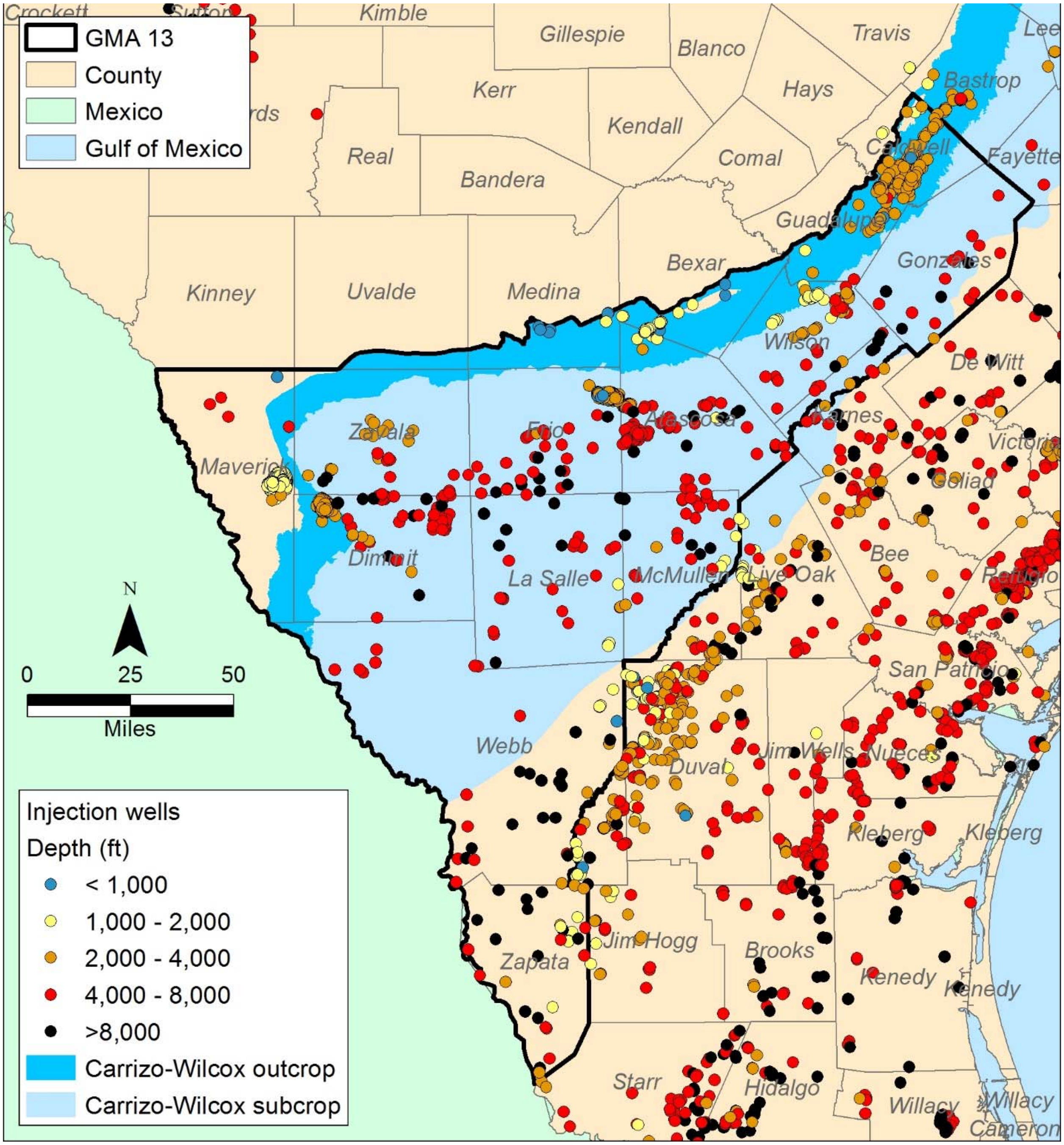


Figure 3-6. **Location and depths of injection wells in the region. Injection wells include Salt Water Disposal wells and wells with injection into producing horizons.**

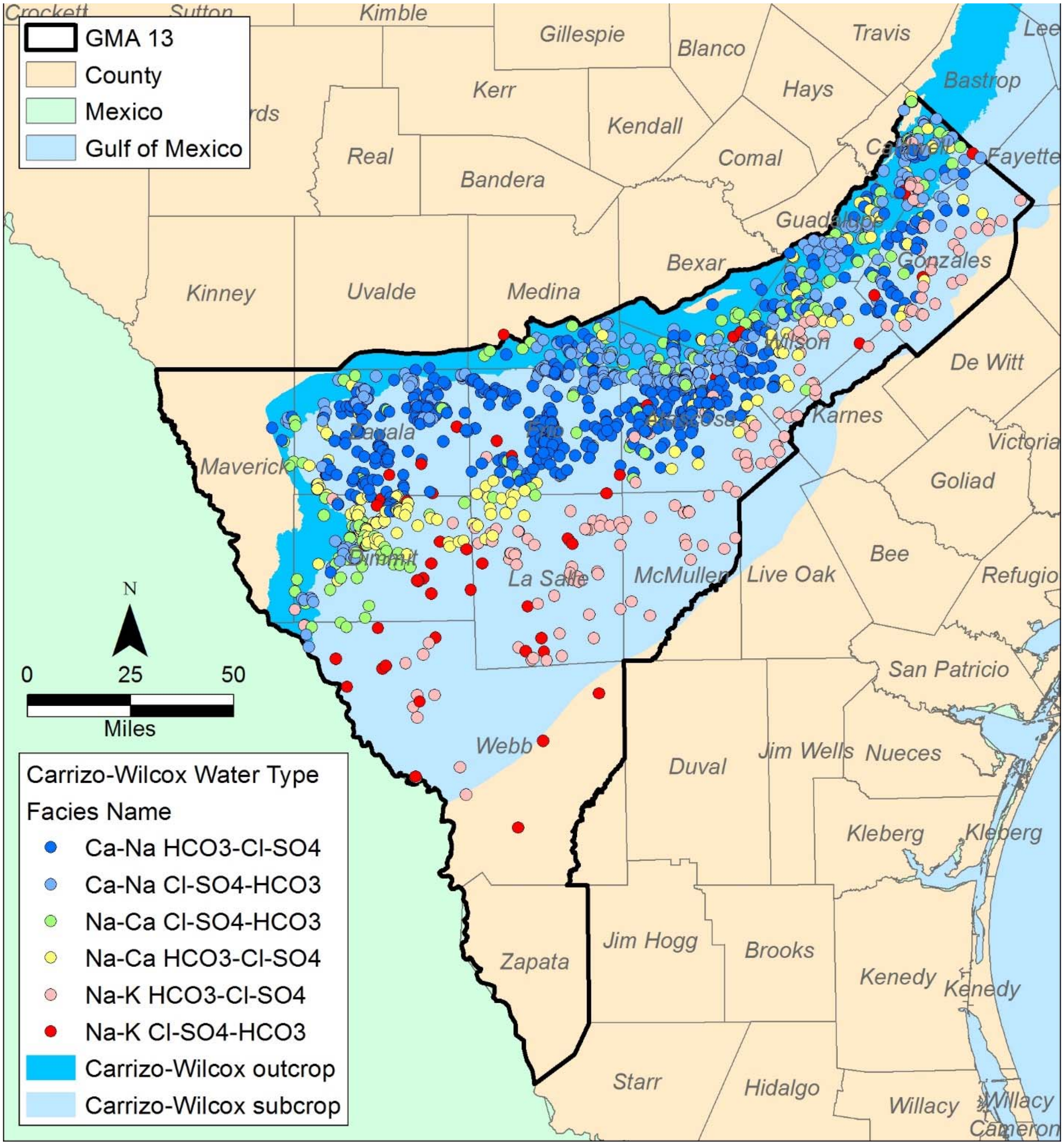


Figure 3-7. **Distribution of dominant hydrochemical facies in the Carrizo-Wilcox aquifer based on the most recent chemical analyses.**

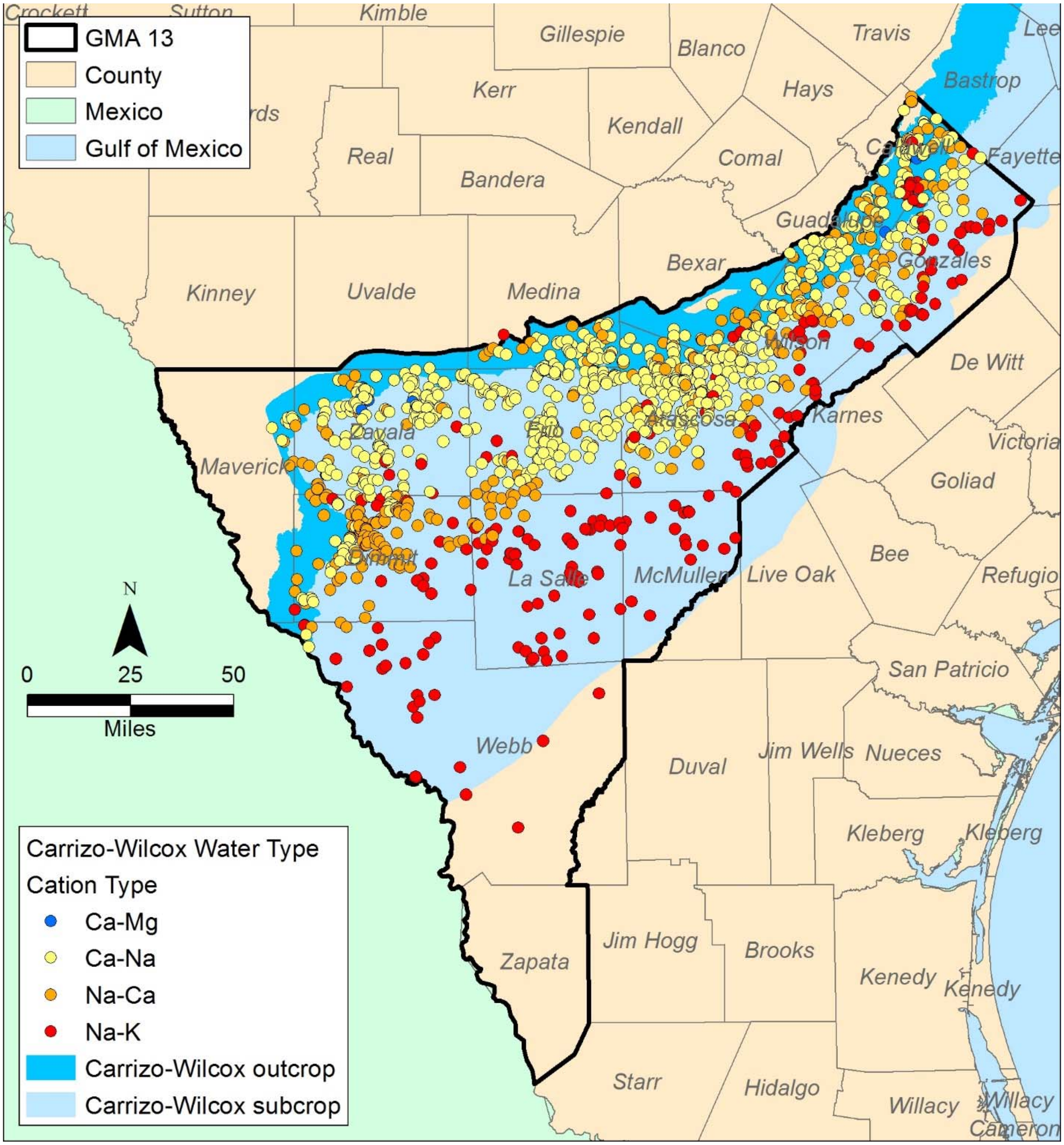


Figure 3-8. **Distribution of dominant cation hydrochemical facies in the Carrizo-Wilcox aquifer based on the most recent chemical analyses. End members (Ca-Mg and Na-K) represent waters with those constituents representing at least 90% of all cations. Ca-Na represents waters with Ca representing between 50% and 90% of all cations and Na-Ca represents waters with Na representing between 50% and 90% of all cations.**

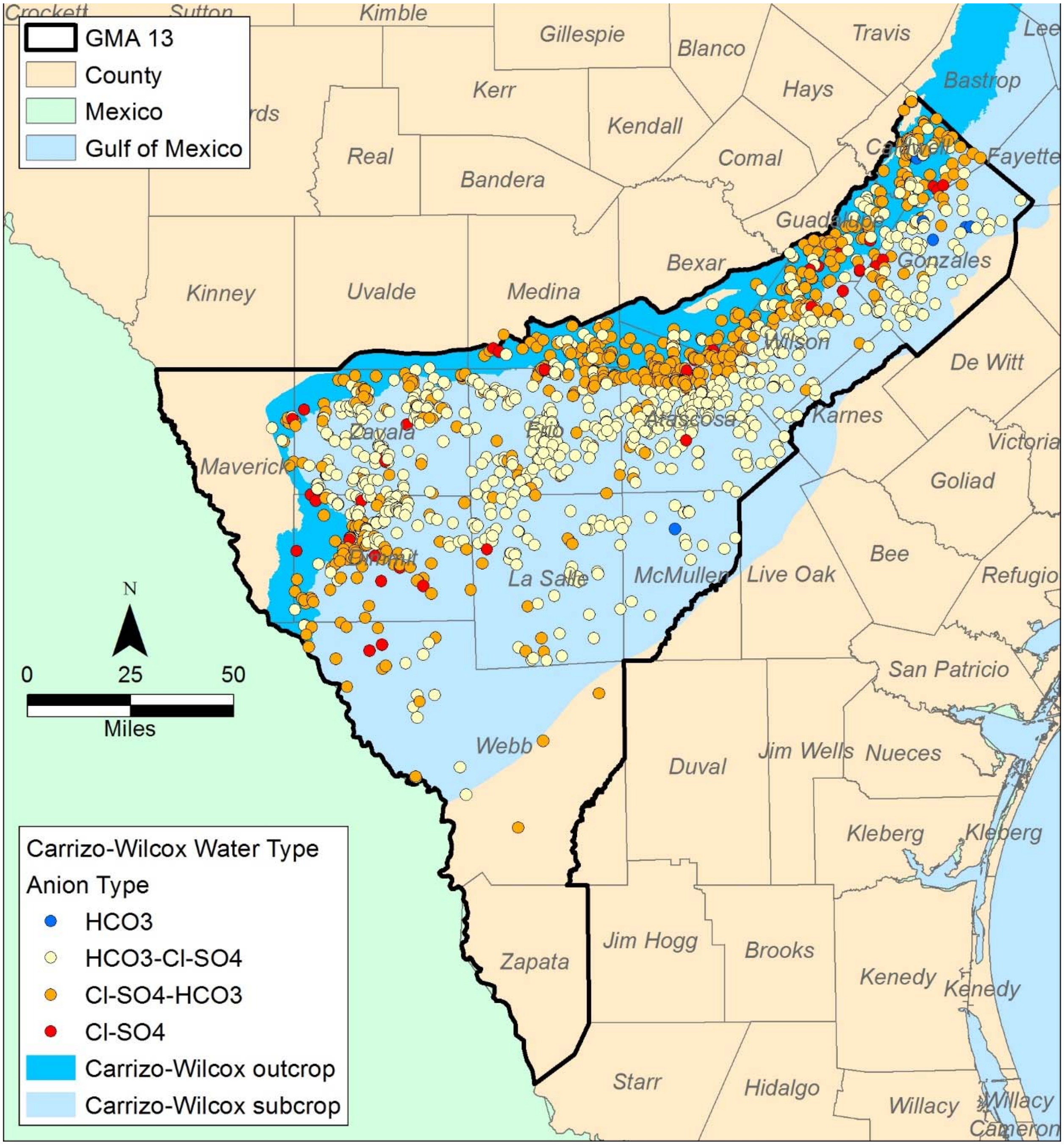


Figure 3-9. **Distribution of dominant anion hydrochemical facies in the Carrizo-Wilcox aquifer based on the most recent chemical analyses. End members (HCO3 and Cl-SO4) represent waters with those constituents representing at least 90% of all anions. HCO3-Cl-SO4 represents waters with HCO3 representing between 50% and 90% of all anions and Cl-SO4-HCO3 represents waters with Cl-SO4 representing between 50% and 90% of all anions.**

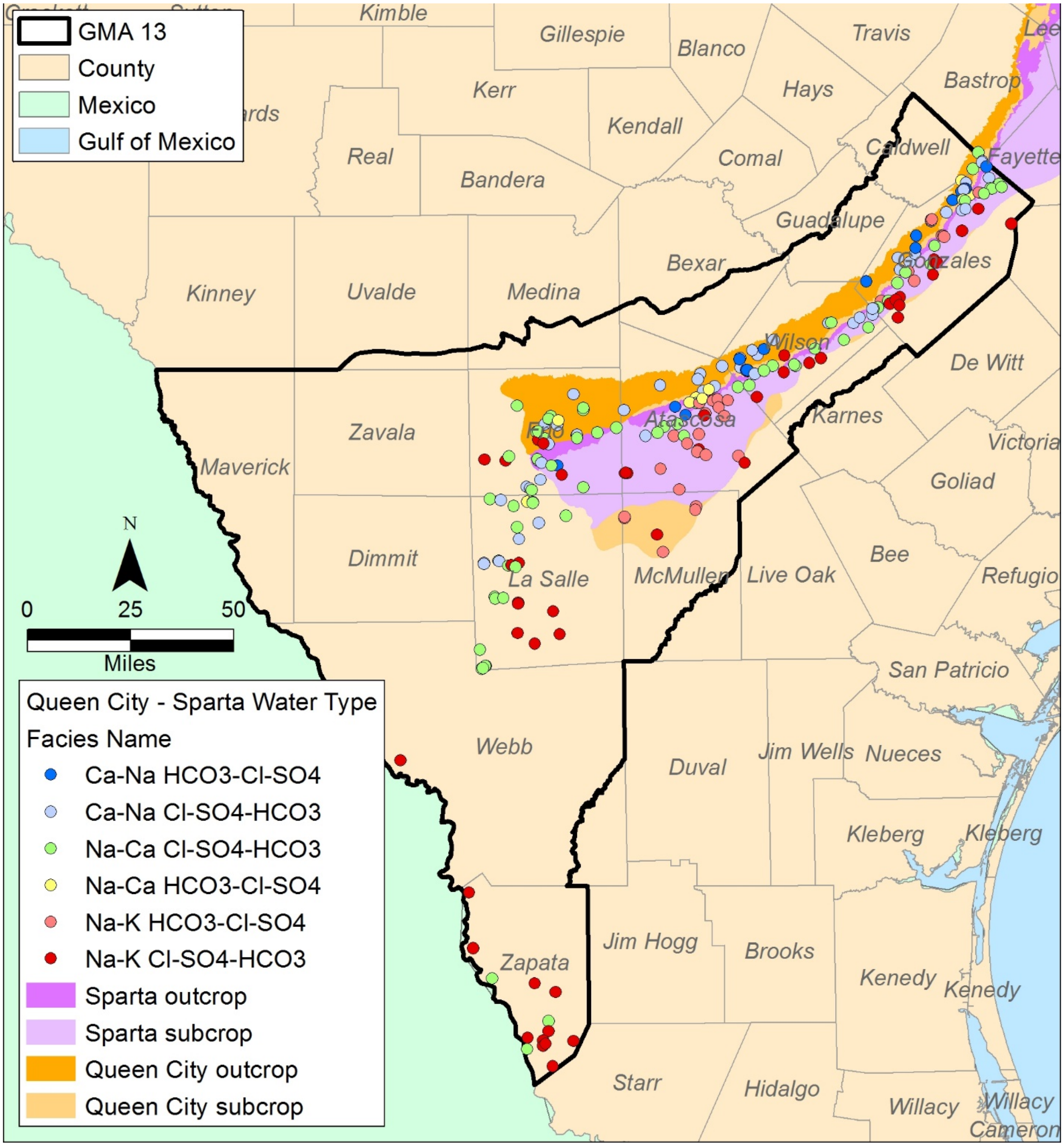


Figure 3-10. **Distribution of dominant hydrochemical facies in the Queen City and Sparta aquifers based on the most recent chemical analyses. Sample locations outside the official aquifer boundaries were collected from Queen City/Sparta-equivalent strata (Bigford, Laredo) in South Texas.**

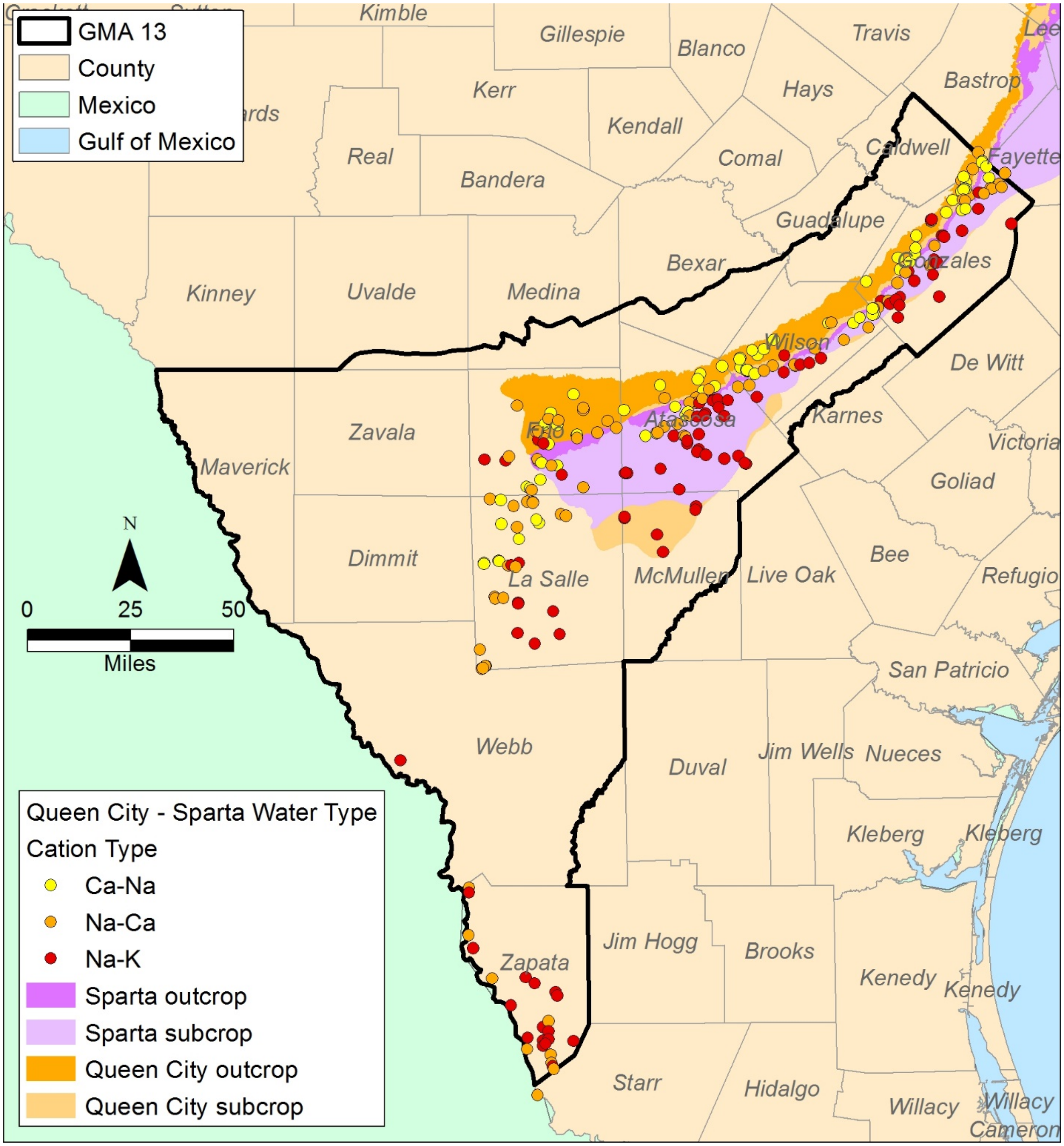


Figure 3-11. **Distribution of dominant cation hydrochemical facies in the Queen City and Sparta aquifers based on the most recent chemical analyses. Sample locations outside the official aquifer boundaries were collected from Queen City/Sparta-equivalent strata (Bigford, Laredo) in South Texas.**

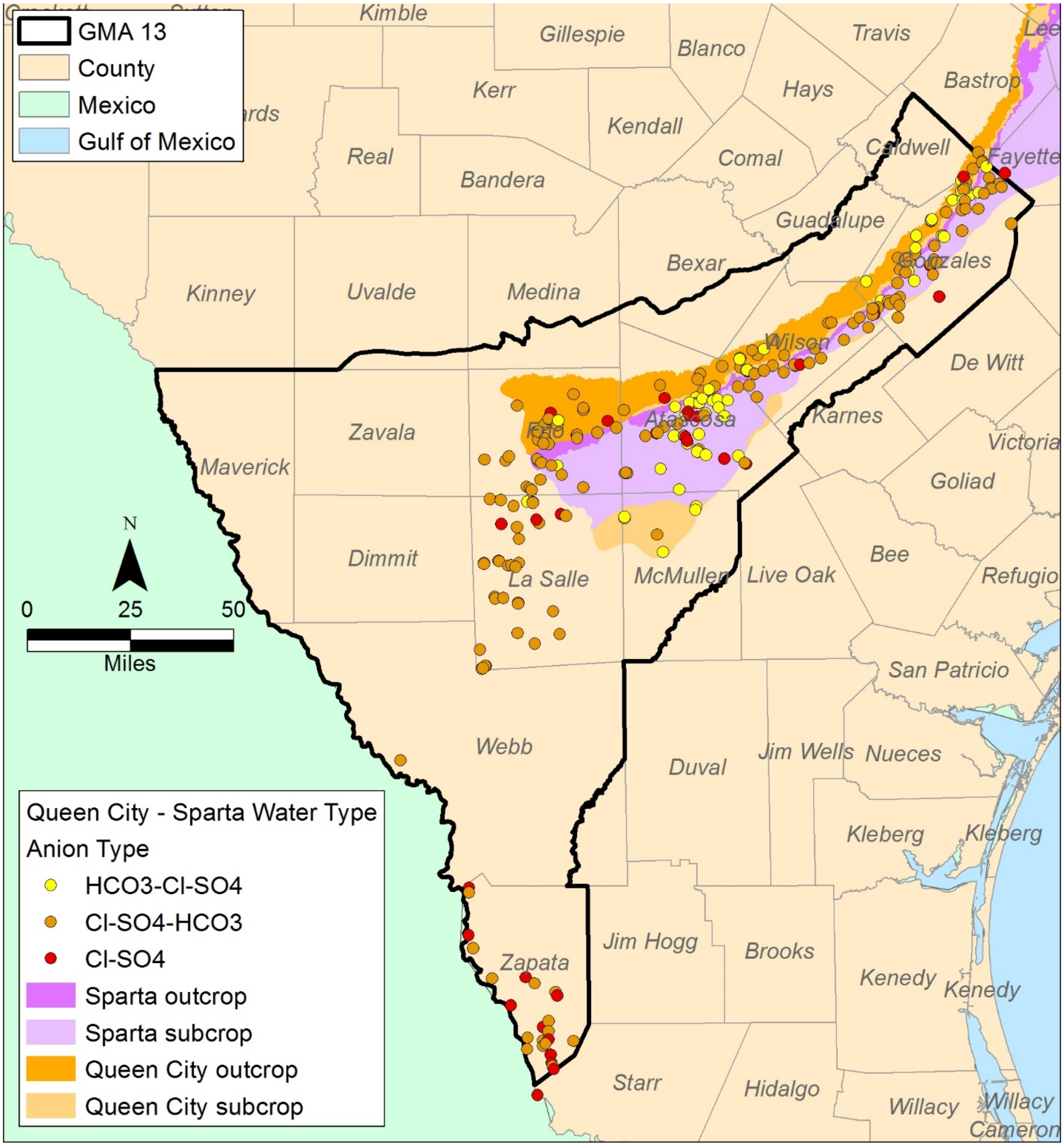


Figure 3-12. **Distribution of dominant anion hydrochemical facies in the Queen City and Sparta aquifers based on the most recent chemical analyses. Sample locations outside the official aquifer boundaries were collected from Queen City/Sparta-equivalent strata (Bigford, Laredo) in South Texas.**

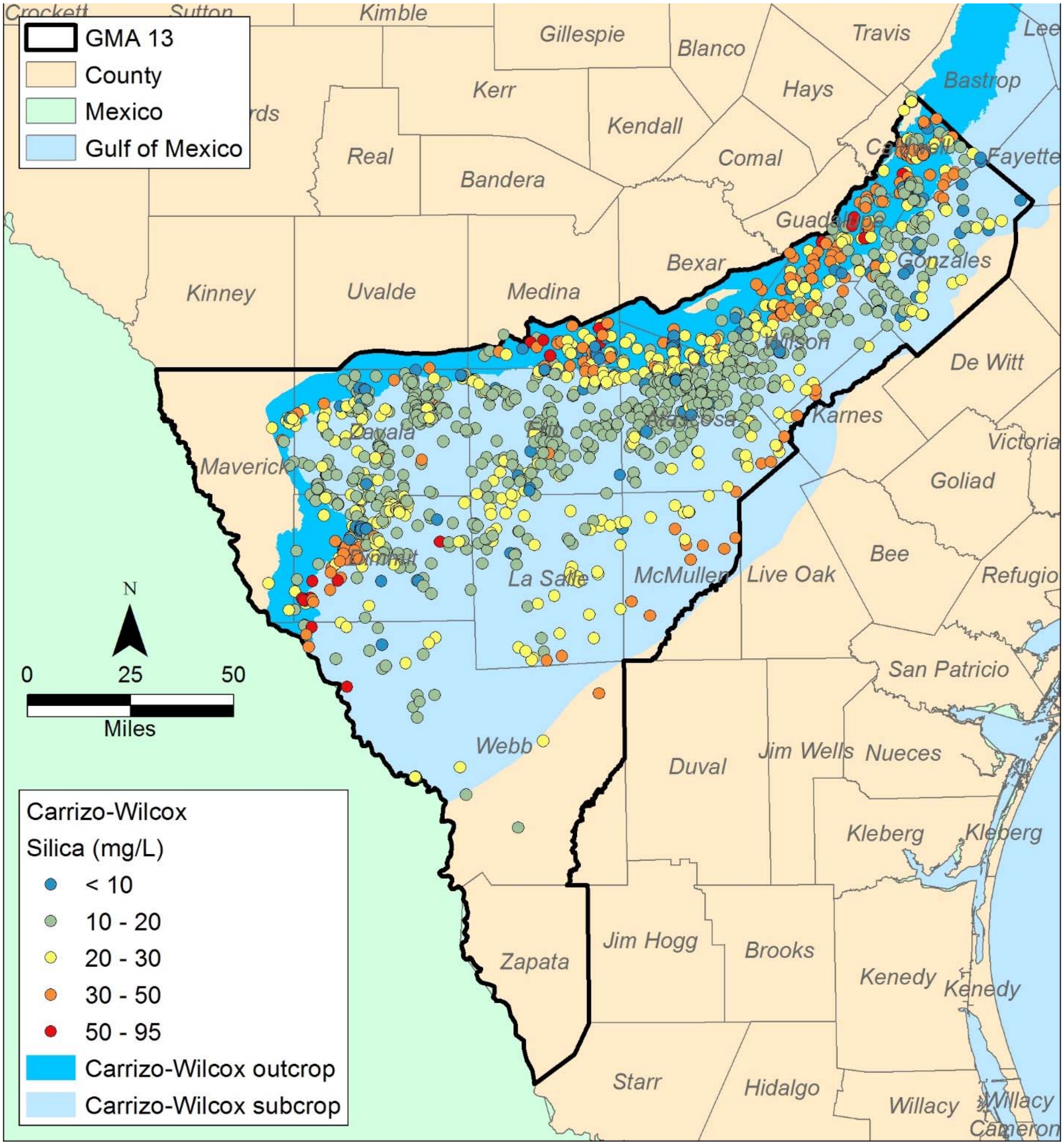


Figure 3-13. Distribution of groundwater silica (SiO2) concentrations in the Carrizo-Wilcox aquifer based on the most recent chemical analyses.

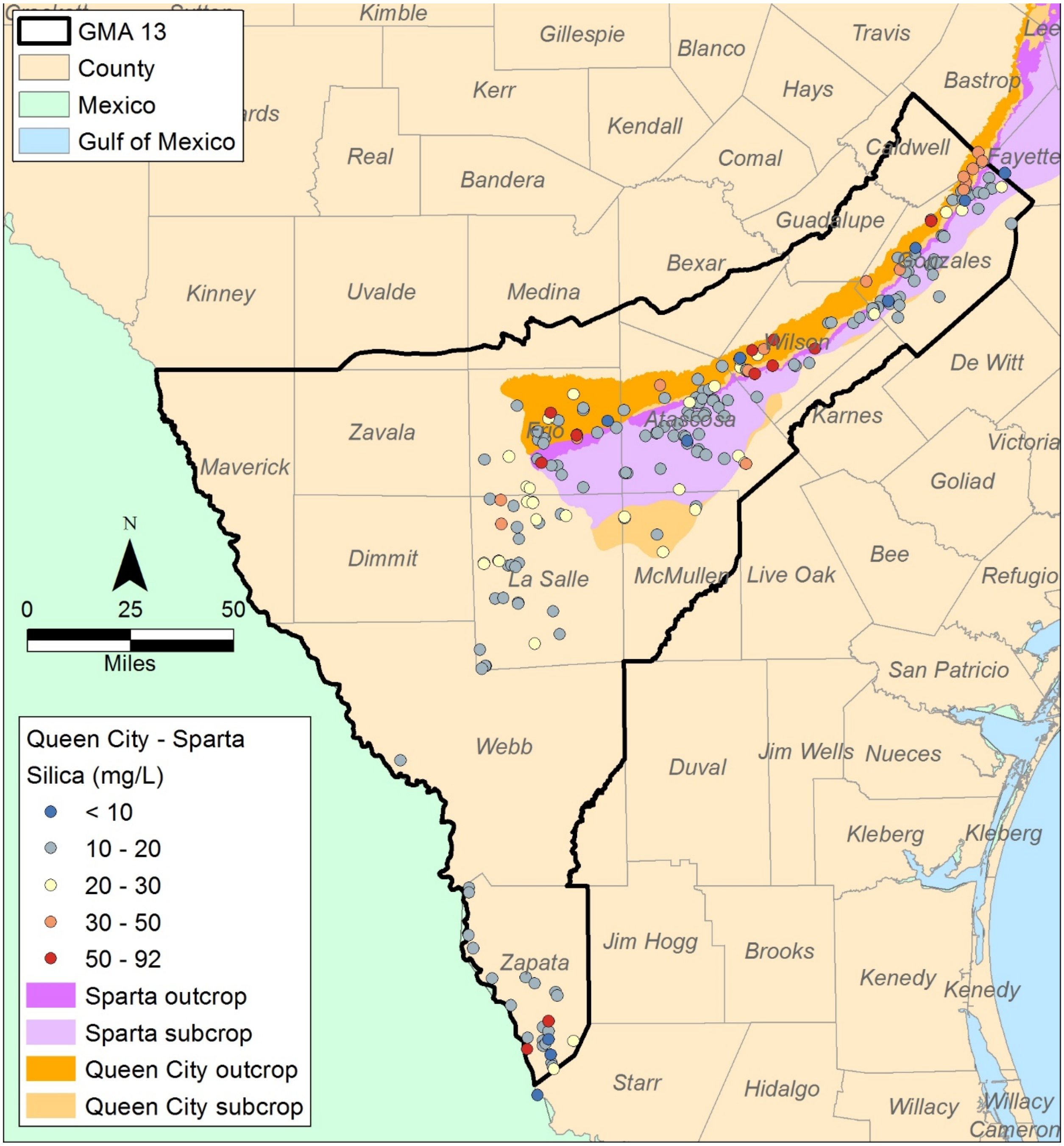


Figure 3-14. **Distribution of groundwater silica (SiO_2) concentrations in the Queen City and Sparta aquifers based on the most recent chemical analyses. Sample locations outside the official aquifer boundaries were collected from Queen City/Sparta-equivalent strata (Bigford, Laredo) in South Texas.**

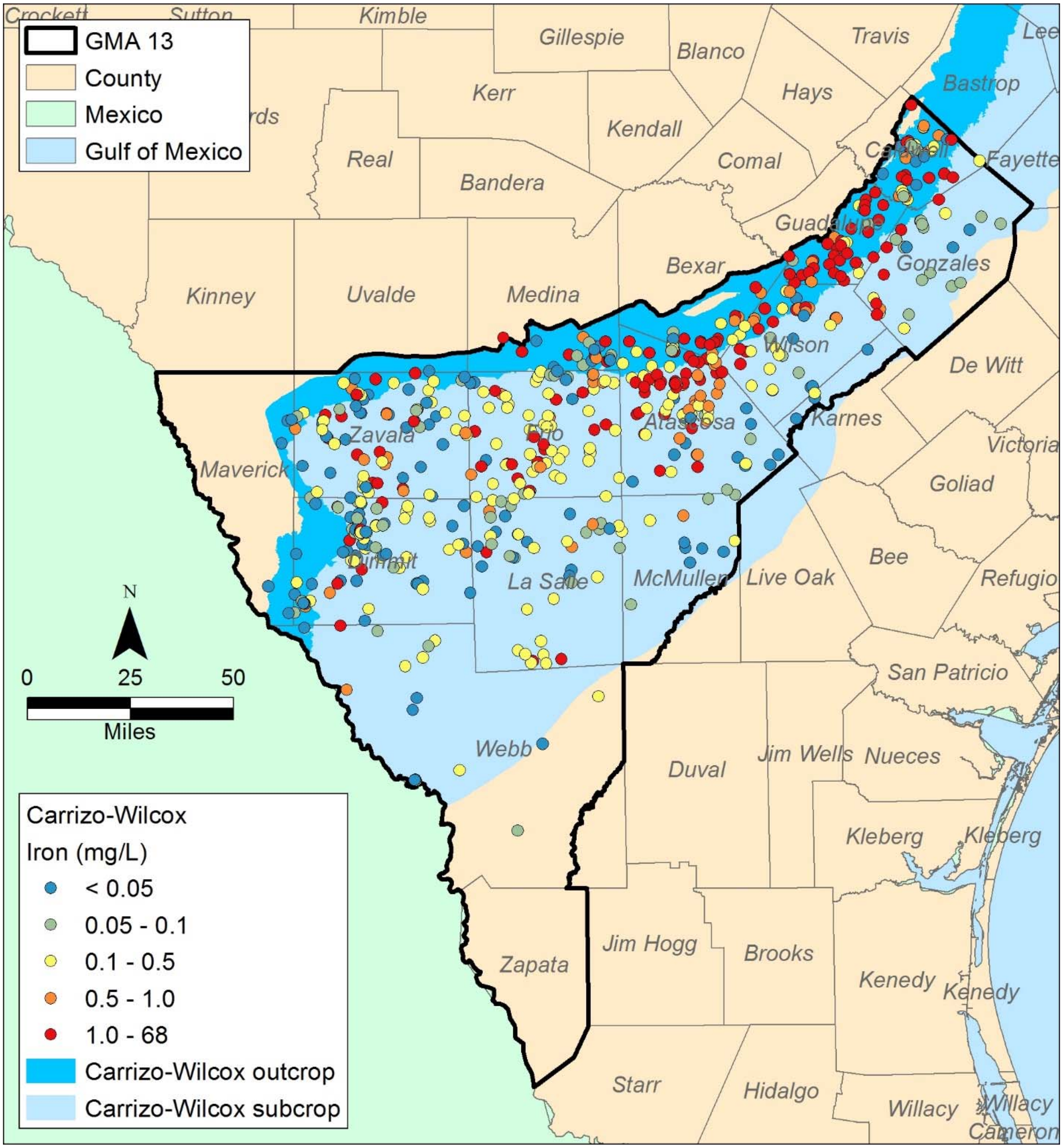


Figure 3-15. Distribution of groundwater iron (Fe) concentrations in the Carrizo-Wilcox aquifer based on the most recent chemical analyses.

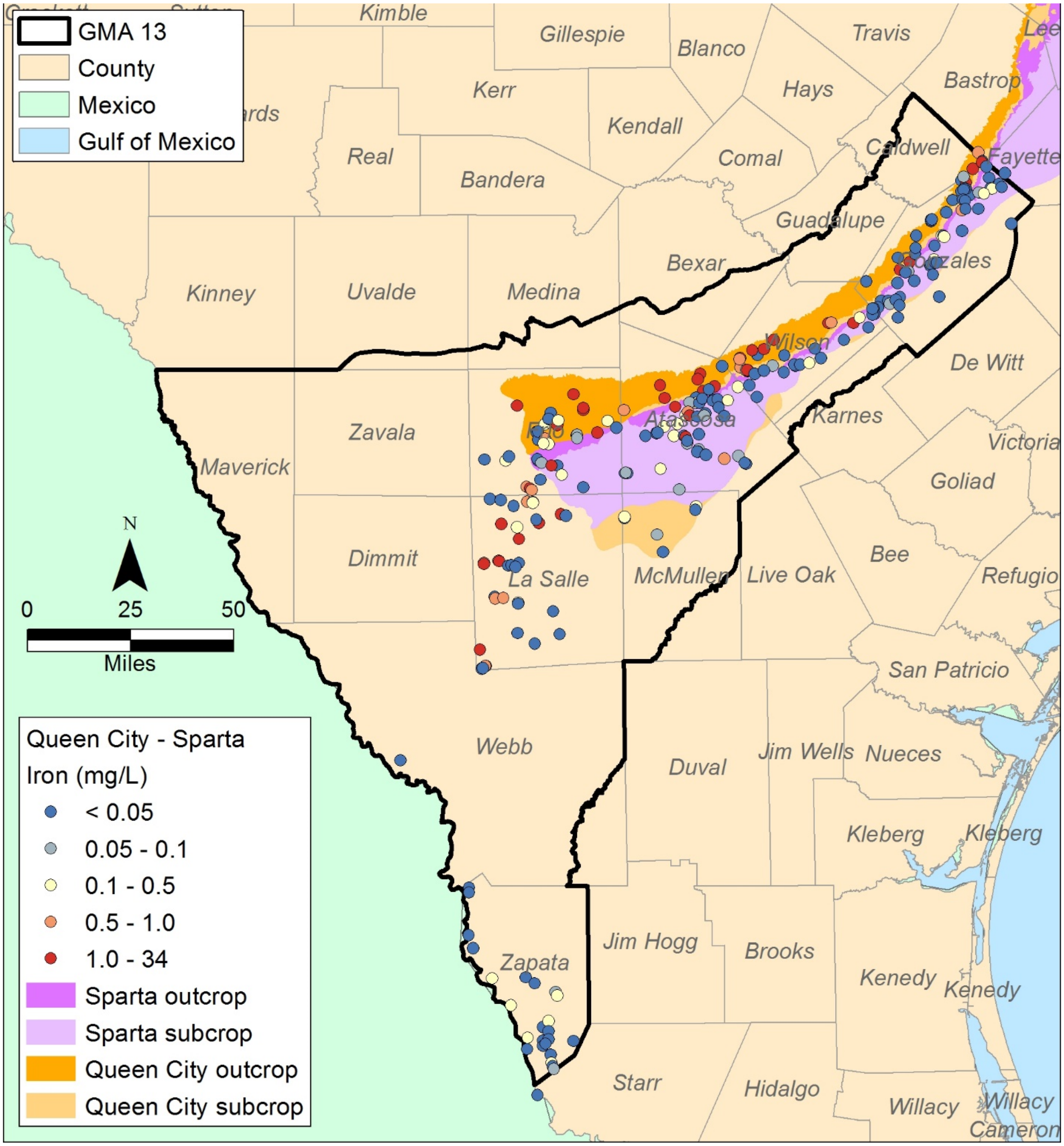


Figure 3-16. **Distribution of groundwater iron (Fe) concentrations in the Queen City and Sparta aquifers based on the most recent chemical analyses. Sample locations outside the official aquifer boundaries were collected from Queen City/Sparta-equivalent strata (Bigford, Laredo) in South Texas.**

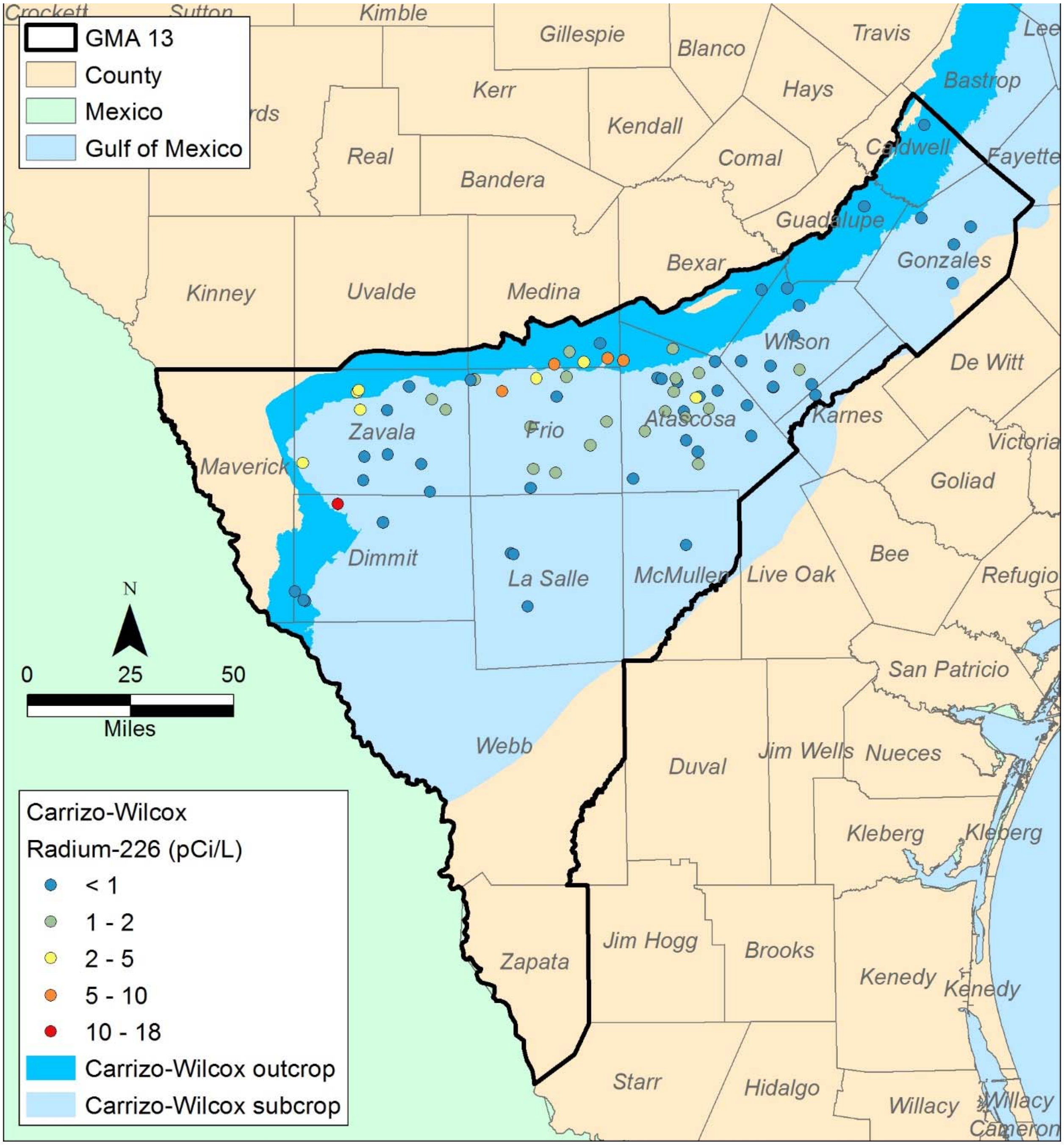


Figure 3-17. **Distribution of groundwater radium-226 (Ra-226) concentrations in the Carrizo-Wilcox aquifer based on the most recent chemical analyses.**

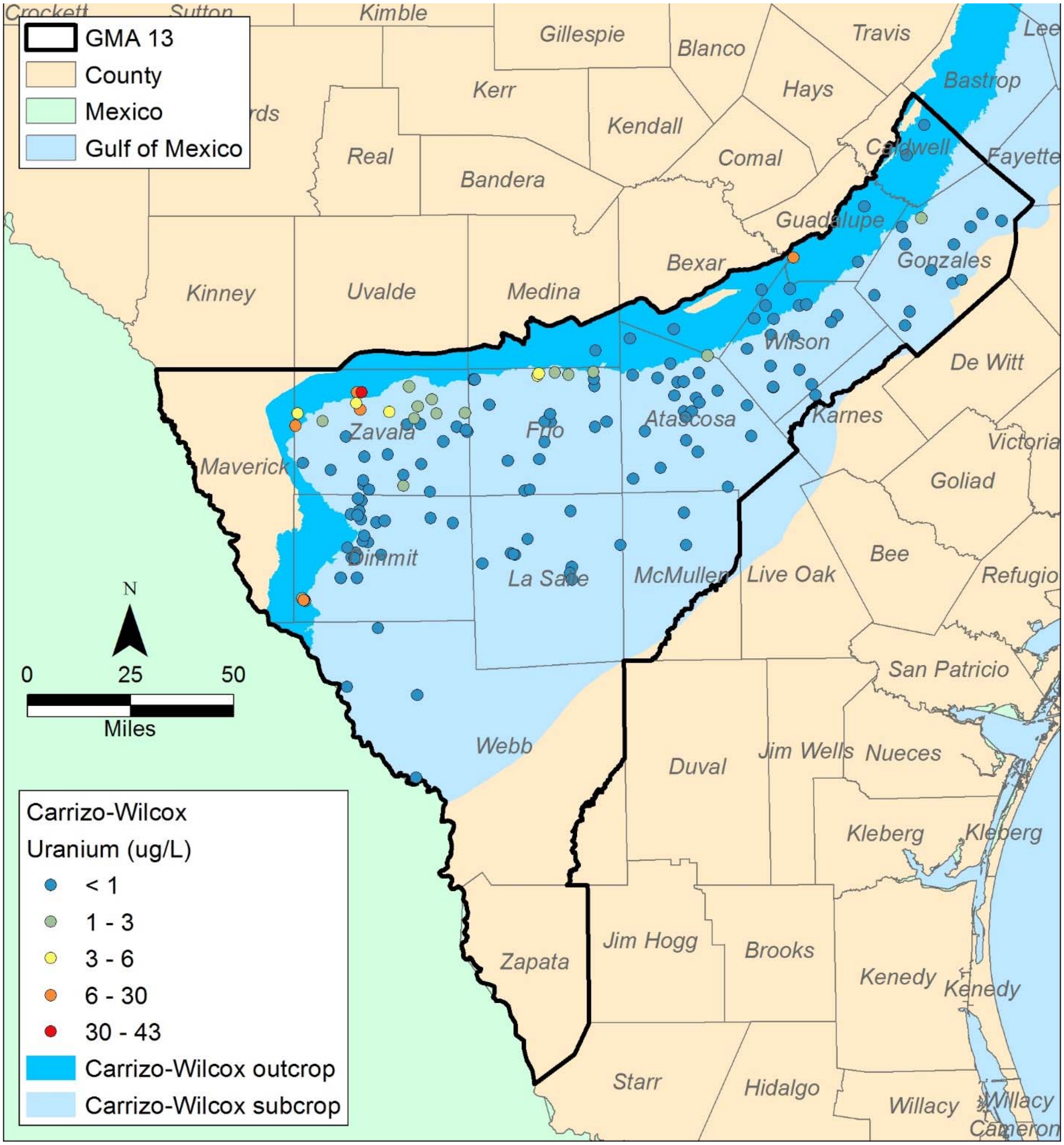


Figure 3-18. **Distribution of groundwater uranium (U) concentrations in the Carrizo-Wilcox aquifer based on the most recent chemical analyses.**

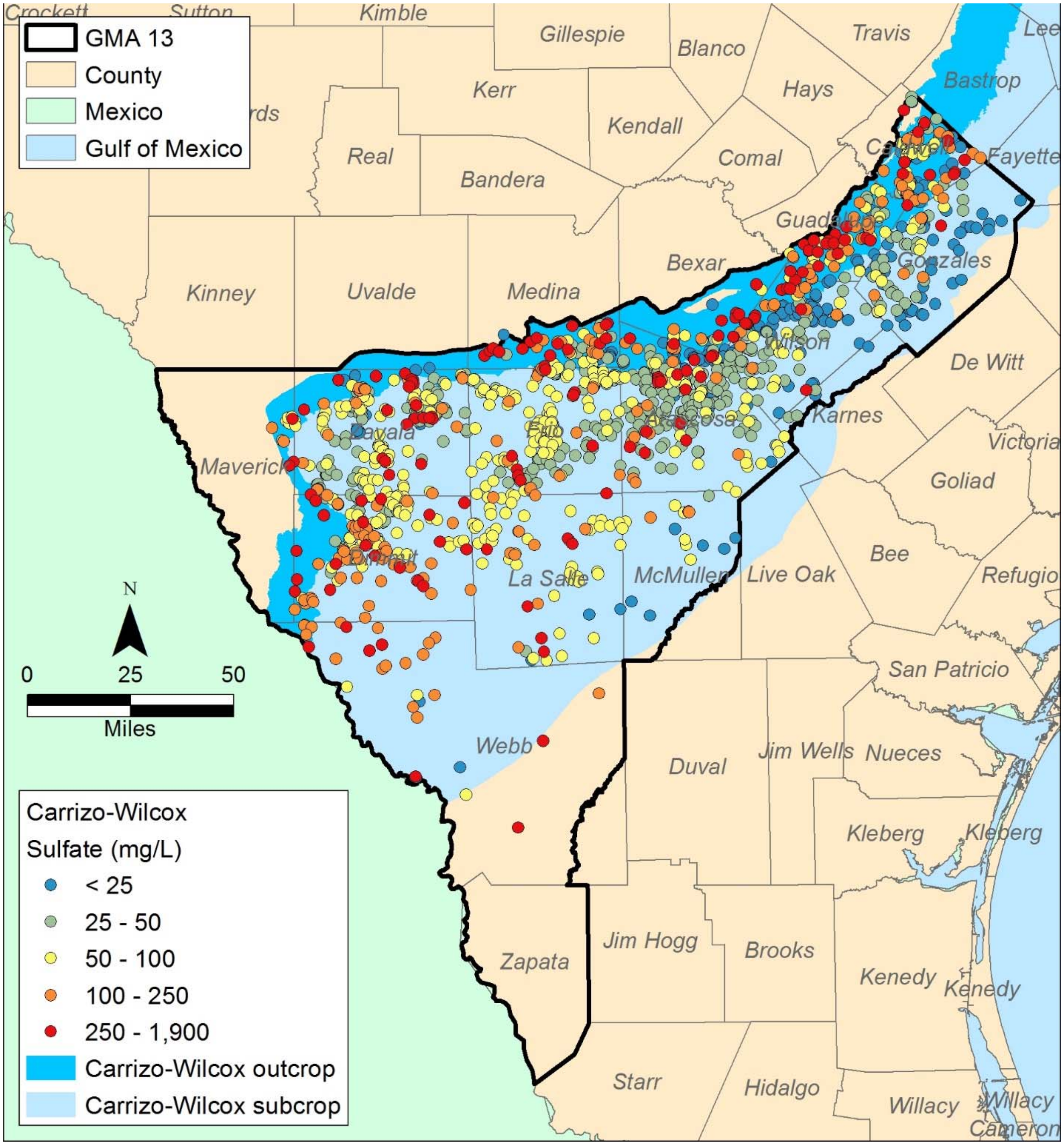


Figure 3-19. **Distribution of groundwater sulfate (SO4) concentrations in the Carrizo-Wilcox aquifer based on the most recent chemical analyses.**

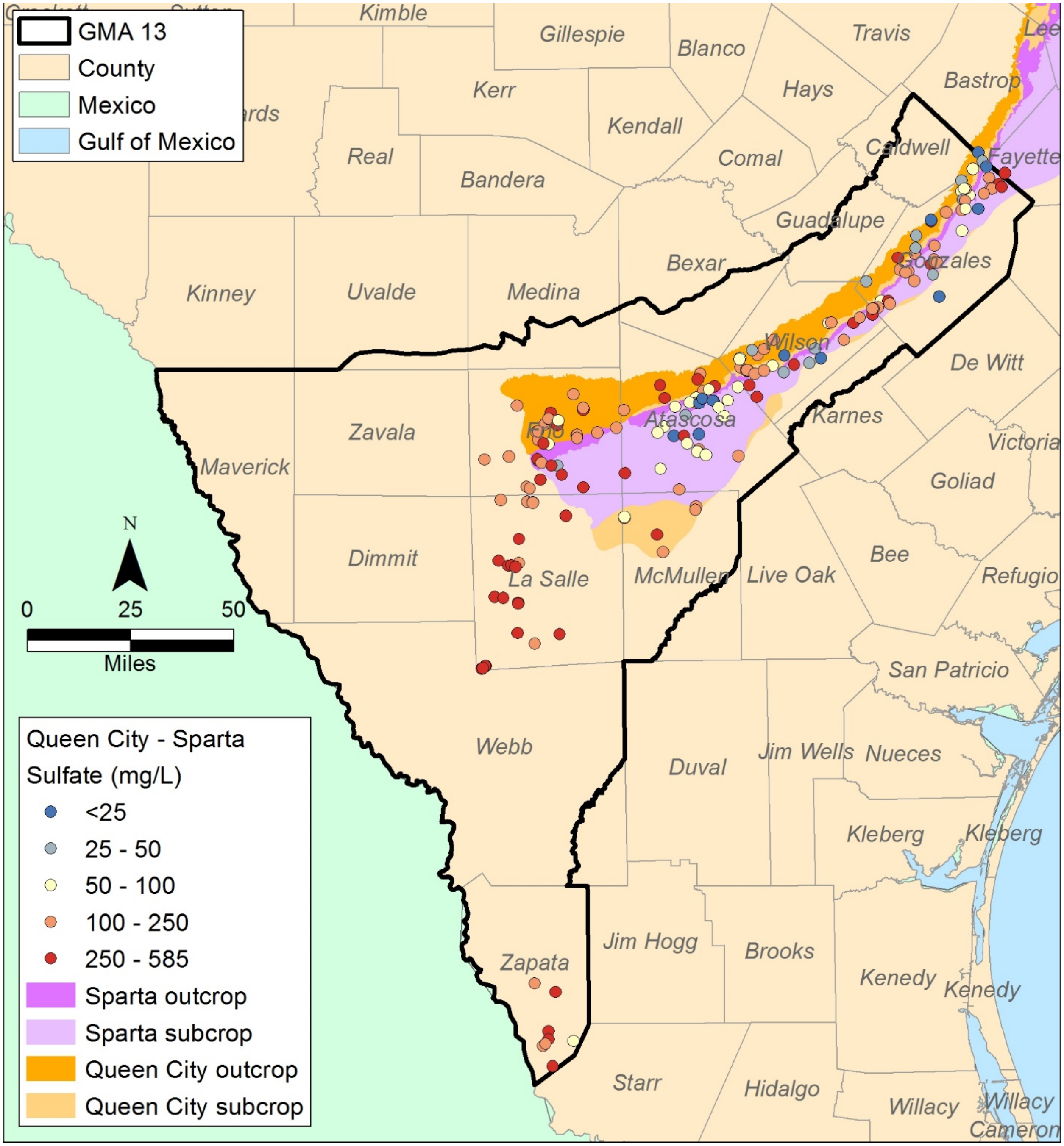


Figure 3-20. **Distribution of groundwater sulfate (SO_4) concentrations in the Queen City and Sparta aquifers based on the most recent chemical analyses. Sample locations outside the official aquifer boundaries were collected from Queen City/Sparta-equivalent strata (Bigford, Laredo) in South Texas.**

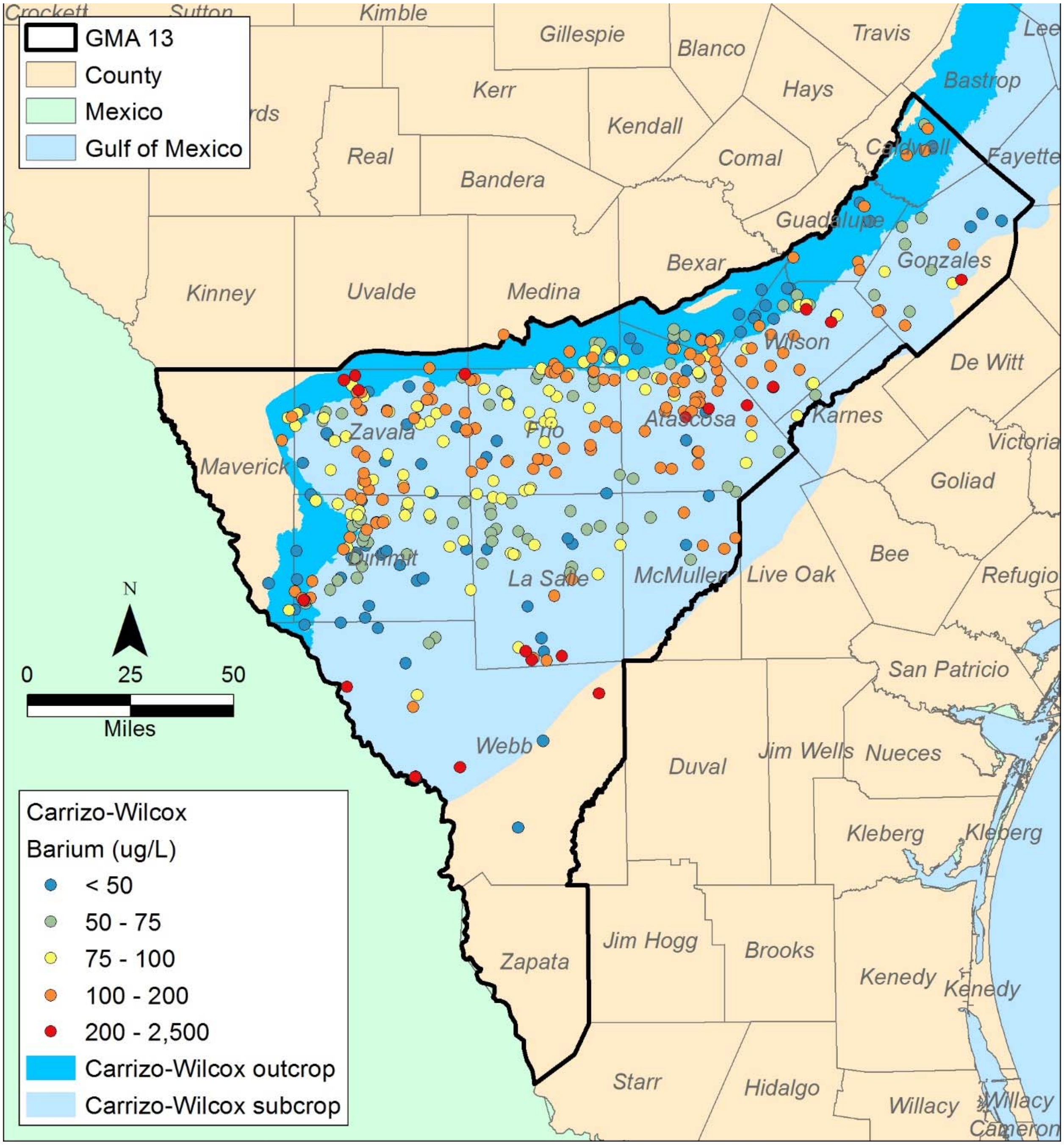


Figure 3-21. **Distribution of groundwater barium (Ba) concentrations in the Carrizo-Wilcox aquifer based on the most recent chemical analyses.**

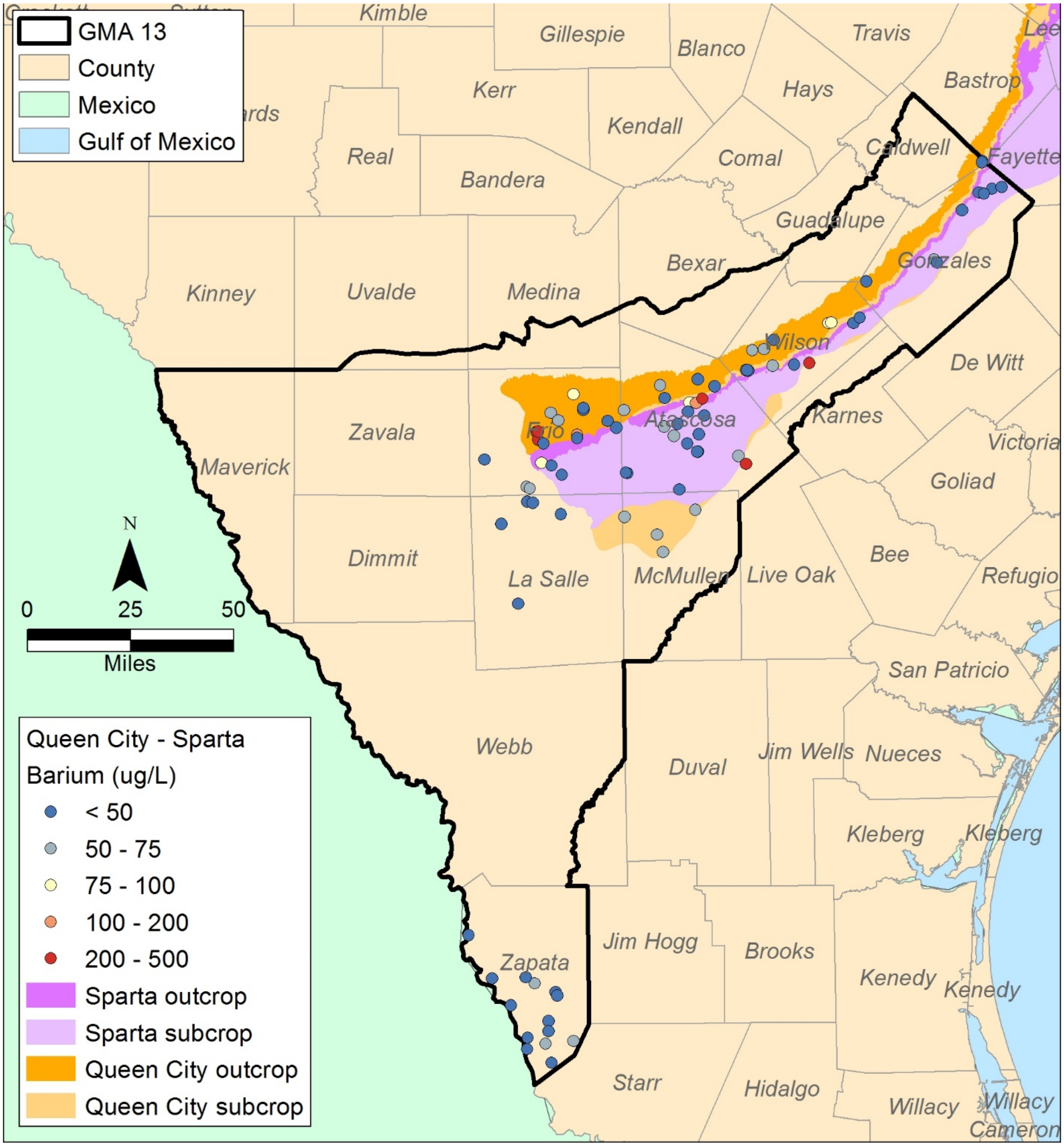


Figure 3-22. **Distribution of groundwater barium (Ba) concentrations in the Queen City and Sparta aquifers based on the most recent chemical analyses. Sample locations outside the official aquifer boundaries were collected from Queen City/Sparta-equivalent strata (Bigford, Laredo) in South Texas.**

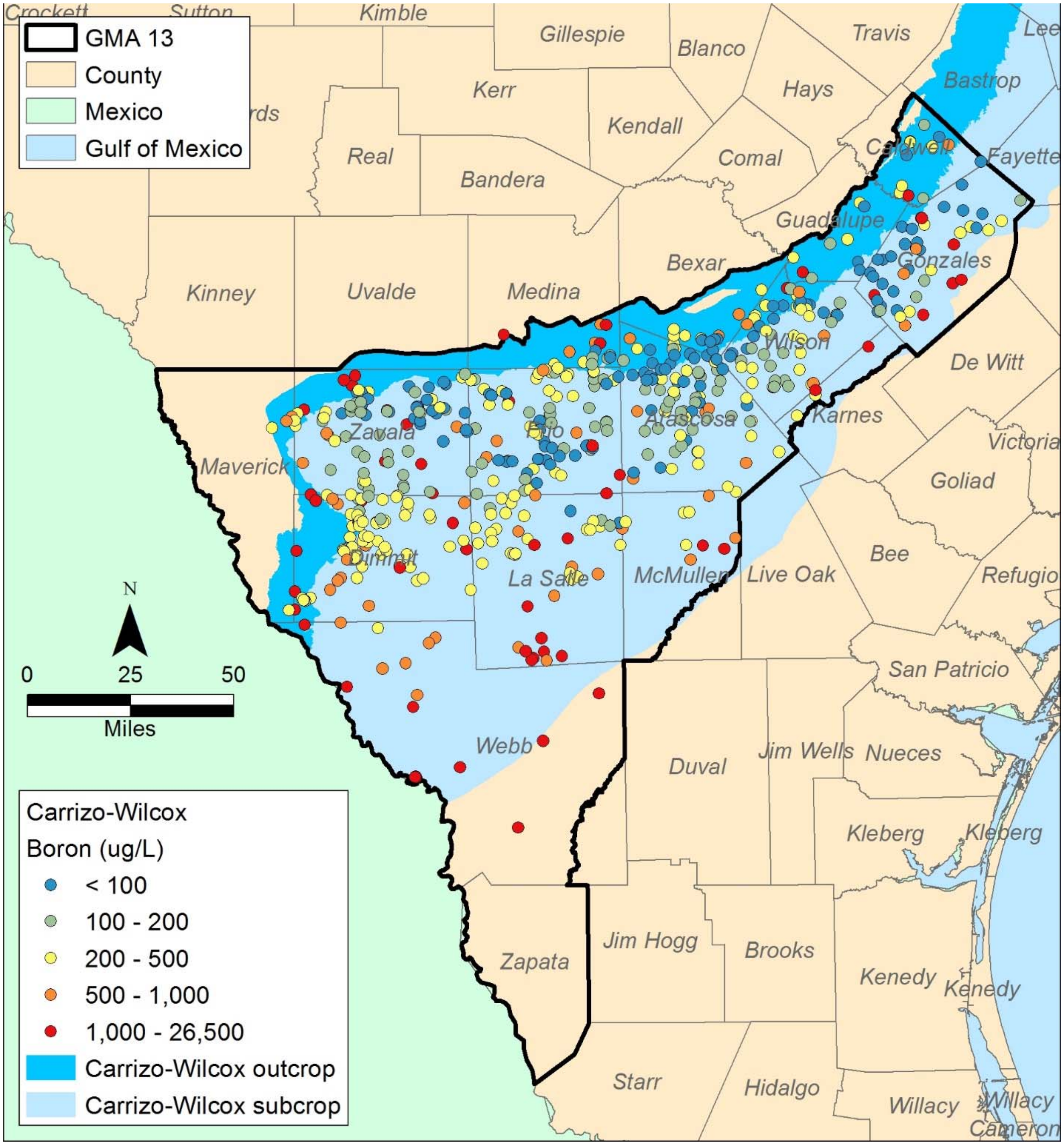


Figure 3-23. Distribution of groundwater boron (B) concentrations in the Carrizo-Wilcox aquifer based on the most recent chemical analyses.

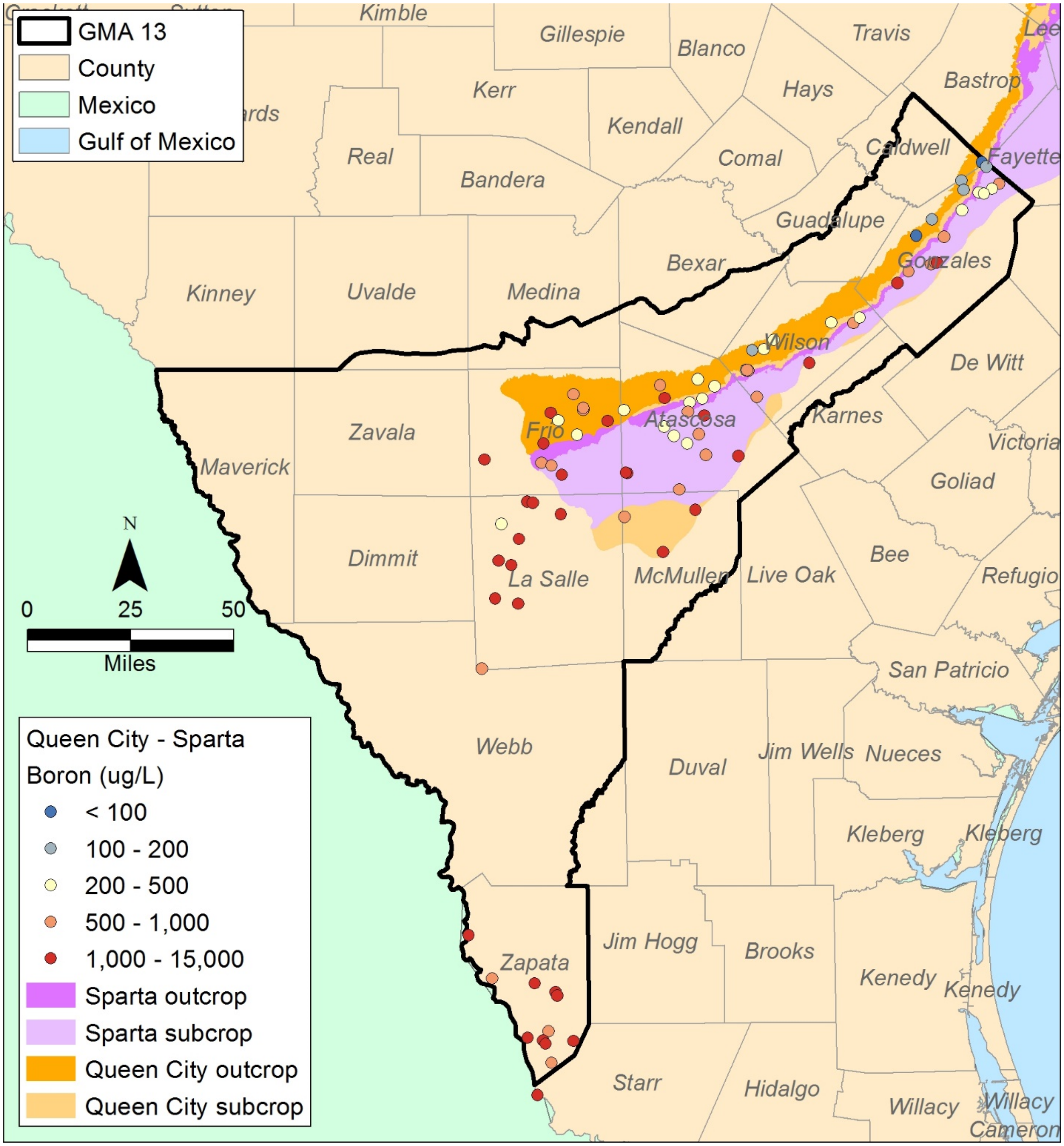


Figure 3-24. **Distribution of groundwater boron (B) concentrations in the Queen City and Sparta aquifers based on the most recent chemical analyses. Sample locations outside the official aquifer boundaries were collected from Queen City/Sparta-equivalent strata (Bigford, Laredo) in South Texas.**

4 Geophysical Log Interpretation

4.1 Carrizo-Wilcox Aquifer

4.1.1 Methods

4.1.1.1 Geophysical Log Database

Geophysical logs (electric logs) from 382 wells were used to correlate and map stratigraphy, and to estimate groundwater salinity (**Figure 4-1**). Digital logs from 191 wells were used to automate calculations and to display lithology and groundwater salinity on cross sections. Petra software (IHS, Inc.) was used for data management, interpretation, and visualization. All geophysical logs used in this study are from one or more of these publicly available sources: TWDB BRACS database, Bureau of Economic Geology (BEG) Geophysical Log Facility, Railroad Commission of Texas.

4.1.1.2 Stratigraphic Correlations

Stratigraphic correlations were guided by type logs published in regional studies (Bebout and others, 1982 2009; Hamlin, 1988; Hargis, 1986). The depositional framework is also based on previous regional studies (Bebout and others, 1982; Fisher and McGowen, 1967; Hamlin, 1988; Hargis, 1985, 1986, 2009; Xue and Galloway, 1993, 1995). In Gulf Coast Tertiary sand/shale sequences, lithologies can be distinguished with confidence on electric logs (SP and resistivity curves) (**Figure 4-2**). Standard subsurface mapping techniques were applied to construct net sand thickness maps separately for sands containing fresh groundwater and those containing brackish groundwater. Depth maps to important salinity boundaries were also constructed. Stratigraphic and structural cross sections were constructed to show depth-related variations in lithology and groundwater quality.

4.1.1.3 Groundwater Salinity Using R_0 Method

Groundwater salinity estimations are based on two methods: (1) empirical relationship between the resistivity of a water-filled formation (R_0) and formation water salinity; and (2) calculation of formation water resistivity (R_w) using a modified version of the Archie equation (Jones and Buford, 1951; Estepp, 1998). The R_0 method involves correlating deep resistivity (long normal or deep induction) with chemical analyses of groundwater samples from the same zone (Fogg and Blanchard, 1986; Hamlin and others, 1988; Collier, 1993; Estepp, 1998). The deep resistivity curve is used to minimize the effects of mud filtrate invasion. Deep R_0 is assumed to be approximately equal to true formation resistivity (R_t). Bed thickness also affects R_0. For beds thinner than about twice the electrode spacing, R_0 does not equal R_t (Jones and Buford, 1951). Therefore, only sand layers greater than 10 ft thick are included on thickness maps and in volume calculations. Where water saturation is 100 percent (no hydrocarbons), R_0 is affected primarily by formation water salinity and hydrochemical composition, temperature, porosity, and lithology (Jones and Buford, 1951; Turcan, 1962; Alger, 1966). Hydraulic conductivity (permeability) also affects resistivity, and resistivity has been used to map recharge and groundwater flow paths (Fogg and others, 1983; Ayers and Lewis, 1985; Ayers and others, 1986). R_0 is most closely related to groundwater salinity in thick, clay-free sands having similar porosities, depositional facies, geographic area, and depth range. The R_0 method works best in unconsolidated to semi-consolidated, sand/shale sequences such as the Gulf Coast Tertiary units. We selected only clean clay-free sands for this analysis.

To develop TDS/R_0 regressions, TDS values from water well chemical analyses from 166 wells were paired with R_0 measurements in nearby petroleum wells, taking care to identify the same zone in both wells. Median distance between wells in the pairs is 8,835 ft (**Figure 4-3**). In cases where the screened interval in the water well was not reported in the TWDB Groundwater Database (GWDB), well depth was used. Most of the water wells produce low TDS groundwater from the Carrizo-upper Wilcox interval; the lower Wilcox interval is poorly represented. A small set of lower Wilcox data (9 wells) was obtained from analyses of high TDS formation water produced in petroleum wells. Plotting TDS versus R_0 for the entire data set yielded a correlation coefficient of 0.87 (**Figure 4-4**). This relatively good correlation suggests that groundwater salinity is the dominant control on R_0 in shallow (<6000 ft) Carrizo-Wilcox sands in South Texas.

TDS/R_0 correlations were refined by dividing the study area into three smaller regions, and developing separate TDS/R_0 regressions for each region (**Figure 4-5**). The regions coincide with Carrizo-upper Wilcox hydrogeologic zones that have distinct lithologies, depositional facies, dissolved-ion abundances, and other aquifer properties (Hamlin, 1988) (**Figure 4-1**, **Table 4-1**). Hydrochemical variations, especially, can affect TDS/R_0 correlations. High bicarbonate concentration, for example, increases resistivity independently of TDS (Jones and Buford, 1951; Alger, 1966; Meyer and others, 2014). Dissolved ions abundances shown in **Table 4-1** are not the same as hydrochemical facies discussed in Section 3. All three hydrogeologic regions have bicarbonate hydrochemical facies, but bicarbonate concentrations are highest in the southwest region (Hamlin, 1988).

TDS/R_0 correlations were used to define R_0 cutoff values in each region for freshwater (TDS <1,000 mg/L), slightly saline water (TDS = 1,000 – 3,000 mg/L), moderately saline water (TDS = 3,000 – 10,000 mg/L), and very saline water (TDS = 10,000 – 35,000 mg/L) (**Table 4-2**). Brackish water includes both slightly saline and moderately saline waters. The TDS/R_0 relationship was not used to map brine (TDS >35,000 mg/L) (Section 4.1.7).

4.1.1.4 Groundwater Salinity Using R_w Method

The R_w method was used to supplement and corroborate the R_0 method, especially in deeper intervals where water well chemical analyses are scarce. Parameters for the R_w equation are porosity (Φ) and the cementation exponent (m), which is an empirical parameter related to compaction, cementation, and grain size (Jones and Buford, 1951; Asquith and others, 2004).

$$R_w = \Phi^m \times R_0 \quad \text{(Equation 4-1)}$$

Values for Φ and m are based primarily on previous studies of Wilcox porosity and petrography (Loucks and others, 1986; McBride and others, 1991; Dutton and Loucks, 2014) supported by water sample measurements of R_w from petroleum wells (Gaither, 1986). The porosity/depth relationship is similar for both Carrizo-Wilcox and Queen City-Sparta aquifers (Loucks and others, 1986). Ranges of Φ and m were tested for sensitivity and reasonable outcome. R_w from equation (4-1) was corrected to a standard surface temperature (75° F) and then converted to TDS through a conductivity relationship that is specific to formation and region (Turcan, 1966; Estepp, 1998).

$$C_w = 10{,}000/R_w \quad \text{(Equation 4-2)}$$

$$TDS = ct \times C_w \quad \text{(Equation 4-3)}$$

where C_w is conductivity, and ct is a proportionality constant that was determined by graphing TDS versus C_w, both of which were measured in groundwater samples from the Carrizo-Wilcox aquifer in South Texas (**Figure 4-6**). Although ct varies with area and formation, differences are minimal, and one value works sufficiently well for the entire Carrizo-Wilcox Aquifer (Fogg and Blanchard, 1986). Conductivities used in **Figure 4-6** are a different data set from hydrochemical data used in Section 3. The R_w method allows R_0/TDS cutoffs to be determined independently from water sample analysis (**Table 4-3**).

Porosity was measured using the neutron-density combination method, which is the most widely used geophysical log porosity method (Asquith and Krygowski, 2004). Neutron and density curves are displayed in porosity units. Caliper and gamma ray or spontaneous potential curves are also required for porosity measurement. A resistivity curve is helpful but not essential. NPHI (neutron porosity) and DPHI (density porosity) curves may be recorded as limestone units or sandstone units, depending on the rock density used to convert the raw data to porosity units. Almost all NPHI (neutron porosity) and DPHI (density porosity) logs in Gulf Coast Tertiary formations are run using a sandstone matrix (density = 2.65 grams per cubic centimeter). Therefore, conversion from limestone to sandstone is not needed, and porosity can be read directly from the log curves. The formation porosity equals the average of the NPHI (neutron porosity) and DPHI (density porosity) readings.

Specific formation and borehole conditions are necessary for accurate porosity log measurements. Porosity must be measured in clean (clay-free) sand or sandstone. The gamma ray and/or spontaneous potential curves are used to identify clean zones. The formation must not contain hydrocarbons, especially natural gas. A resistivity curve can help identify hydrocarbons. Thick sands also help avoid hydrocarbons. The porosity measurement should be taken in the middle or lower part of a thick sand, because hydrocarbons migrate to the upper part. Porosity logging tools are pads that are pressed against the borehole wall and must maintain contact with that wall for accurate readings. The caliper logging tool measures borehole diameter and is used to detect rough or washed out locations, where the porosity pad might lose contact with the borehole wall. Accurate neutron-density porosity measurements are only possible where the borehole wall is smooth and not enlarged by washout or caving.

4.1.1.5 Resistivity Cutoffs

Resistivity cutoffs from the R_0 method (**Table 4-2**) were used to estimate groundwater salinity mainly in Carrizo-upper Wilcox sands, whereas cutoffs from the R_w method (**Table 4-3**) were used mainly in lower Wilcox sands. For similar groundwater salinities, resistivities in Carrizo-Wilcox sands increase from northeast to southwest (**Figure 4-5**). Reasons for southwest-increasing resistivities have not been documented, but increasing bicarbonate concentration and decreasing porosity and permeability are probably important factors. Similar resistivity increases are present in the lower Wilcox interval relative to the Carrizo-upper Wilcox interval. In the Southwest region, however, lithologies and aquifer properties are similar for both the Carrizo-upper Wilcox and the lower Wilcox, and R_0 cutoffs are similar there as well (compare **Tables 4-2** and **4-3**).

4.1.1.6 Discussion of Resistivity Methods

The empirical TDS/R_0 method is a quick and effective way to map regional resources of fresh and brackish groundwater in some aquifers. Cutoff values of R_0 can be determined that distinguish broad categories of groundwater salinity: fresh, slightly saline, moderately saline, and very saline. Where TDS data are scarce, the computational R_w method can be used to calculate R_0 cutoff values independently. Although the correlation between TDS and R_0 is commonly fair to good ($R^2 > 0.7$), other parameters significantly affecting R_0 are hydrochemistry, porosity, lithology, grain size, diagenesis, temperature, pressure, and borehole conditions. Variations in well logging instrumentation and practice, especially between old and new wells, also affect measured R_0. Therefore, the methods described in this report do not precisely calculate TDS from R_0. More quantitative methods are available for calculating TDS from electric logs, but they are less amenable to regional reconnaissance. Instead, the R_0 and R_w methods provide rough estimates of groundwater in-place, which can be used in calculations of producible groundwater. In addition, these methods provide mappable parameters, such as net thickness of brackish groundwater sands, which can be used to locate and rank the resource.

4.1.1.7 Determination of Brine Distribution

Separate methods were used to map brine (TDS >35,000 mg/L) in the Carrizo-Wilcox Aquifer in GMA 13. Empirical TDS/R_0 methods do not work well at very high salinities, where large salinity changes typically correlate to tiny R_0 differences. We inferred from the distribution of very saline groundwater and TDS measurements that brine is a minor component of the Carrizo-Wilcox flow system updip from the Wilcox growth-fault zone. To test this hypothesis, we collected high TDS measurements from oil and gas wells and plotted their distribution relative to the GMA 13 boundaries (**Figure 4-7**). These data suggest that brine is restricted to the Wilcox growth-fault zone. TDS values updip from the growth-fault zone are all in the very saline or moderately saline categories and agree well with TDS estimated from R_0. TDS values in the growth-fault zone are highly variable and include very saline and brine groundwater. TDS variation in the growth-fault zone reflects fault-compartmentalized flow systems and release of connate waters from compacting shales (Bebout and others, 1982). However, the growth-fault zone impinges upon GMA 13 in Webb and Zapata counties (Zapata County is not part of the Carrizo-Wilcox Aquifer analysis). The southeast part of Webb County includes brine in thin isolated sands in the lower and middle Wilcox (**Figure 4-7**).

The Carrizo-Wilcox Aquifer in GMA 13 is underlain by shale intervals that are typically several thousand feet thick. Below the thick shales, Cretaceous sandstones and limestones commonly contain brine, and the brine wells shown in **Figure 3-5** are all screened in Cretaceous intervals. The thick shale aquitards, however, preclude any possibility of a salinity interface between the Wilcox Group and underlying Cretaceous formations.

4.1.2 Results

Sand distribution and geometry are important aquifer properties, and mapping sand thicknesses is the first step in quantifying groundwater volumes. Using lithology and groundwater salinity interpretations from electric logs, we constructed a series of maps (**Figures 4-8** to **4-23**) and cross sections (**Figures 4-24** to **4-29**) to display locations and thickness of Carrizo-Wilcox sands having fresh, slightly saline, moderately saline, and very saline groundwater.

4.1.2.1 Carrizo-Upper Wilcox

The Carrizo-upper Wilcox interval ranges from greater than 90 percent sand near outcrop in the northeast to about 50 percent sand along the Rio Grande in the southwest (Hamlin, 1988). Carrizo-upper Wilcox sand thickens into a large depocenter located south of San Antonio (**Figure 4-8**). Coarse-grained, bed-load fluvial channel systems dominate the Carrizo updip from the sand depocenter (Hamlin, 1988). Along the downdip margin of the study area and in the Wilcox growth-fault zone, the upper Wilcox was deposited in wave-dominated delta and associated barrier/strandplain systems (Fisher, 1969; Edwards, 1980, 1981). Specific depositional environments within the sand depocenter are not well documented but probably comprise bed-load fluvial channel facies interfingering with coalesced delta front and shoreface facies.

The Carrizo-upper Wilcox interval contains fresh or brackish groundwater across most of the study area. The thickest freshwater zones are located in fluvial sands in the north and northeast parts of the study area (**Figures 4-9**, **4-24** to **4-27**). Sands containing fresh groundwater are thinner in the west and southwest (**Figures 4-9**, **4-28** to **4-29**). Thickness of freshwater sands decreases abruptly along the downdip margin of the study area, coinciding locally with regional fault zones (**Figure 4-9**). These normal faults are located updip from the Wilcox growth-fault zone (**Figure 4-1**). In Gulf Coast Tertiary aquifers, groundwater salinity changes commonly occur near faults and result from the interaction between descending low-TDS meteoric water and expulsing high-TDS deep-basin formation water (Kreitler, 1979; Galloway, 1984; Hamlin, 1988).

In Carrizo-upper Wilcox sands, fresh groundwater grades downdip into brackish groundwater. Sands containing slightly saline groundwater form a discontinuous belt of maximum thickness near the downdip margin of the study area (**Figure 4-10**). Carrizo-upper Wilcox sands containing slightly saline groundwater are also widespread across the western part of the study area (**Figure 4-10**). Thick Carrizo-upper Wilcox sands containing slightly saline groundwater are well developed locally in Webb, La Salle, McMullen, Live Oak, and Karnes counties (**Figures 4-24** to **4-28**).

Carrizo-upper Wilcox sands containing moderately saline groundwater display locations and thickness patterns similar to those of slightly saline groundwater sands, although the thickest moderately saline groundwater sands are located farther downdip (compare **Figures 4-10** and **4 11**). Thick Carrizo-upper Wilcox sands containing moderately saline groundwater are well developed locally in Webb, McMullen, and Karnes counties (**Figures 4-25**, **4-27**, **4-29**). In the northeast, where the transition between fresh groundwater and saline groundwater occurs across a relatively short distance, both slightly and moderately saline groundwater zones form narrow, discontinuous belts (**Figures 4-10**, **4-11**, **4-24**, **4-25**).

In the Carrizo-upper Wilcox, sands containing very saline groundwater are located along the southeast boundary of GMA 13. Very saline groundwater in the Carrizo-upper Wilcox lies mostly outside of GMA 13 except in Webb County (**Figure 4-12**). Very saline groundwater sands are thickest in the northeast (**Figures 4-24** and **4-25**). No brine is present in the Carrizo-upper Wilcox interval in GMA 13 (**Figure 4-7**).

4.1.2.2 Middle Wilcox

The middle Wilcox interval is shale-dominated in GMA 13. Net sand thickness is mostly less than 300 feet (**Figure 4-13**). The middle Wilcox is composed primarily of thin sands and thick shales that were deposited in a marine transgressive environment (Xue and Galloway, 1995; Hargis, 2009). The middle Wilcox potentially forms aquitards in places where shales are especially thick (**Figures 4-24** to **4-26**). We constructed a percent sand map of the middle Wilcox to highlight areas where flow barriers may exist between the lower Wilcox and the Carrizo-upper Wilcox. Areas where sand percentages are less than about 30 percent (shale > 70%), have the greatest potential to form flow barriers (**Figure 4-14**). In the far northeast, the middle Wilcox thickens greatly into a feature called the Yoakum Canyon (**Figure 4-24**). During the time of middle Wilcox deposition, the Yoakum Canyon was a large submarine channel that eroded into the underlying lower Wilcox and subsequently filled with middle Wilcox shale (Hoyt, 1959; Dingus and Galloway, 1990).

The middle Wilcox interval is dominated by brackish and saline groundwater, although minor fresh groundwater is present locally in outcrop and the shallow subsurface. Middle Wilcox sands containing fresh groundwater are thickest (up to about 100 ft) in Zavala and Frio counties (**Figure 4-15**). The cross sections show that middle Wilcox sands containing fresh groundwater are rare (**Figures 4-27**, **4-28**). Slightly saline groundwater in the middle Wilcox is more widespread than fresh groundwater (**Figure 4-16**). Middle Wilcox sands containing slightly saline groundwater are thickest in Frio and Atascosa counties (**Figures 4-26**, **4-27**). Moderately saline groundwater in the middle Wilcox is also widespread but thin (**Figure 4-17**). Middle Wilcox sands containing moderately saline groundwater are shifted downdip compared to sands containing slightly saline groundwater (compare **Figures 4-16** and **4-17**), although the two brackish groundwater salinity types are commonly interbedded in the middle Wilcox (**Figures 4-26** to **4-28**). Sands containing very saline groundwater in the middle Wilcox are located along the southeast boundary of GMA 13 in the northeast but are more widespread in the southwest (**Figure 4-18**). Sands containing brine in the middle Wilcox are restricted to southeast Webb County (**Figure 4-7**) in thin sands enclosed in thick shales (southeast end of cross section F, **Figure 4-29**).

4.1.2.3 Lower Wilcox

In South Texas, the lower Wilcox interval is less sandy than the Carrizo-upper Wilcox but more sandy than the middle Wilcox. Percent sand in the lower Wilcox interval generally decreases from 60 percent sand near the outcrop and in the northeast to less than 10 percent sand locally in the southwest and downdip. The thickest sands in the lower Wilcox interval are in the northeast on the San Marcos Arch (**Figure 4-19**). In the Rio Grande Embayment, lower Wilcox net sand patterns are strike aligned and decrease updip and downdip from an elongated depocenter (**Figure 4-19**). Fisher and McGowen (1967) interpreted these sand thickness patterns to represent a delta system in the northeast flanked by a barrier-strandplain system to the southwest. The Yoakum Canyon is expressed on the lower Wilcox net sand map as a sand-poor, dip-oriented trend in Gonzales County (**Figure 4-19**).

Similar to the middle Wilcox, the lower Wilcox interval is dominated by brackish and saline groundwater. Minor fresh groundwater is present locally in outcrop and the shallow subsurface especially in Zavala, Frio, and Atascosa counties (**Figure 4-20**). None of the cross sections shows fresh groundwater in the lower Wilcox. Lower Wilcox sands containing slightly saline or moderately saline groundwater are mainly restricted to the north and northeast (**Figures 4-21**, **4 22**). Thus, maximum brackish groundwater in the lower Wilcox underlies maximum fresh groundwater in the Carrizo-upper Wilcox interval (compare **Figures 4-9** with **4-21** and **4-22**). Sands containing slightly and moderately saline groundwater in the lower Wilcox are well developed in Frio, Atascosa, and Wilson counties (**Figures 4-25** to **4-27**). The lower Wilcox interval contains mostly very saline groundwater in the southwest (Webb County), in the northeast (Gonzales County), and along the downdip margin of the study area (**Figure 4-23**). Abrupt changes in groundwater salinity in map view (**Figures 4-22**, **4-23**) suggest that fault-related groundwater mixing probably influences distribution of brackish groundwater in the lower Wilcox interval in the northeast. Recent research on methane occurrence in the Carrizo-Wilcox and Queen City aquifers in Gonzales County supports groundwater mixing through faults in the northeast (Nicot and others, 2017). In the southwest poor sand development and low rainfall recharge in outcrop are probably the main controls on brackish groundwater distribution (Hamlin, 1988). Sands containing brine in the lower Wilcox are restricted to southeast Webb County (**Figure 4-7**) in thin sands enclosed in thick shales (southeast end of cross section F, **Figure 4-29**).

4.1.2.4 Structural Depths

Fresh and brackish groundwater intervals extend to greater depths in the Carrizo-Wilcox aquifer in South Texas than they do in other Texas aquifers (LBG-Guyton Associates, 2003). To show depth distribution of groundwater salinity, we constructed depth maps to the bases of fresh and brackish groundwater, as well as selected structural cross sections (**Figures 4-30** to **4-36**). The base (deepest occurrence) of fresh groundwater ranges from 500 ft below land surface near the outcrop to greater than 5,000 ft below surface downdip mainly in Live Oak County (**Figures 4-30**, **4-34**). In the northeast base of fresh groundwater is mostly less than 3000 ft below surface (**Figures 4-30**, **4-33**). In parts of Webb County, base of freshwater is less than 1500 ft below surface (**Figure 4-36**).

The base of slightly saline groundwater ranges from 500 ft below surface near outcrop to greater than 6,000 ft below surface downdip (**Figures 4-31**, **4-34**). The base of moderately saline groundwater ranges from about 500 ft below surface at outcrop to greater than 6,500 ft below surface downdip (**Figure 4-32**). The deepest occurrences of both fresh and brackish groundwater are in the Carrizo-upper Wilcox interval. In the lower Wilcox interval, depth to base of brackish water ranges from 5,000 ft in the northeast to 1,200 ft in the southwest (**Figures 4-33**, **4-36**). In GMA 13 the base of very saline groundwater coincides with the base of the Wilcox Group except for a small area in southeast Webb County that is in the Wilcox growth-fault zone (**Figure 4-7**).

4.1.2.5 Faults

Structural faults are common in the Carrizo-Wilcox Aquifer in GMA 13 (**Figure 4-37**). Faults are zones of slippage and deformation that disrupt sedimentary layers. Large faults may have vertical displacements that completely separate aquifer layers, and thus form flow barriers. Most of the faults in the Carrizo-Wilcox Aquifer are small and have displacements of 100 ft or less. These small faults offset aquifer layers but generally do not completely separate the layers. Most faults in the Carrizo-Wilcox probably affect groundwater flow by inhibiting horizontal flow and increasing vertical flow, and groundwater mixing (Kreitler, 1979; Galloway, 1984). Ewing (1991) and Hargis (2009) mapped faults in GMA 13, and we show their larger faults on the groundwater salinity sand thickness maps (**Figures 4-9** to **4-12**, **4-15** to **4-18**, **4-20** to **4-23**). As mentioned in the section on freshwater in the Carrizo-upper Wilcox (Section 4.2.1), abrupt groundwater salinity changes are apparent across many faults especially those in the northeast (for example, **Figures 4-9**, **4-22**).

4.1.2.6 Brackish Groundwater Production Areas

We mapped two potential brackish groundwater production areas (PPAs) within the Carrizo-Wilcox Aquifer in GMA 13. Initial selection of PPAs was based mainly on thickness of sands containing slightly saline or moderately saline groundwater. Once the areas were selected, we investigated potential hydrogeologic barriers that would be sufficient to separate the production areas from the rest of the aquifer and that might prevent significant impact to groundwater availability or quality in layers containing fresh groundwater. Hydraulic connectivity between brackish groundwater production areas and freshwater areas of the Carrizo-Wilcox Aquifer might be accomplished in fault zones or across leaky aquitards. A sand-dominated, hydraulically conductive interval that separates overlying fresh groundwater from underlying brackish groundwater might act as a leaky aquitard. We also conducted three dimensional flow modeling to estimate impacts of brackish groundwater production on fresh groundwater resources (Section 6).

In the Carrizo-Wilcox Aquifer in GMA 13, PPAs are in the lower Wilcox interval where it is separated from fresh groundwater in the Carrizo-upper Wilcox interval by the middle Wilcox aquitard. Approximate locations of the PPAs are shown on the map (**Figure 4-37**) as generalized boundaries not meant to encompass final areas where brackish groundwater can be produced without impacting fresh groundwater resources. The structural cross sections show more focused PPA boundaries in relation to faults and aquifer layering (**Figures 4-34, 4-35**). Across the north part of the study area, abundant brackish groundwater in present so that the PPAs could be merged into one area. However, differences between them are gradational but real (**Table 4-4**), and we concluded that it would be more effective to analyze them separately. The impact of producing brackish groundwater from these PPAs is considered in more detail in Section 6.

The properties of the PPAs are summarized in **Table 4-4**, and both contain some fresh groundwater alongside brackish water resources. PPA #1 is located south of San Antonio (**Figure 4-37**), and is not associated with faults, which, if present, could have acted as possible conduits for groundwater mixing (**Figure 4-34**). The shale-dominated (75-90% shale) nature of the middle Wilcox also forms a potential hydrogeologic barrier in PPA #1. PPA #2 is located mainly in Frio County and is bounded on the updip side by a fault that potentially hinders the isolation of brackish water zones (**Figures 4-37**, **4-35**). The middle Wilcox is also sandier in PPA #2 (50-60% shale), decreasing its effectiveness as a hydrogeologic barrier. Because of these reasons, significant impacts to groundwater availability or water quality in any area of the Carrizo-Wilcox Aquifer or adjacent aquifers may not be preventable for both PPA #1 and PPA #2

4.1.2.7 Injection Wells in Brackish Groundwater Production Areas

The PPAs include 100 Class II injections wells within their current generalized boundaries. Almost all of these wells (93) inject below the base of brackish groundwater (**Figure 4-38**). Vertical distance from the PPAs to these deeper injection zones ranges from a few feet to over 6,000 ft. In PPA #1, two closely spaced injection wells inject into the Queen City Aquifer about 2,000 ft above the top of brackish groundwater in the Carrizo-Wilcox Aquifer (**Figure 4-38**).

4.2 Queen City and Sparta Aquifers

4.2.1 Methods

4.2.1.1 Geophysical Log Database

Geophysical logs (electric logs) from 434 wells were used to correlate and map stratigraphy and to estimate groundwater salinity in the Queen City and Sparta aquifers **(Figure 4-39**). Digital logs from 175 wells were used to automate calculations and to display lithology and groundwater salinity on cross sections. Petra software (IHS, Inc.) was used for data management, interpretation, and visualization. All geophysical logs used in this study are from one or more of these publically available sources: TWDB BRACS database, Bureau of Economic Geology (BEG) Geophysical Log Facility, Railroad Commission of Texas.

4.2.1.2 Stratigraphic Correlations

The Queen City and Sparta stratigraphic and depositional frameworks followed here are based on key regional studies by Guevara and Garcia (1972) and Ricoy and Brown (1977). Wise (2014) compares specific correlation schemes by these and other authors. We were guided by these previous studies, although formation correlations presented here are our own. There is a change is formation names and contacts in the Queen City and Sparta outcrops in South Texas. Northeast of the Frio River, Queen City and Sparta sandy outcrops are separated by the shale-dominated Weches Formation, whereas southwest of the Frio River, the same stratigraphic interval is mapped as Bigford, El Pico Clay, and Laredo formations **(Figure 4-40**). Surface contacts between formations in these two areas generally do not coincide. Nevertheless, the Queen City and Sparta aquifers in the subsurface are continuous across the entire study area from Zapata County in the south to Gonzales County in the north (Guevara and Garcia, 1972; Ricoy and Brown, 1977) **(Figure 4-41**).

In Gulf Coast Tertiary sand/shale sequences, lithologies can be distinguished with confidence on electric logs (SP and resistivity curves). As with the Carrizo-Wilcox aquifer, standard subsurface mapping techniques were applied to construct net sand thickness maps separately for sands containing fresh groundwater and those containing brackish groundwater. A depth map to the base of brackish groundwater in the Queen City and Sparta aquifers was constructed. Cross sections were constructed to show depth-related variations in lithology and groundwater quality.

4.2.1.3 Groundwater Salinity from Electric Logs

Groundwater salinity estimations for Queen City and Sparta sands are based on the R_0 method as described previously for the Carrizo-Wilcox aquifer. The R_0 method is the most effective way to estimate groundwater salinities in Gulf Coast Tertiary formations at depths ranging from near surface to about 6000 feet. These simple sand-shale sequences are commonly poorly consolidated and only minimally altered by diagenetic process. Temperatures and pressures are relatively low compared to deeper formations, and pore-filling fluids are mostly water.

To develop TDS/R_0 regressions for the Queen City and Sparta aquifers, TDS values from water well chemical analyses from 66 wells were paired with R_0 measurements in nearby petroleum wells, taking care to identify the same zone in both wells. In cases where the exact screened interval in the water well was not reported in the TWDB Groundwater Database (GWDB), well depth was used. Median distance between wells in the pairs is 8,180 ft **(Figure 4-42**). The correlation between resistivity (R_0) and groundwater salinity is excellent for Queen City and Sparta sands, 80 percent of resistivity variance being controlled by groundwater salinity **(Figure 4-43**). We used the same TDS/R_0 regression for both aquifers, because little variation with location (region) or aquifer was observed. The correlation is sufficiently good to distinguish between very saline and brine groundwater (**Table 4-5**). Using these R_0 cutoffs, we estimated groundwater salinity in every Queen City and Sparta sand that is greater than 10 ft thick. We selected only clean, clay-free sands for this analysis.

4.2.2 Results

Sand distribution and geometry are important aquifer properties, and mapping sand thicknesses is the first step in quantifying groundwater volumes. Using lithology and groundwater salinity interpretations from electric logs, we constructed a series of maps **(Figures 4-44** to **4-53**) and cross sections **(Figures 4-54** to **4-61**) to display locations and thickness of Queen City and Sparta sands having fresh, slightly saline, moderately saline, and very saline groundwater. Sands containing brine groundwater were not mapped owing to their limited distribution along the southeast boundary of GMA 13 and in the northeast.

4.2.2.1 Queen City Aquifer

Sands in the Queen City aquifer form a large depocenter of maximum thickness that extends from northern Zapata to Atascosa counties **(Figure 4-44**). Total sand thickness exceeds 800 ft in the depocenter. The Queen City is composed mostly of shale updip from the depocenter in Dimmit and Zavala counties **(Figure 4-57**). The Queen City is also shaly downdip and in the northeast **(Figures 4-60** and **4-61**).

The Queen City aquifer contains fresh groundwater near outcrop and in several areas in La Salle, Frio, and Atascosa counties **(Figure 4-45**). Freshwater sands in the Queen City are generally located near the bottom of the aquifer in proximity to freshwater in the Carrizo-upper Wilcox, especially in areas where the Reklaw shale aquitard is thin **(Figures 4-57** and **4-58**). Prior to large scale groundwater pumping, high pressures in the Carrizo-upper Wilcox aquifer caused freshwater leakage into the superjacent Queen City aquifer (Hamlin, 1988).

Most groundwater in the Queen City aquifer in GMA 13 is brackish (slightly and moderately saline). The large sand depocenter is composed mainly of brackish groundwater sands **(Figures 4-46** and **4-47**). Slightly saline groundwater sands are thickest in La Salle and McMullen counties, whereas moderately saline groundwater sands are thickest in Webb County. Zapata County also contains thick brackish groundwater sands in the Queen City **(Figure 4-54**).

Brackish groundwater sands in the Queen City aquifer grade downdip into very saline groundwater sands **(Figures 4-54** to **4-58**). Very saline groundwater sands are best developed along the southeastern boundary of GMA 13, but thinner very saline sands are pervasive in updip areas **(Figure 4-48**). In the northeast the Queen City is dominated by very saline groundwater sands except in or near outcrop **(Figures 4-60** and **4-61**). Brine groundwater is present in thin Queen City sands in downdip areas and more generally in the northeast **(Figures 4-57** to **4-61**).

4.2.2.2 Sparta Aquifer

Sparta sands form a depocenter of maximum thickness that overlies and extends slightly updip relative to the Queen City sand depocenter **(Figure 4-49**). Total Sparta sand exceeds 250 ft in thickness in Webb County **(Figure 4-49**). Similar to the Queen City, Sparta sands are thin in the northeast **(Figures 4-59** to **4-61**). Sands in the Sparta aquifer thin and pinch out completely (zero sand) along the southeastern boundary of GMA 13 **(Figure 4-49**).

Fresh groundwater in the Sparta aquifer is limited to a north-oriented trend through Webb, La Salle, and Frio counties (western freshwater trend) and locally in the northeastern outcrop **(Figure 4-50**). The Sparta western freshwater trend may be an important local source of shallow potable groundwater in an area where the Queen City is brackish and the Carrizo-upper Wilcox is deep **(Figures 4-55** to **4-57**).

Brackish groundwater sands in the Sparta aquifer dominate the sand depocenter **(Figures 4-51** and **4-52**). Thick brackish groundwater sands in both the Queen City and Sparta aquifers are stacked in the southwest **(Figures 4-54** to **4-56**). In the Sparta aquifer moderately saline groundwater sands are best developed in Zapata and southern Webb counties **(Figure 4-52**), whereas slightly saline groundwater sands are best developed in northern Webb and La Salle counties **(Figure 4-51**).

Very saline groundwater sands in the Sparta aquifer are best developed downdip in the southeast and throughout the northeast **(Figure 4-53**). Very saline and brine sands in the Sparta are mostly thin **(Figures 4-57** to **4-61**).

4.2.2.3 Weches and Reklaw Shale Aquitards

The Weches and Reklaw formations form shale aquitards across the eastern and southern parts of GMA 13. Both formations are greater than 90 percent shale, but thicknesses vary. The Reklaw shale thickens eastward (downdip) but is essentially missing in Frio, Zavala, Dimmit, and western Webb counties **(Figure 4-62**). The Reklaw is not recognized in these western counties, where the equivalent interval is part of the Bigford Formation **(Figure 4-40**). The Weches aquitard is thin in the same western counties **(Figures 4-55** to **4-58**). The Weches Formation is not recognized southwest of the Frio River, but forms a part of the El Pico Clay **(Figure 4-40**). The El Pico Clay is equivalent to the Weches and the upper part of the Queen City, and can be identified on our cross sections as shale-dominated parts of the Queen City aquifer in updip areas in the west **(Figures 4-55** to **4-57**).

4.2.2.4 Structural Depths

Groundwater salinities in aquifers in GMA 13 do not increase steadily with depth, but are complexly interbedded instead. Brackish groundwater sands in the Queen City and Sparta aquifers commonly overlie freshwater sands in the Carrizo-Wilcox aquifer. Therefore, mapping the base of freshwater or brackish water can be misleading. It may be possible, however, to develop brackish groundwater in the Queen City and Sparta aquifers without impacting freshwater in the underlying Carrizo-upper Wilcox aquifer. In that case a map of depth to the base of brackish groundwater in the Queen City and Sparta aquifers would be useful. Depth to the base of brackish groundwater in these aquifers generally follows a dip-oriented trend of deepening to the southeast **(Figure 4-63**).

4.2.2.5 Brackish Groundwater Production Areas

We mapped one potential brackish groundwater production area (PPA) within the Queen City and Sparta aquifers in GMA 13 **(Figure 4-64**). Initial selection of PPAs was based mainly on thickness of sands containing slightly saline or moderately saline groundwater. Once the areas were selected, we investigated potential hydrogeologic barriers that would be sufficient to separate the production areas from the rest of the aquifer and that might prevent significant impact to groundwater availability or quality in layers containing fresh groundwater. We also conducted three dimensional flow modeling to estimate impacts of brackish groundwater production on fresh groundwater resources (Section 6).

The PPA encompasses both the Queen City and Sparta aquifers and is located in La Salle, Atascosa, and McMullen counties **(Figure 4-64**). In the PPA, thick brackish groundwater sands grade downdip into saline groundwater sands **(Figure 4-58**). The Reklaw aquitard forms a potential hydrogeologic barrier to cross-formational flow with the underlying Carrizo-Wilcox aquifer. The Cook Mountain Formation is a shale dominated interval that overlies the Sparta aquifer and forms a barrier to upward cross-formation flow **(Figure 4-40**). The entire interval between top of Sparta and land surface is shale-dominated across most of GMA 13. Barrier to lateral flow within the aquifers are more difficult to identify as a result of the interfingered nature of the brackish and freshwater sands. The PPA contains fresh groundwater in the Queen City Aquifer, and the lack of sufficient hydrogeologic barriers may lead to significant impacts to freshwater resource availability or quality in the Queen City-Sparta or adjacent aquifers. The impact of producing brackish groundwater from this PPA is considered in more detail in Section 6.

4.2.2.6 Injection Wells in Brackish Groundwater Production Areas

The PPA includes 36 Class II injections wells, all of which inject below the base of brackish groundwater in the Queen City and Sparta aquifers **(Figure 4-65**). Vertical distance from the PPA to these deeper injection zones ranges from about 200 feet to over 2,000 ft. All of the injection wells in the PPA are below the Queen City aquifer.

Table 4-1. Hydrogeologic properties of the Carrizo-upper Wilcox interval in the TDS/R_0 regions shown on Figure 4-1. All properties except sandstone percent from Hamlin (1988).

Region	Hydraulic Conductivity Mean (ft/day)	Transmissivity Mean (ft^2/day)	Sandstone Mean Percent	Most Abundant Dissolved Ions
Southwest	24.7	4,815	53	HCO_3, Na, Cl
Central	35.7	14,845	65	Ca, HCO_3
Northeast	35.6	21,933	78	Na, HCO_3

Table 4-2. R_0 cutoff values based on the TDS/R_0 empirical relationships (Figure 4-5).

Region	Freshwater	Slightly Saline Water	Moderately Saline Water	Very Saline Water
Southwest	> 34	16 – 34	7 – 16	< 7
Central	> 29	13 – 29	5 – 13	< 5
Northeast	> 25	10 – 25	4 – 10	< 4

Table 4-3. R_0 cutoff values calculated using the R_w method.

TDS (mg/L)	Depth range (ft)	Temperature (ºF)	Porosity (%)	m	ct	R_w	R_0
1,000	< 3,000	110	30	1.8	0.56	3.78	33
3,000	3,000 – 6,000	158	25	2.1	0.56	0.87	16
10,000	4,000 – 7,000	177	20	2.4	0.56	0.23	11

Table 4-4. Potential Brackish Groundwater Production Areas in the Carrizo-Wilcox aquifer in GMA 13 (Figure 4-36).

Area Number	Counties	Aquifer Layer	Brackish Groundwater Type	Depths (ft)	Hydrogeologic Barriers
1	Wilson Atascosa	Lower Wilcox	mostly moderately saline	1500 – 5500	Middle Wilcox layer 75-90% shale
2	Frio Zavala	Lower Wilcox	mostly slightly saline	1500 – 4500	Middle Wilcox layer 50-60% shale

Table 4-5. R_0 cutoffs values based on the TDS/R_0 empirical relationship for the Queen City and Sparta aquifers (Figure 4-43).

Salinity Classification	Total Dissolved Solids (mg/L)	R_0 Cut-offs (ohm-m)
Freshwater	< 1,000	> 20
Slightly saline water	1,000 – 3,000	9 – 20
Moderately saline water	3,000 – 10,000	4 – 9
Very saline water	10,000 – 35,000	2 – 4
Brine	> 35,000	< 2

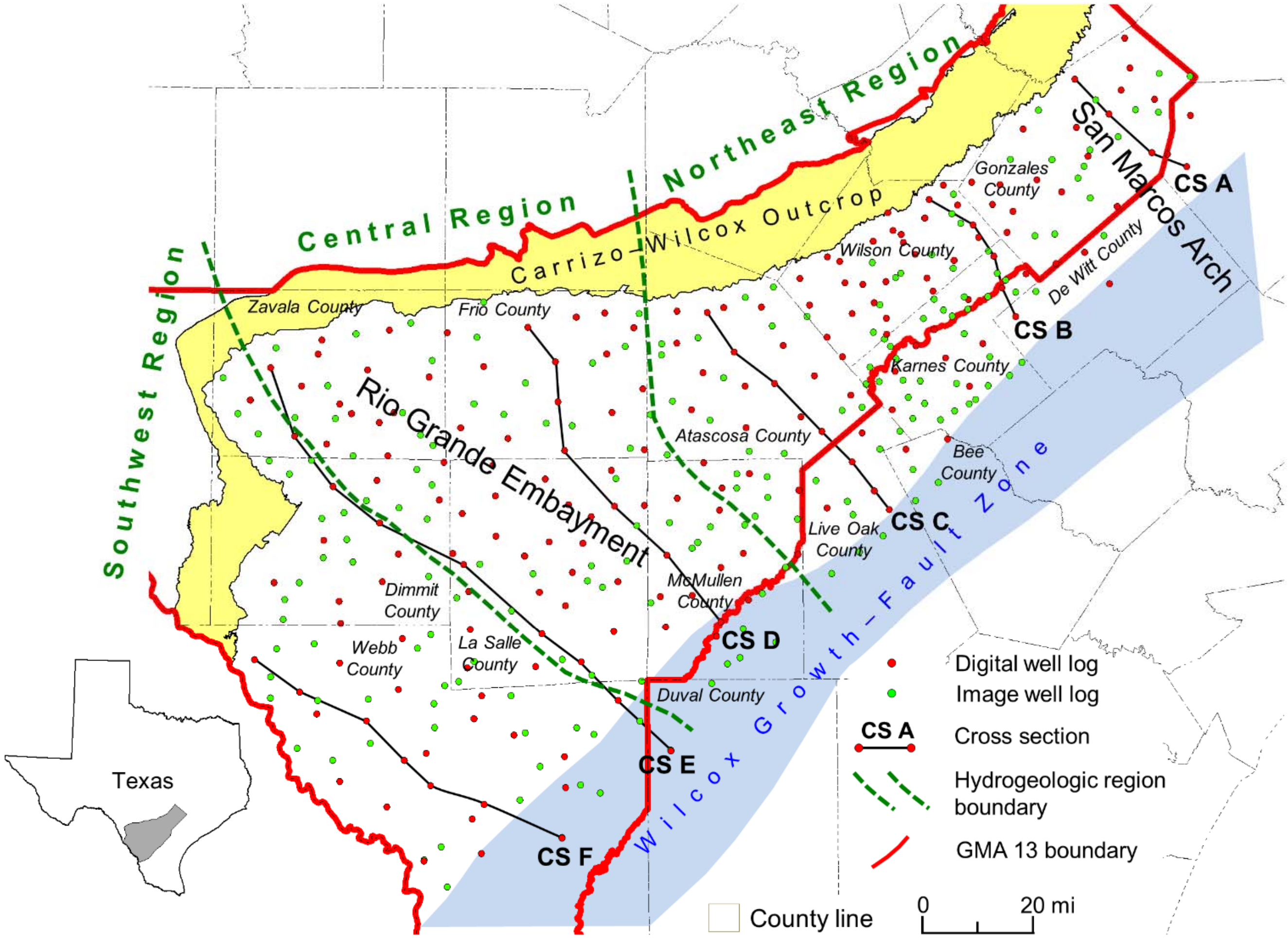


Figure 4-1. **Location of study area in GMA 13 showing electric log well control, cross section lines, and Carrizo-Wilcox outcrop. The Wilcox growth-fault zone is also shown (Ewing, 1990). The area was divided into hydrogeologic regions (Hamlin, 1988) for separate TDS/R_0 regressions.**

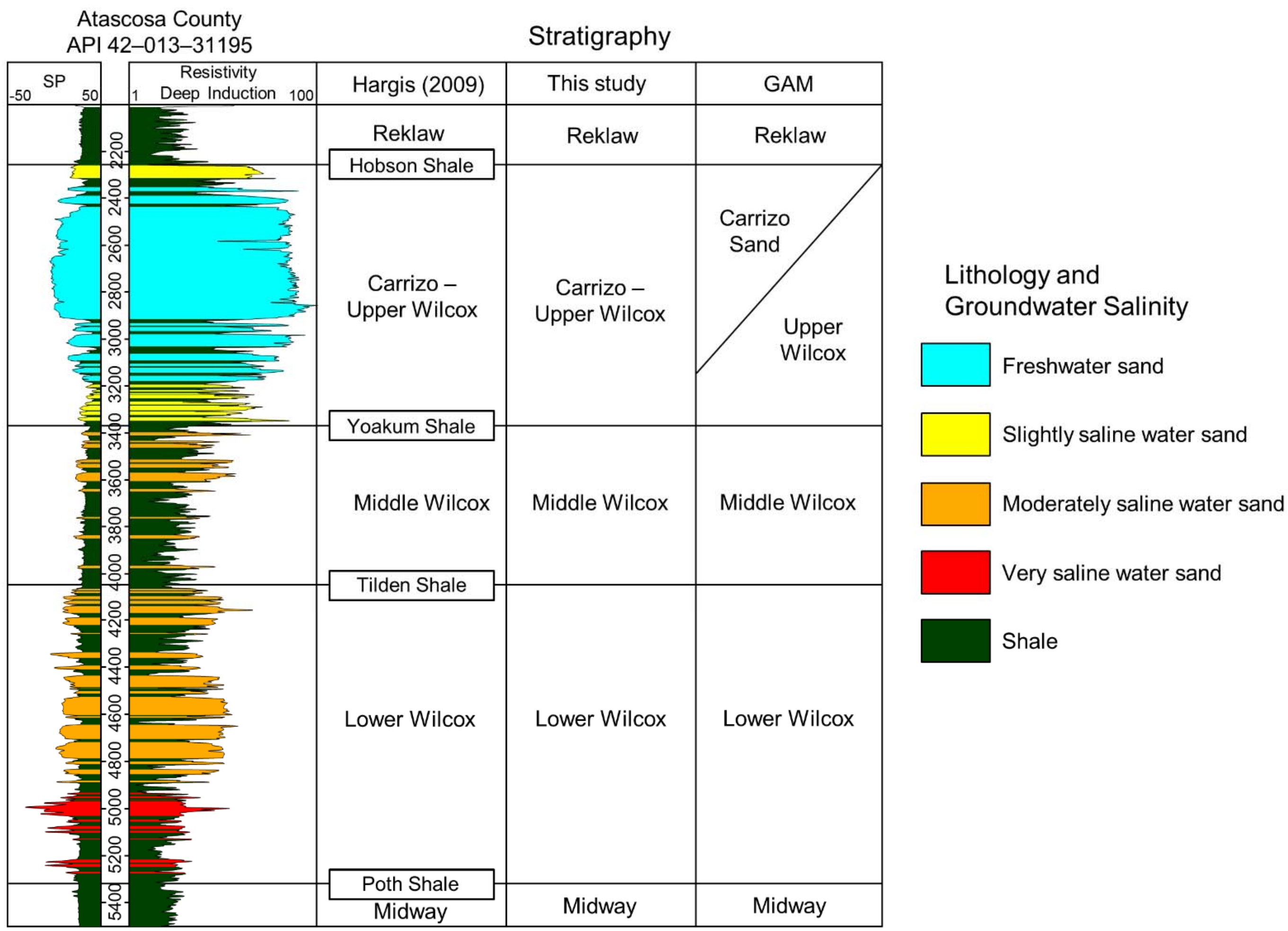


Figure 4-2. **Typical electric log showing SP (spontaneous potential) and resistivity curves through the Carrizo-Wilcox Aquifer. Both lithology (sand/shale) and groundwater salinity were interpreted from the electric log (see text for details). Aquifer stratigraphy follows well established subdivision of the Wilcox Group in South Texas. Prominent shales identified by Hargis (2009) were used to help correlate the three layers. Layering from the Groundwater Availability Model (GAM) is also shown (Kelley and others, 2004).**

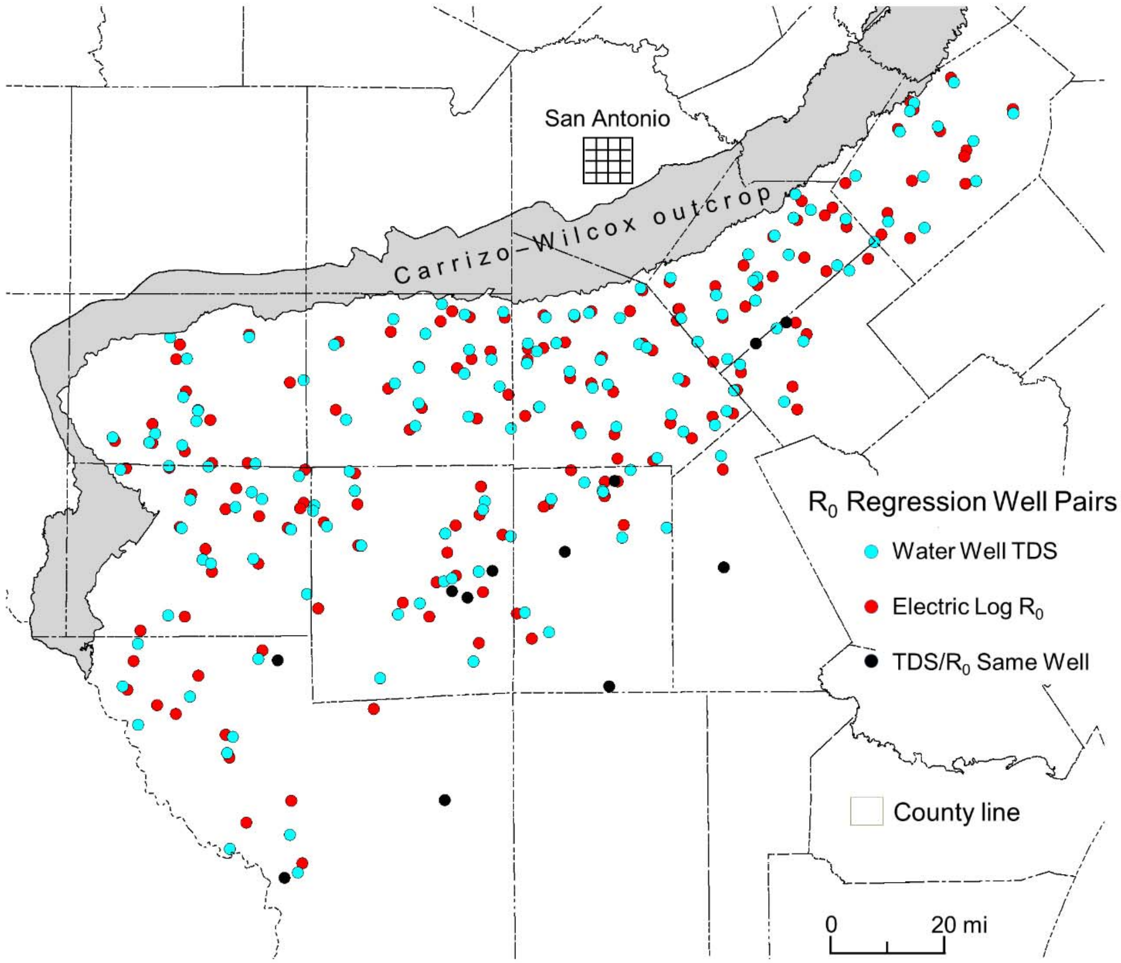


Figure 4-3. Wells used to develop TDS/R_0 regressions. Most TDS data (blue dots) come from water wells, whereas most resistivity data (red dots) come from petroleum wells. A few wells have both data types (black dots).

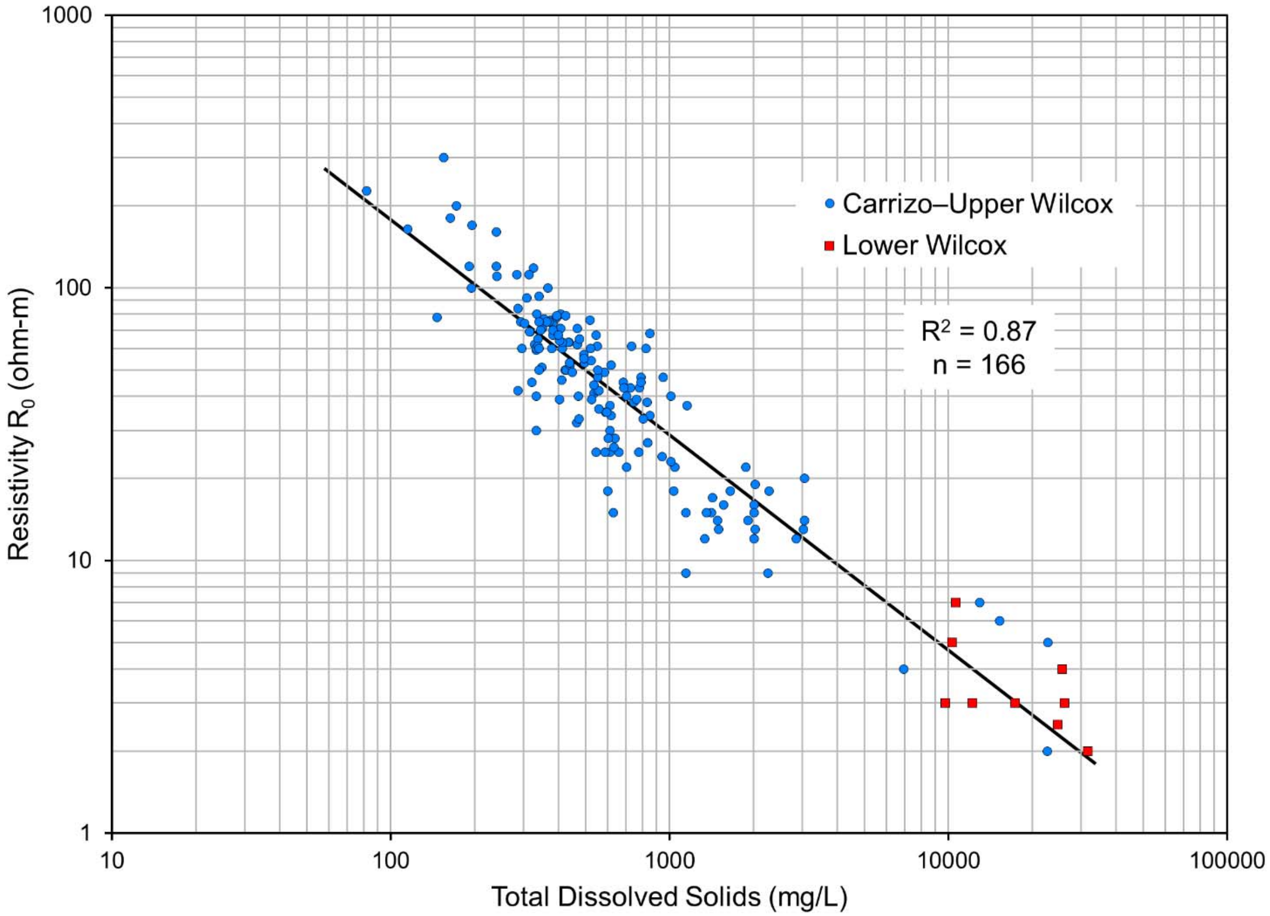


Figure 4-4. **Total dissolved solids (TDS) versus deep resistivity (R_0) for all well pairs in the study area.**

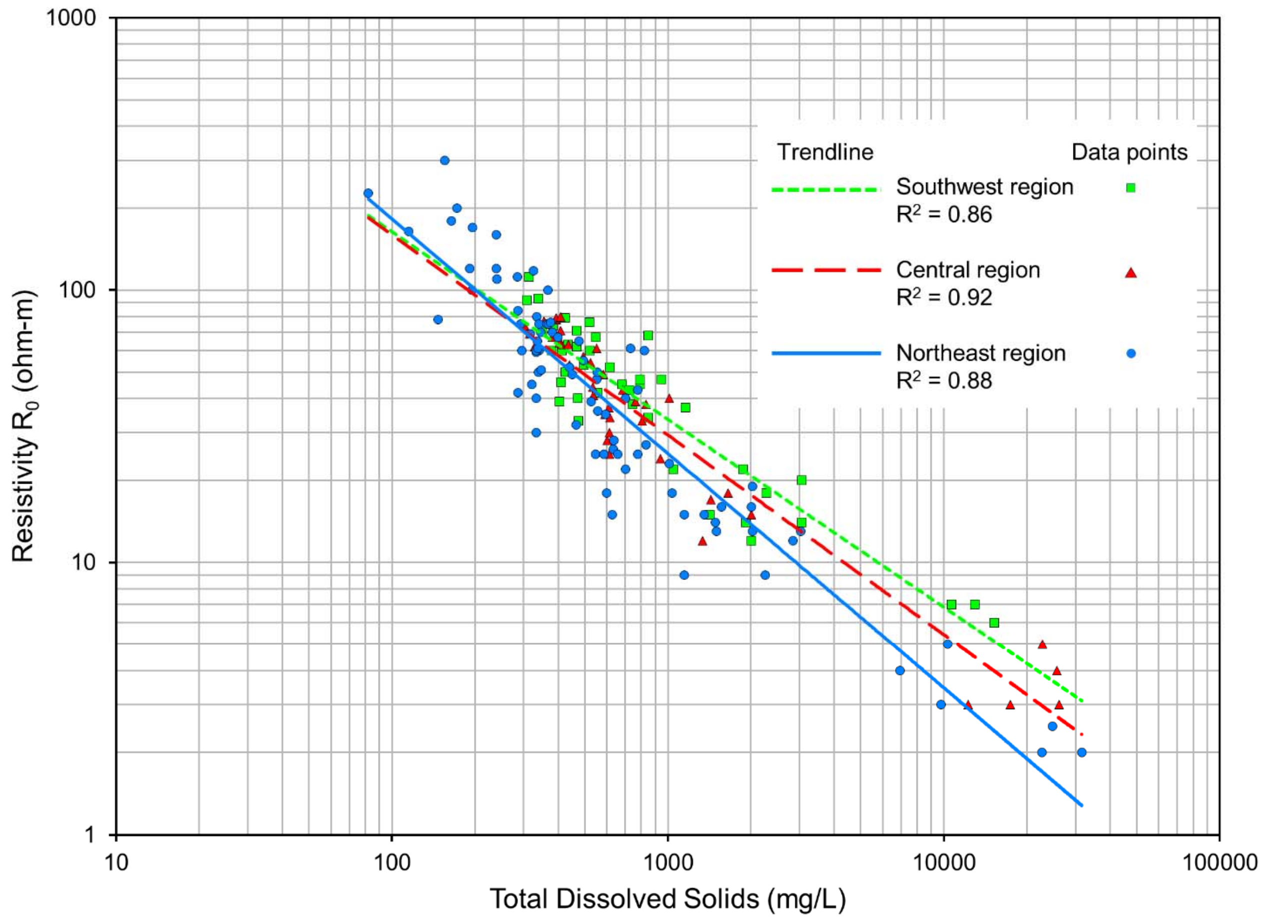


Figure 4-5. TDS versus deep resistivity (R_0) showing separate regressions for each of the three hydrogeologic regions (Figure 4-1).

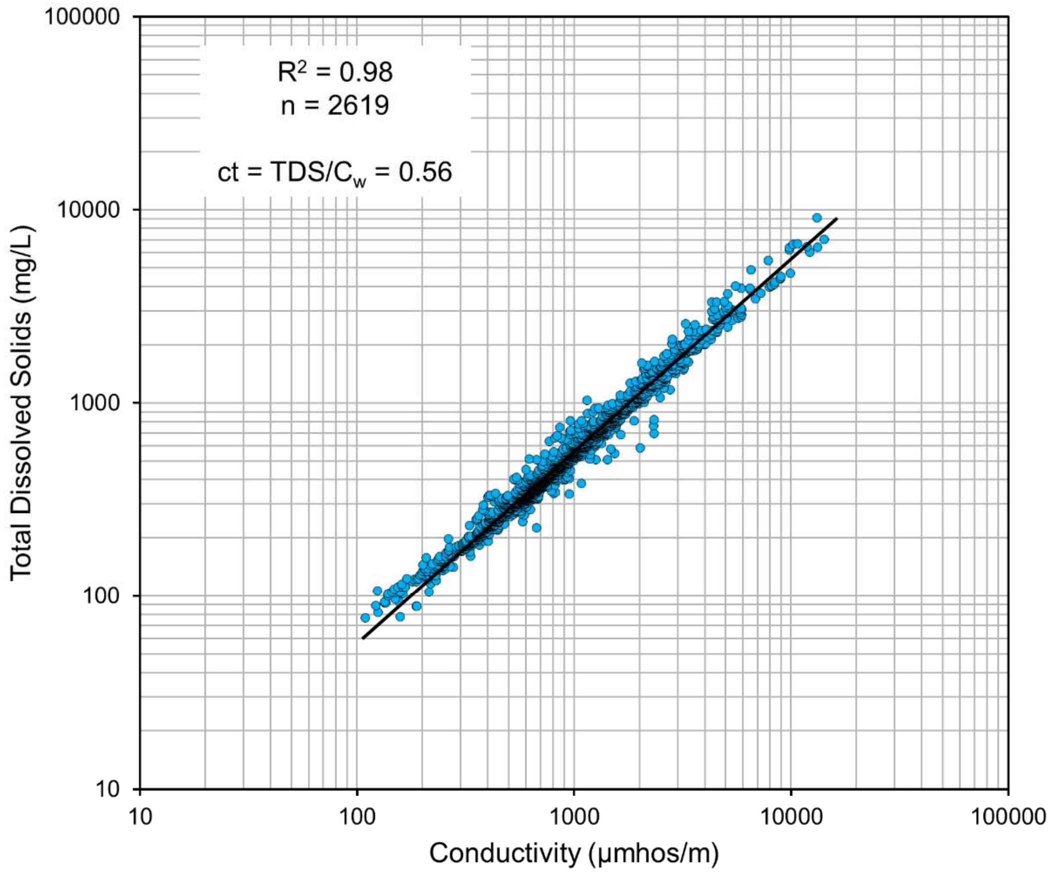


Figure 4-6. **Graph of conductivity (C_w) versus TDS for the study area. Both C_w and TDS were measured in water well samples. C_w and TDS are related by a proportionality constant (ct), which is specific to area and formation. Most of these data are from the Carrizo-upper Wilcox, but in South Texas, a single value of ct is valid for the entire Carrizo-Wilcox aquifer.**

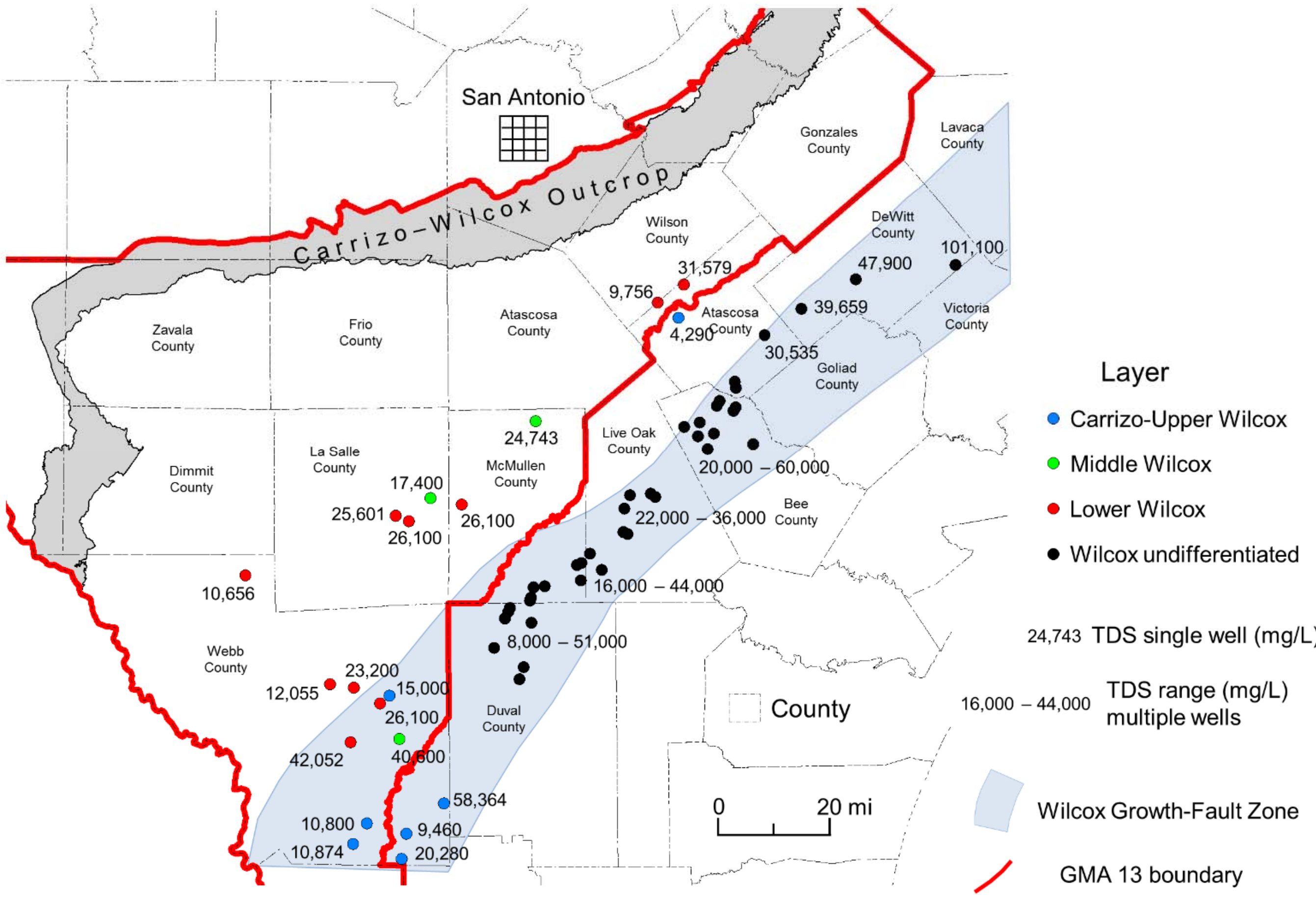


Figure 4-7. High groundwater salinities from oil and gas wells. Data from Taylor (1975) and Gaither (1986).

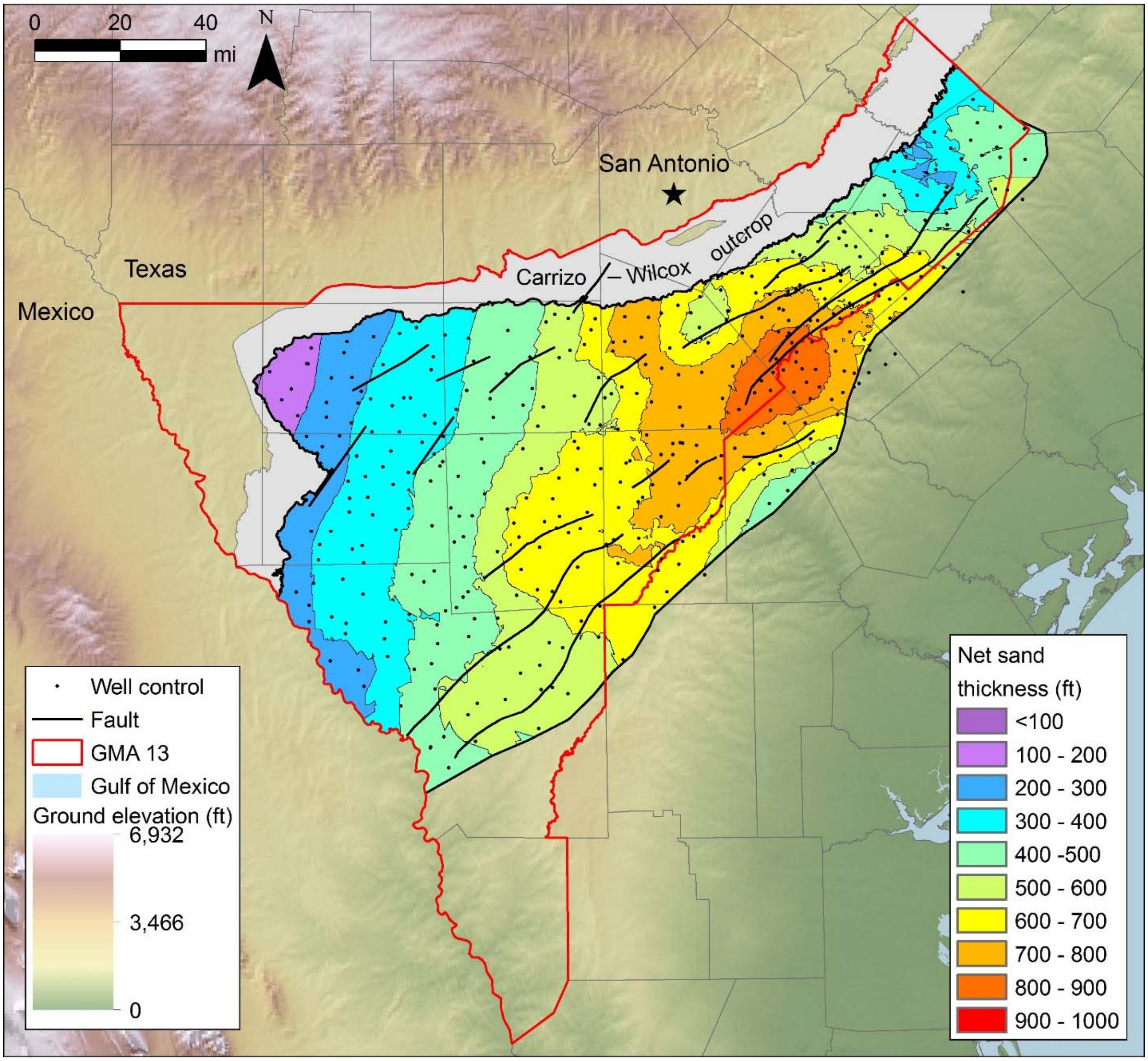


Figure 4-8. **Carrizo-upper Wilcox net sand thickness. Maximum sand thicknesses in the Carrizo-upper Wilcox form a depocenter south of San Antonio.**

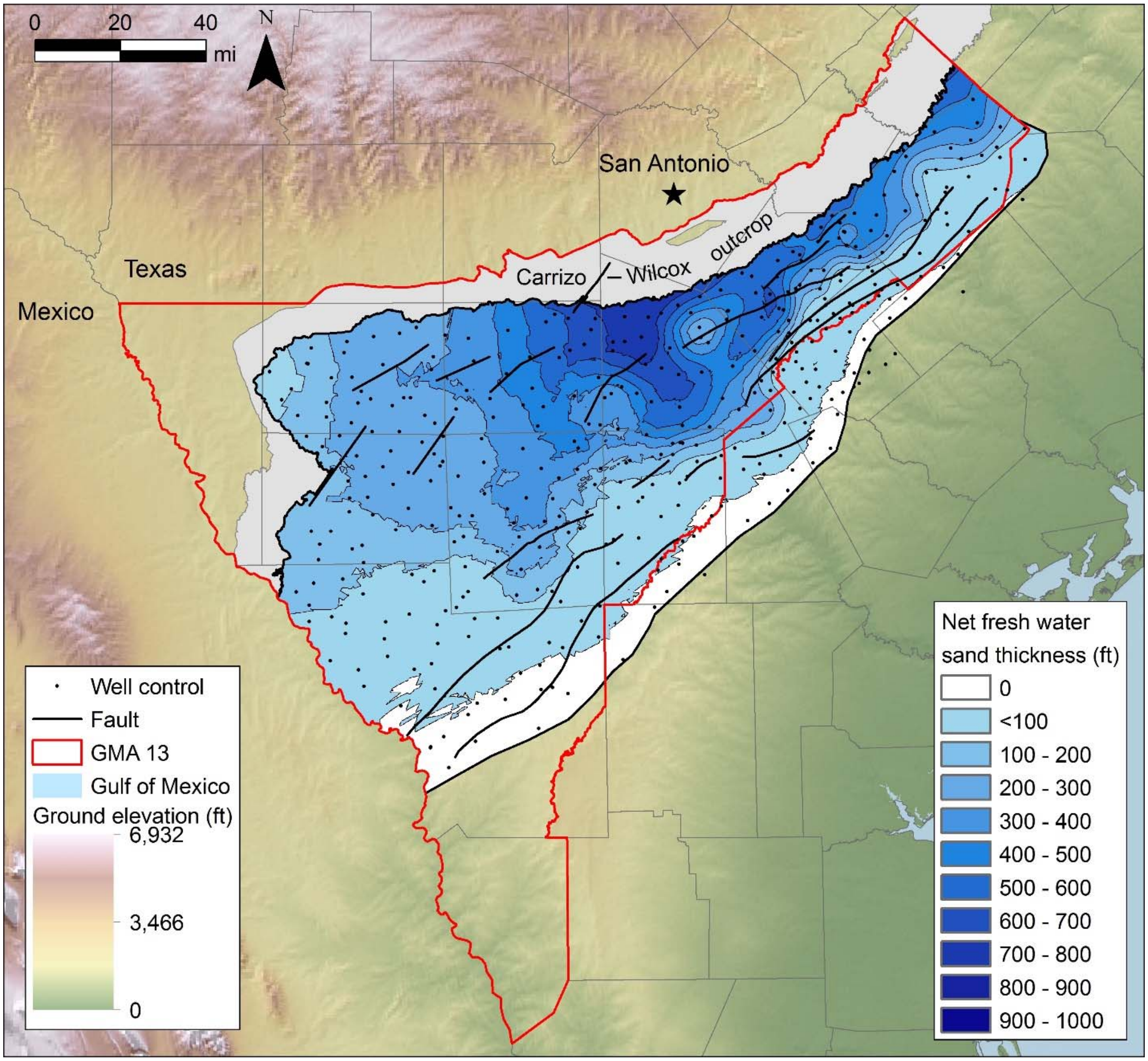


Figure 4-9. Net thickness of sand containing fresh groundwater in the Carrizo-upper Wilcox interval. Fault zones modified from Ewing (1991) and Hargis (2009). Groundwater salinities increase abruptly across some of these regional faults.

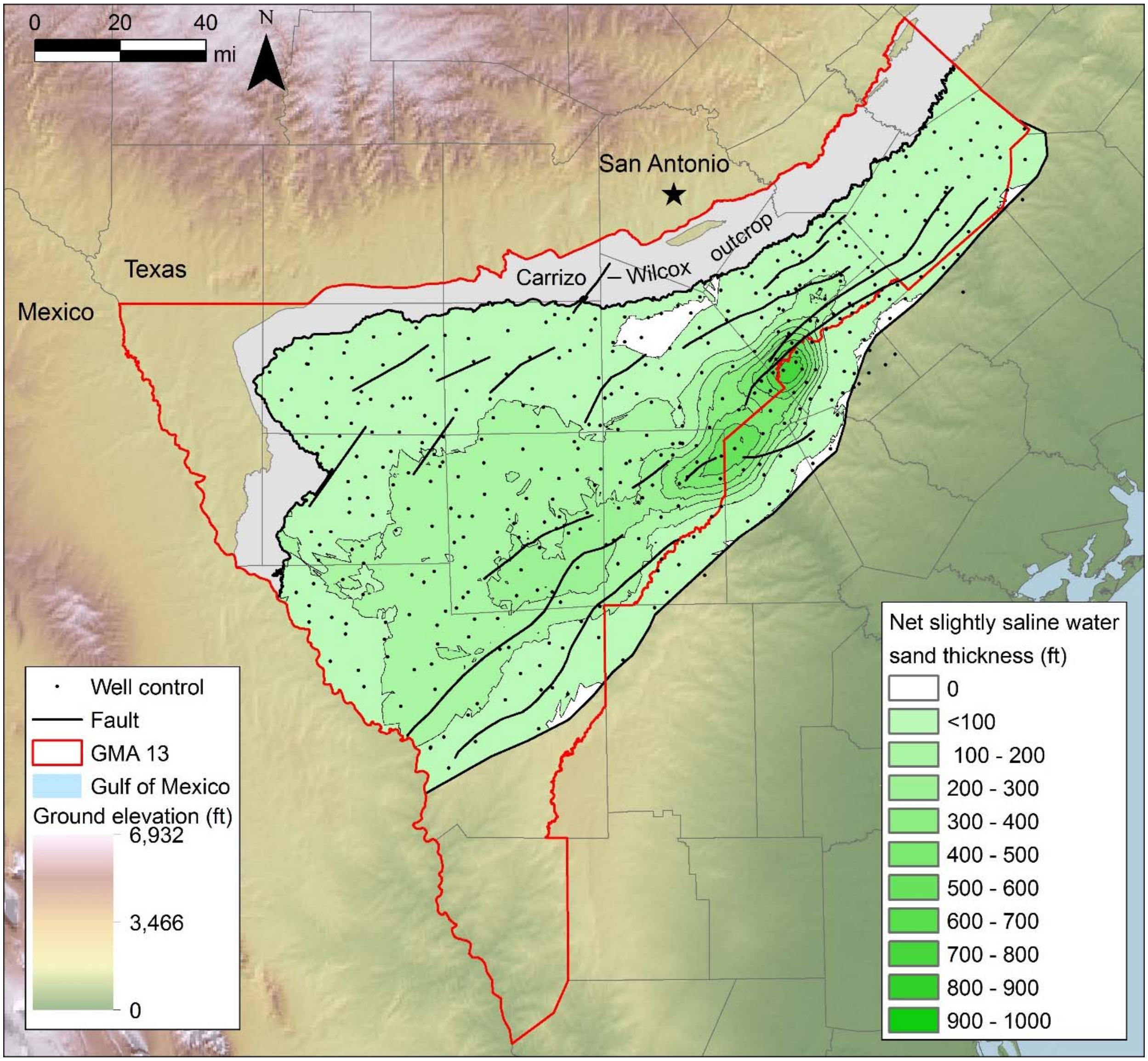


Figure 4-10. **Net thickness of sand containing slightly saline groundwater in the Carrizo-upper Wilcox interval. Fault zones modified from Ewing (1991) and Hargis (2009).**

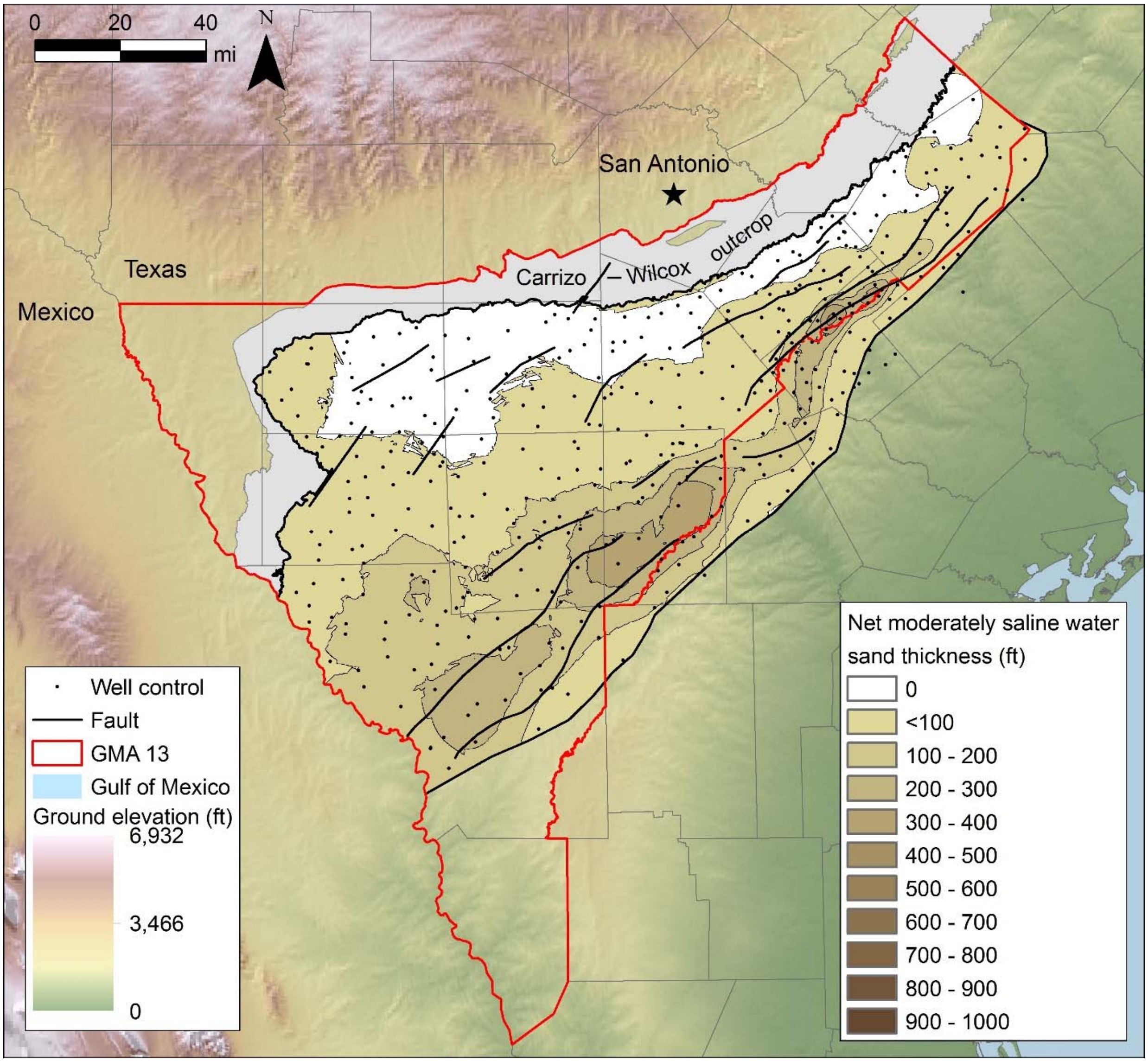


Figure 4-11. **Net thickness of sand containing moderately saline groundwater in the Carrizo-upper Wilcox interval. Fault zones modified from Ewing (1991) and Hargis (2009).**

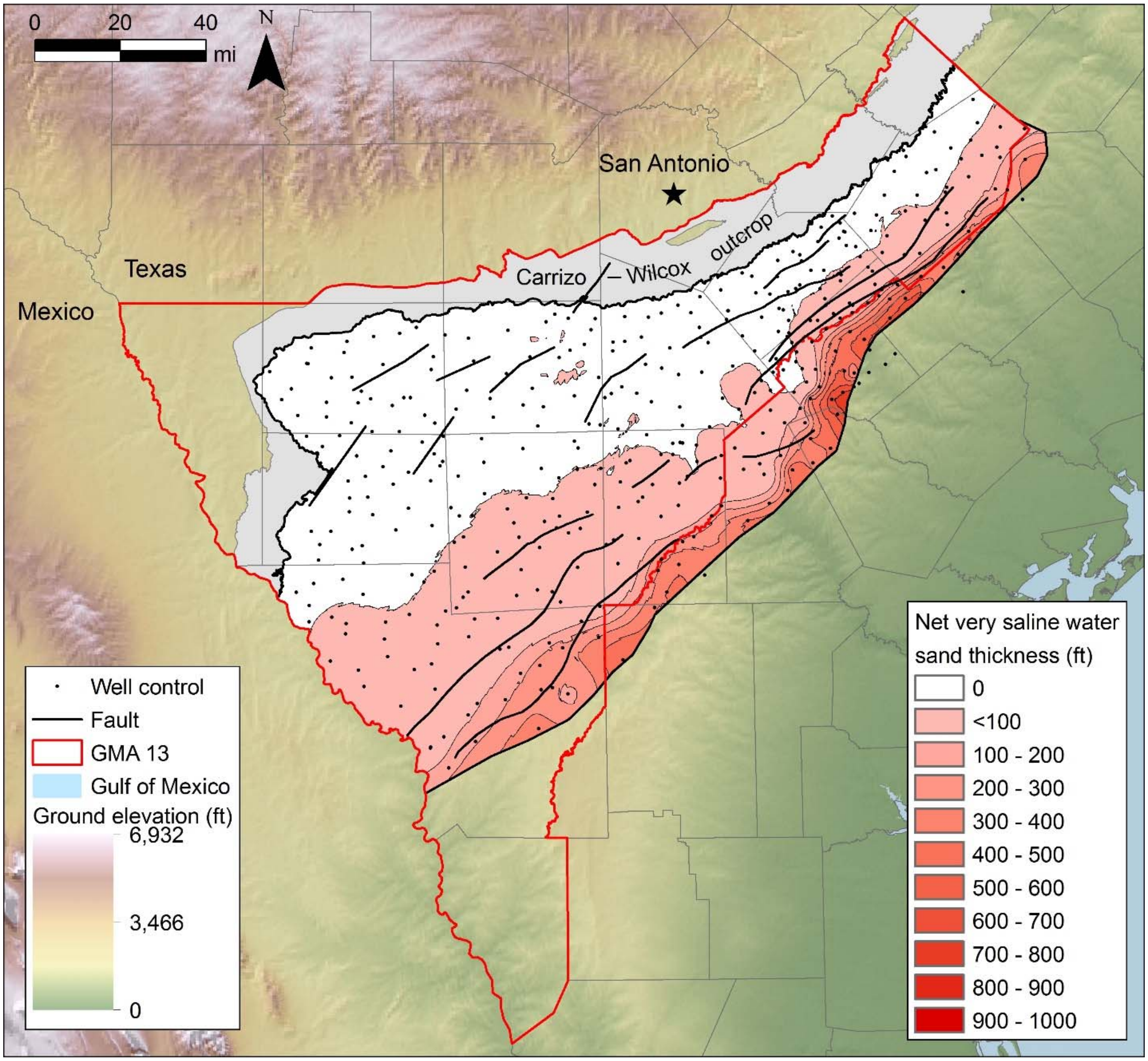


Figure 4-12. Net thickness of sand containing very saline groundwater in the Carrizo-upper Wilcox interval. Fault zones modified from Ewing (1991) and Hargis (2009).

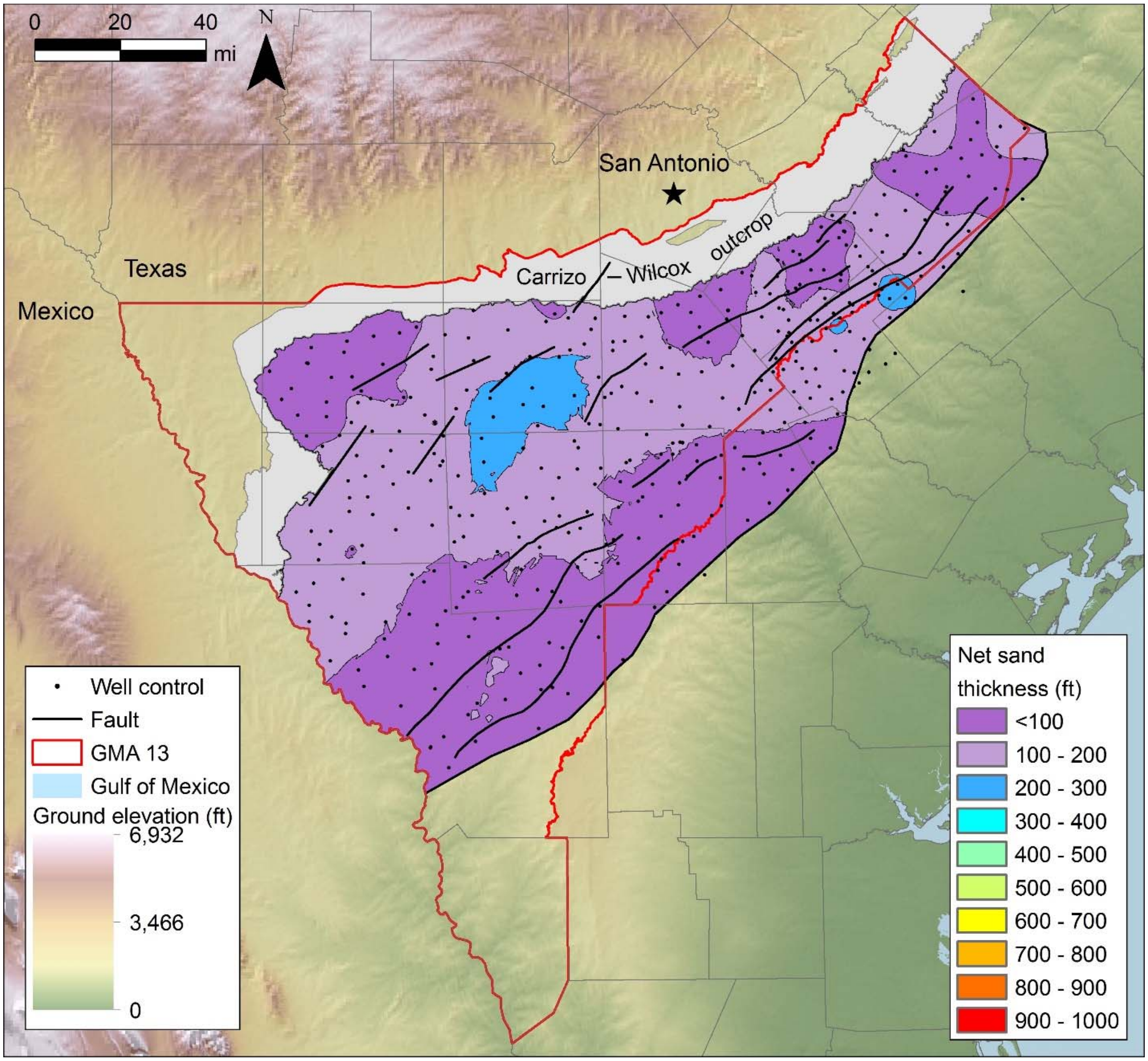


Figure 4-13. **Middle Wilcox net sand thickness. The middle Wilcox is typically a low-sand, high-shale interval.**

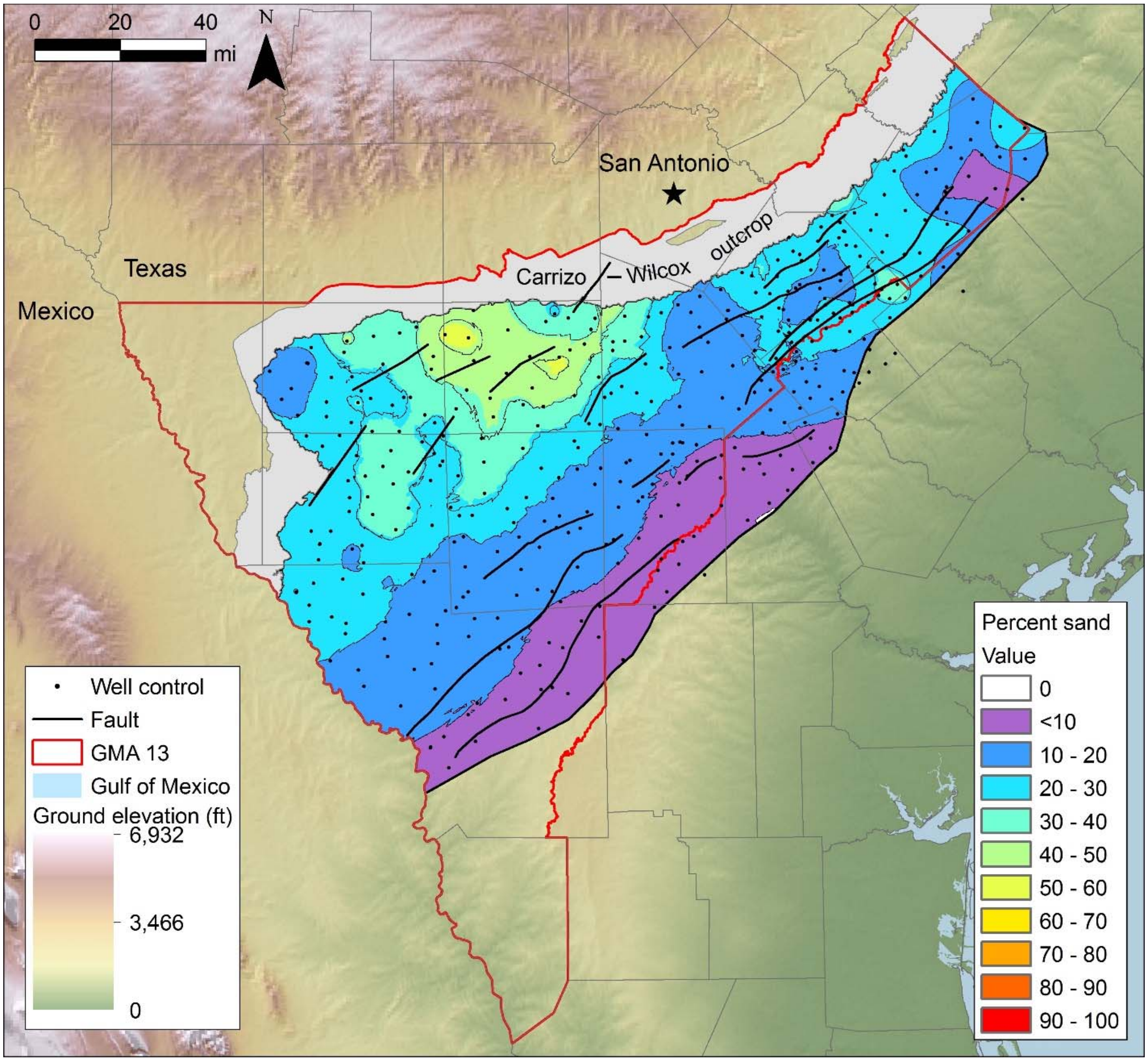


Figure 4-14. **Middle Wilcox percent sand (net sand thickness / total interval thickness). The middle Wilcox is typically >50% shale (<50% sand), but in large parts of GMA 13, the middle Wilcox is >70% shale.**

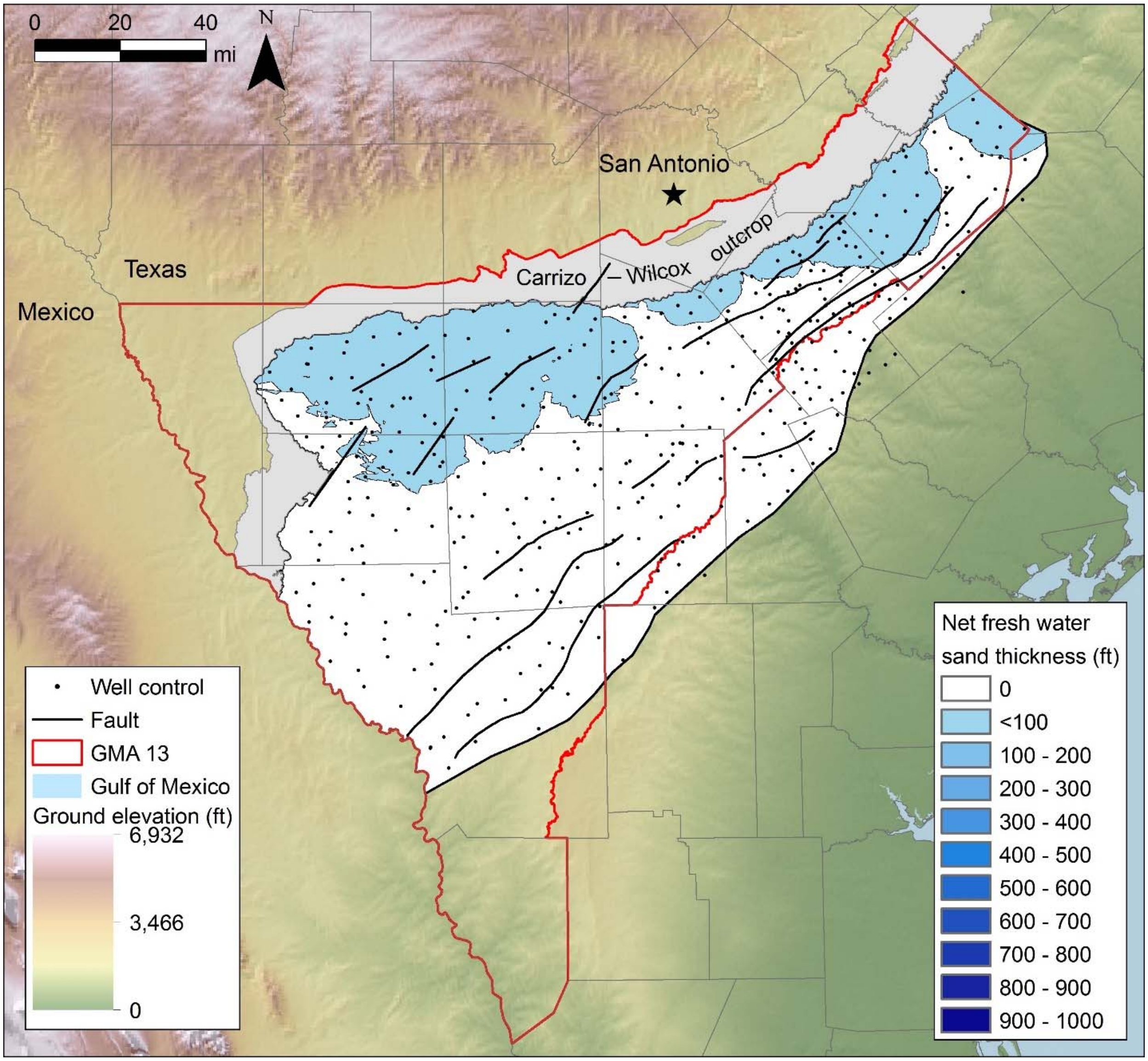


Figure 4-15. Net thickness of sand containing fresh groundwater in the middle Wilcox interval. Fault zones modified from Ewing (1991) and Hargis (2009).

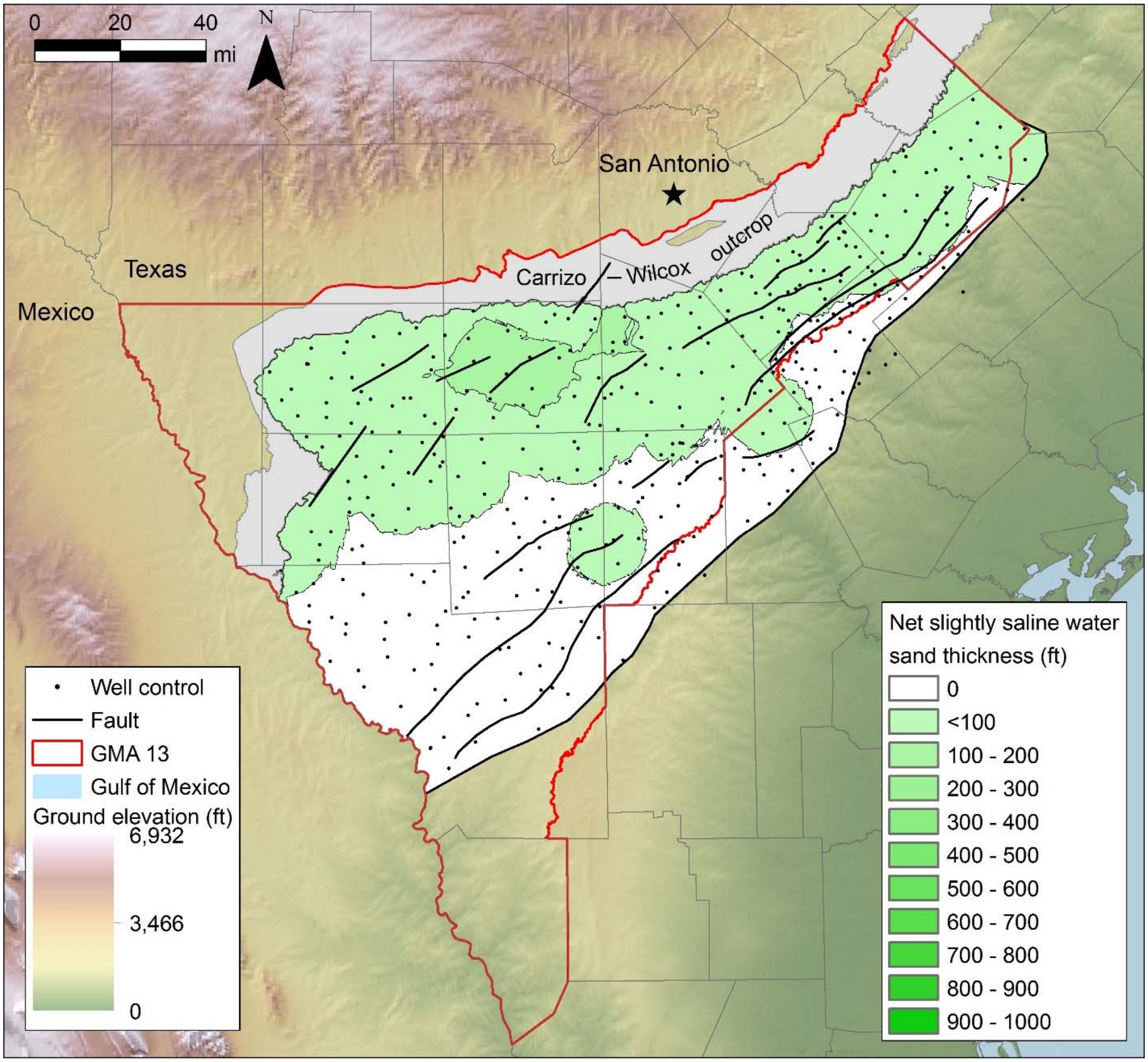


Figure 4-16. **Net thickness of sand containing slightly saline groundwater in the middle Wilcox interval. Fault zones modified from Ewing (1991) and Hargis (2009).**

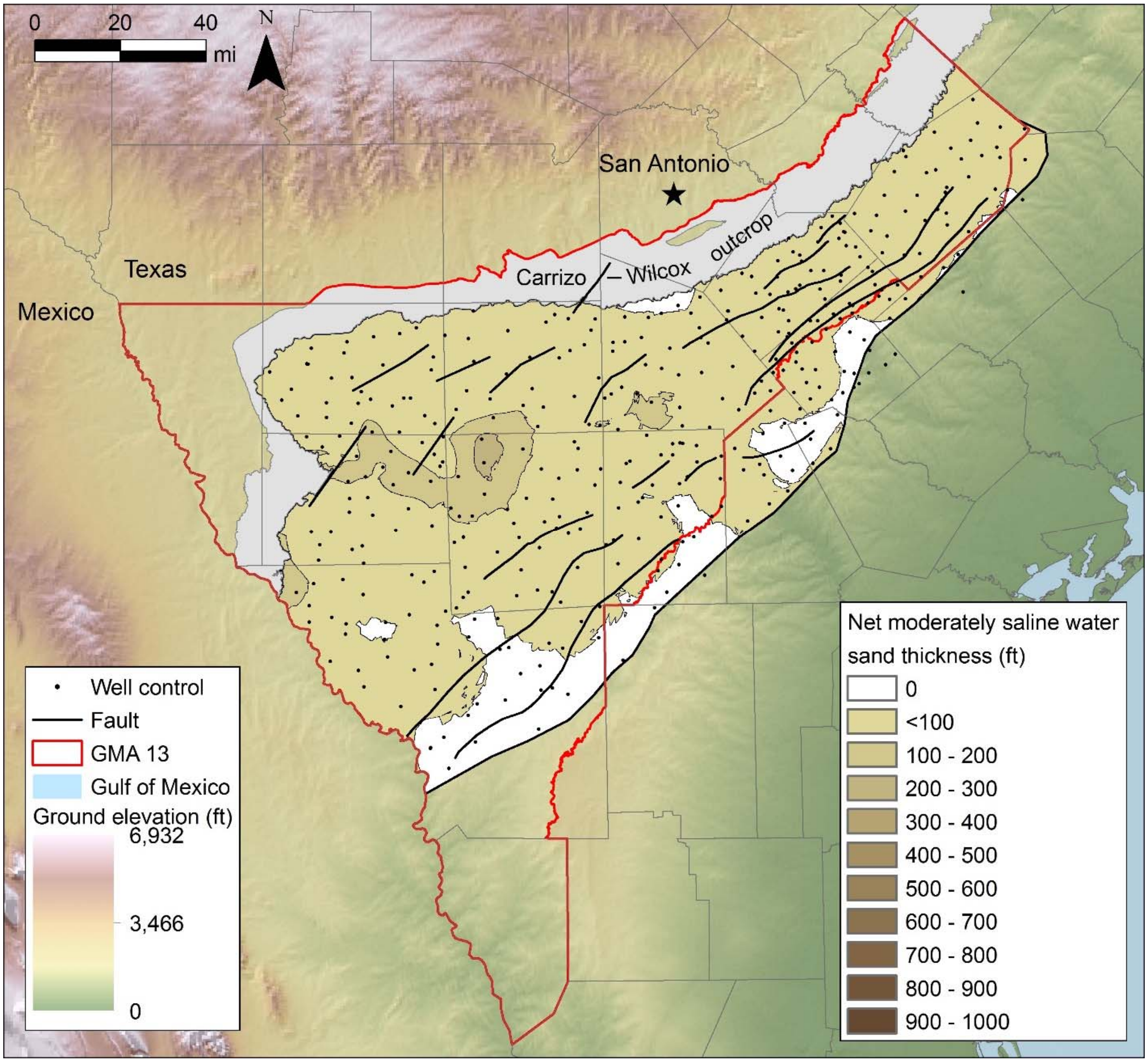


Figure 4-17. **Net thickness of sand containing moderately saline groundwater in the middle Wilcox interval. Fault zones modified from Ewing (1991) and Hargis (2009).**

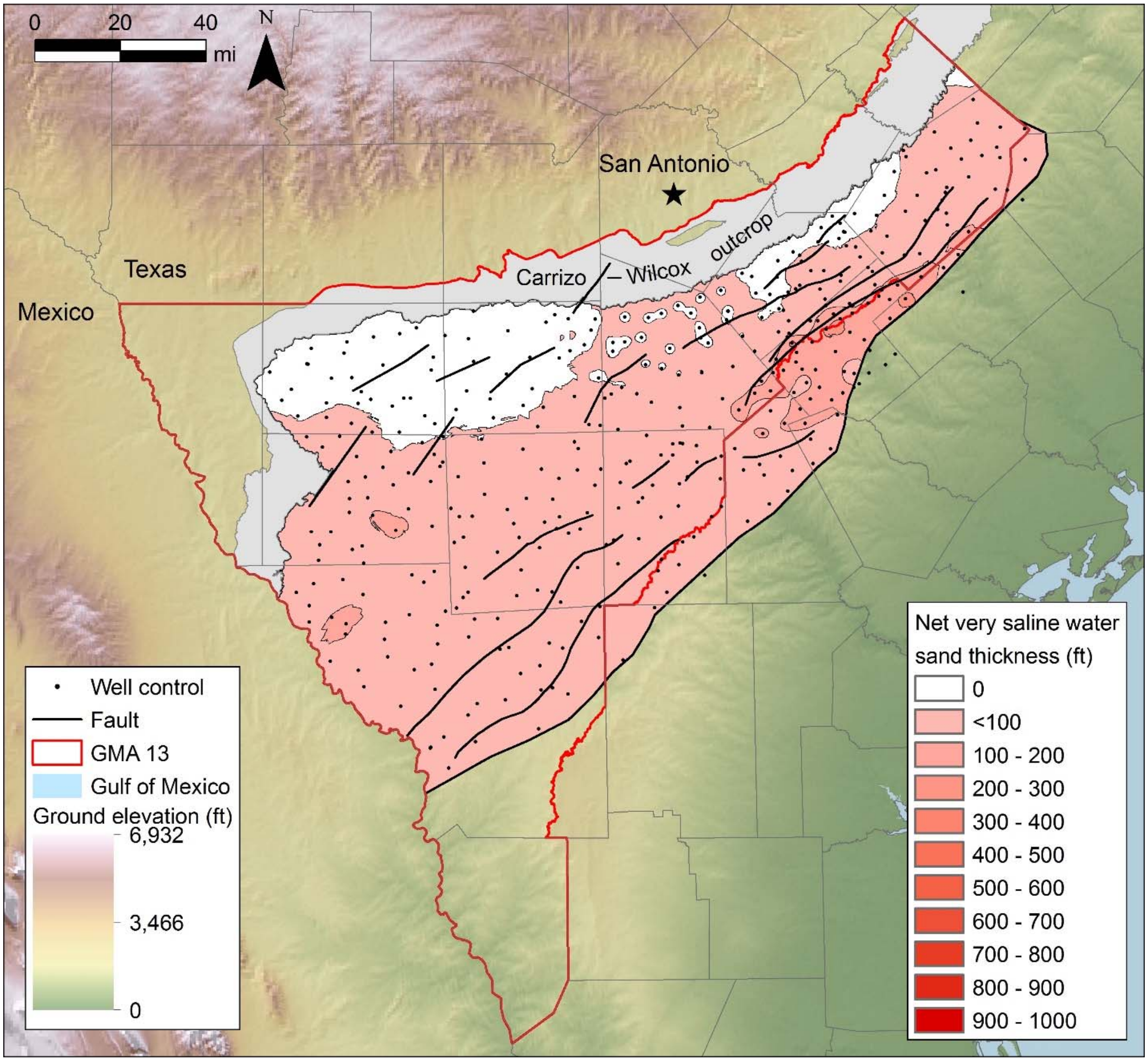


Figure 4-18. Net thickness of sand containing very saline groundwater in the middle Wilcox interval. Fault zones modified from Ewing (1991) and Hargis (2009).

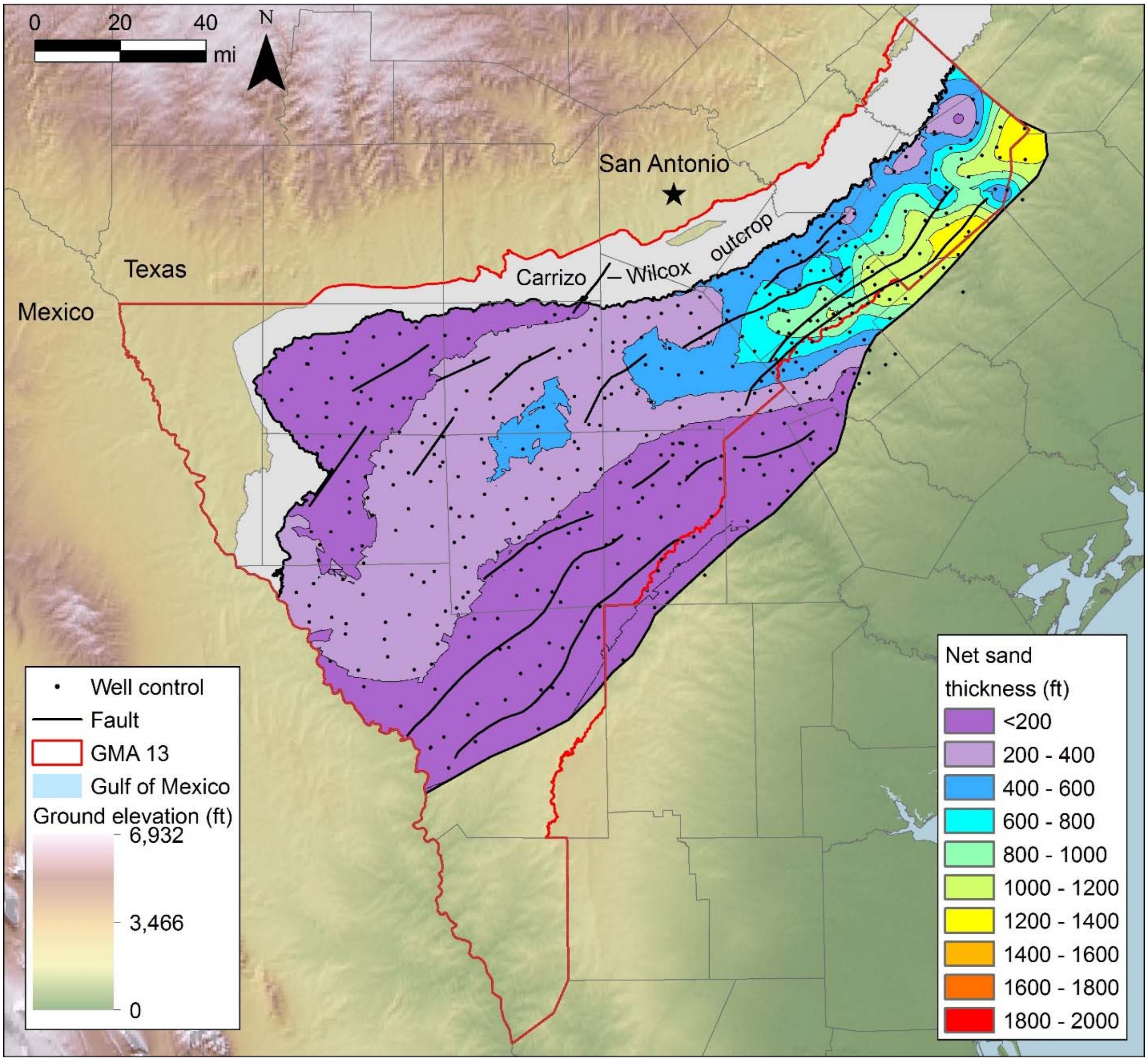


Figure 4-19. Lower Wilcox net sand thickness. Maximum sand thicknesses in the lower Wilcox are located in the northeast part of the study area. The shale-filled Yoakum Canyon erosionally truncates lower Wilcox sands.

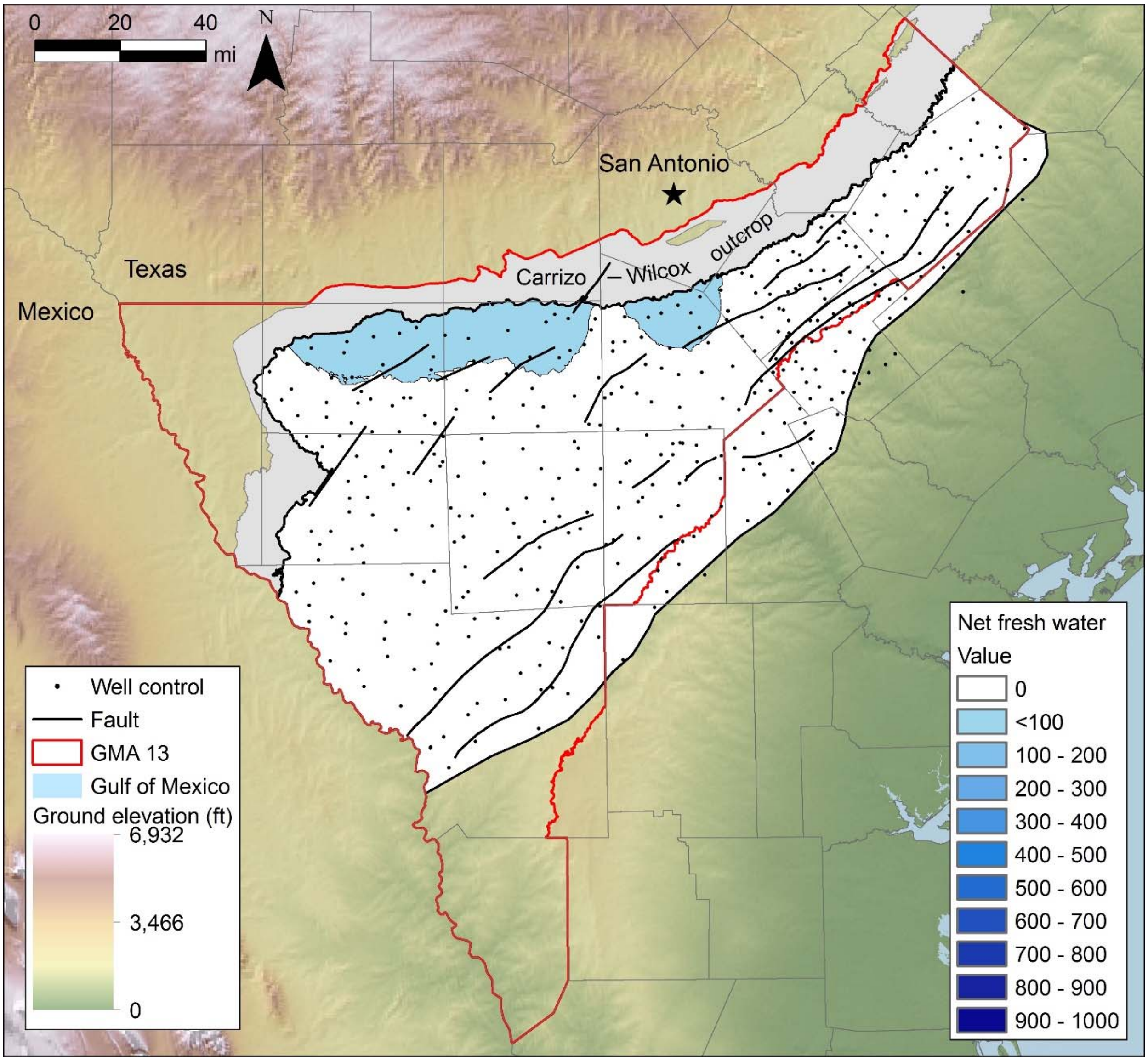


Figure 4-20. **Net thickness of sand containing fresh groundwater in the lower Wilcox interval. Fault zones modified from Ewing (1991) and Hargis (2009).**

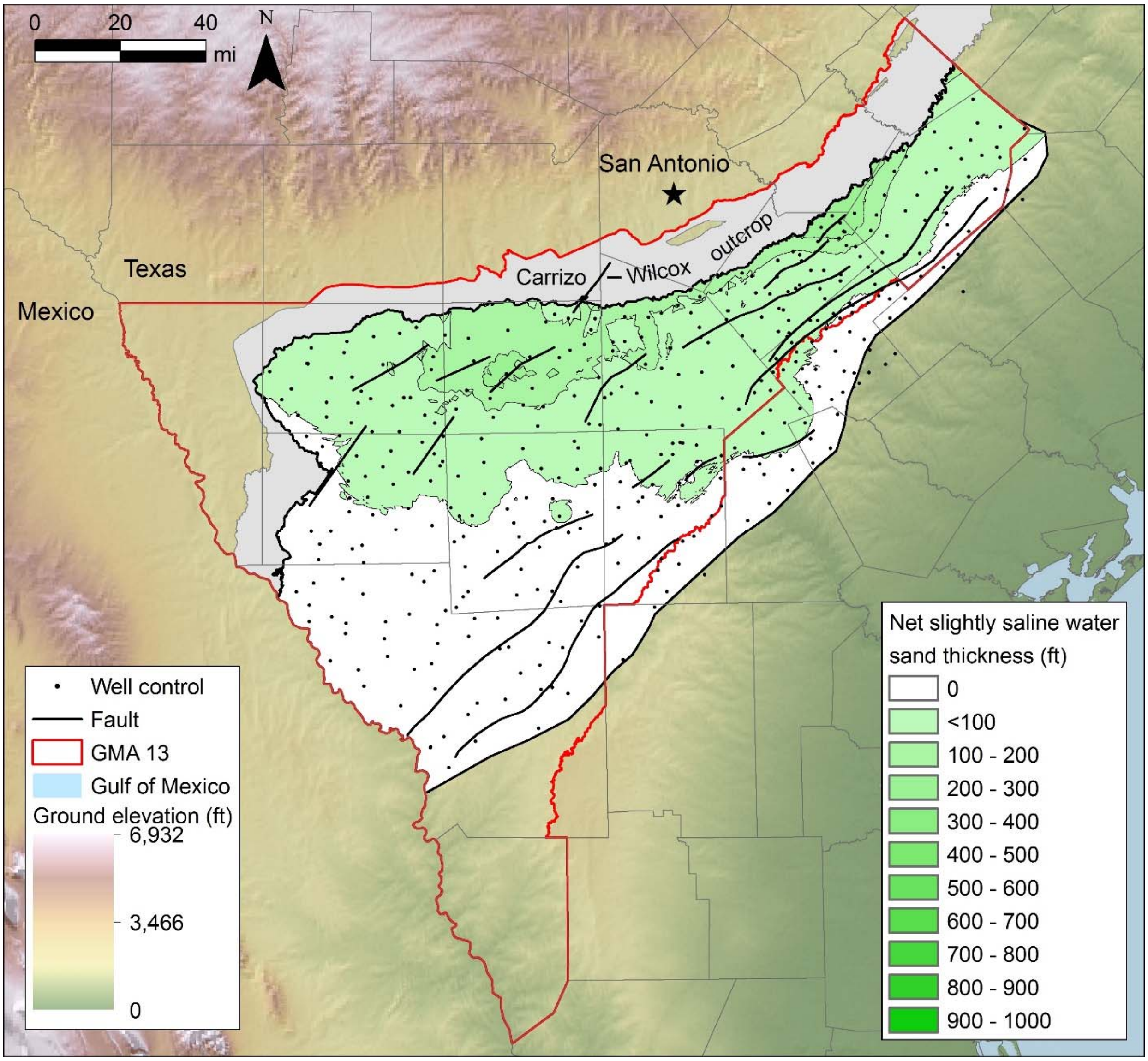


Figure 4-21. Net thickness of sand containing slightly saline groundwater in the lower Wilcox interval. Fault zones modified from Ewing (1991) and Hargis (2009).

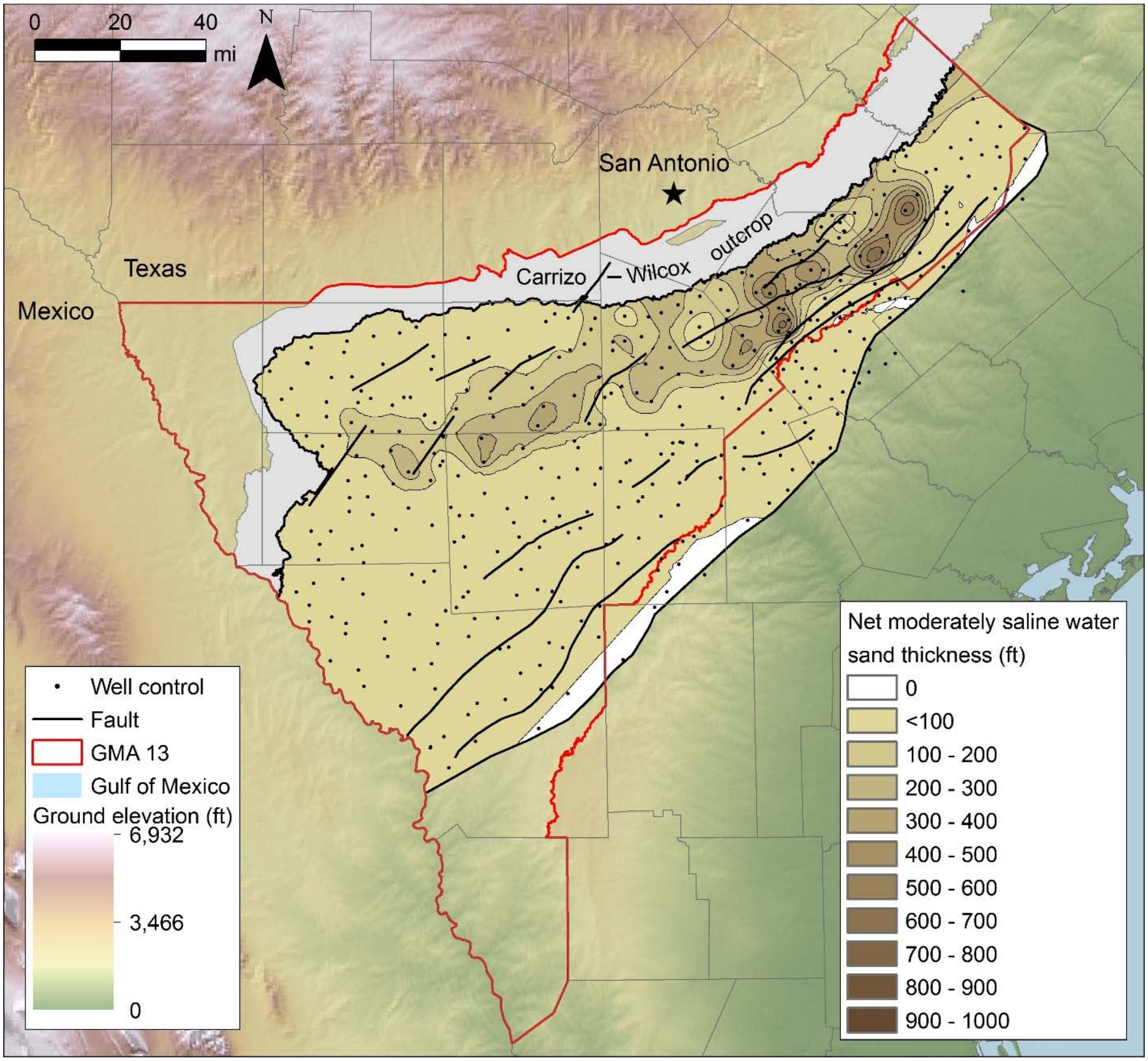


Figure 4-22. **Net thickness of sand containing moderately saline groundwater in the lower Wilcox interval. Fault zones modified from Ewing (1991) and Hargis (2009).**

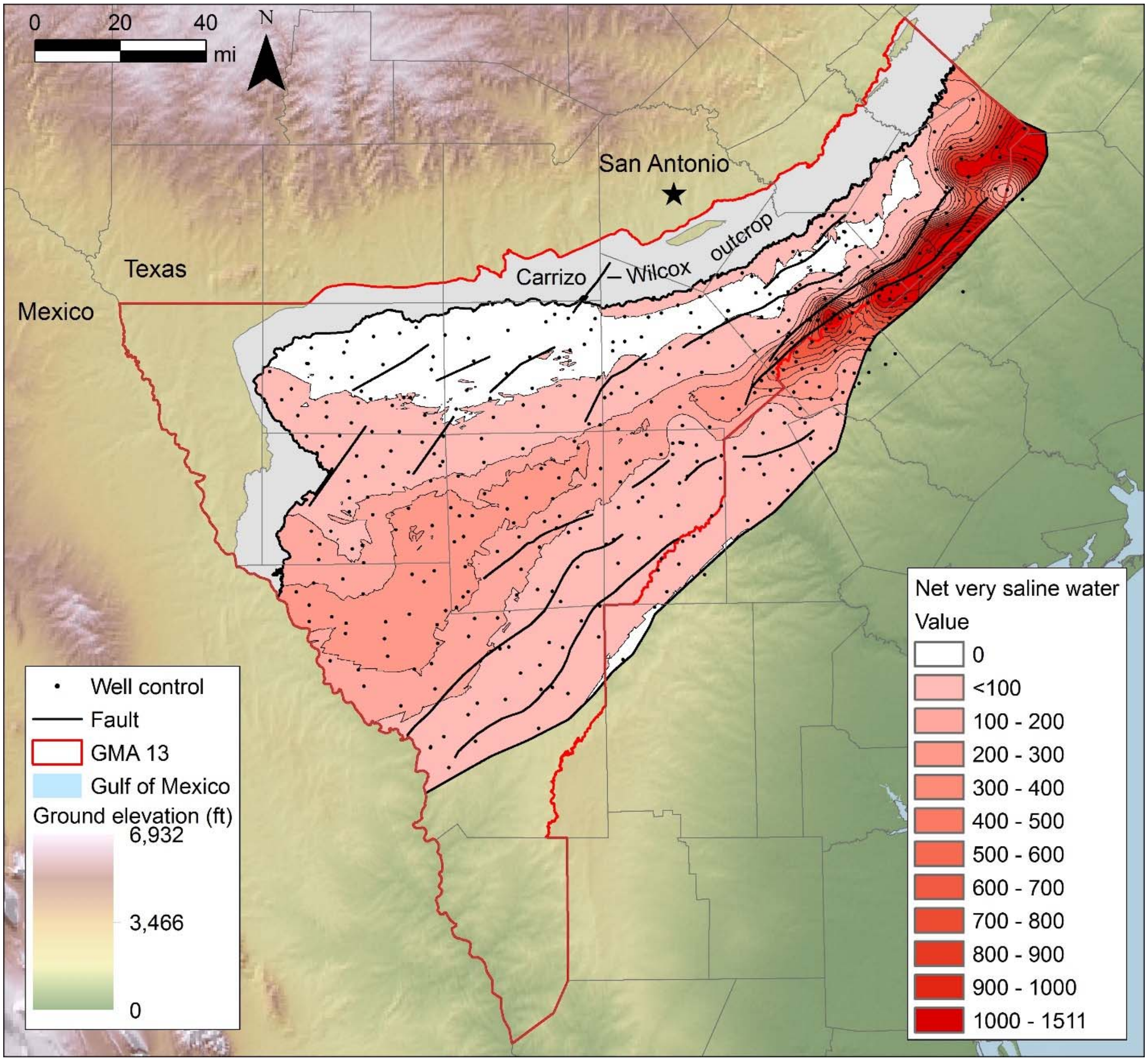


Figure 4-23. **Net thickness of sand containing very saline groundwater in the lower Wilcox interval. Fault zones modified from Ewing (1991) and Hargis (2009).**

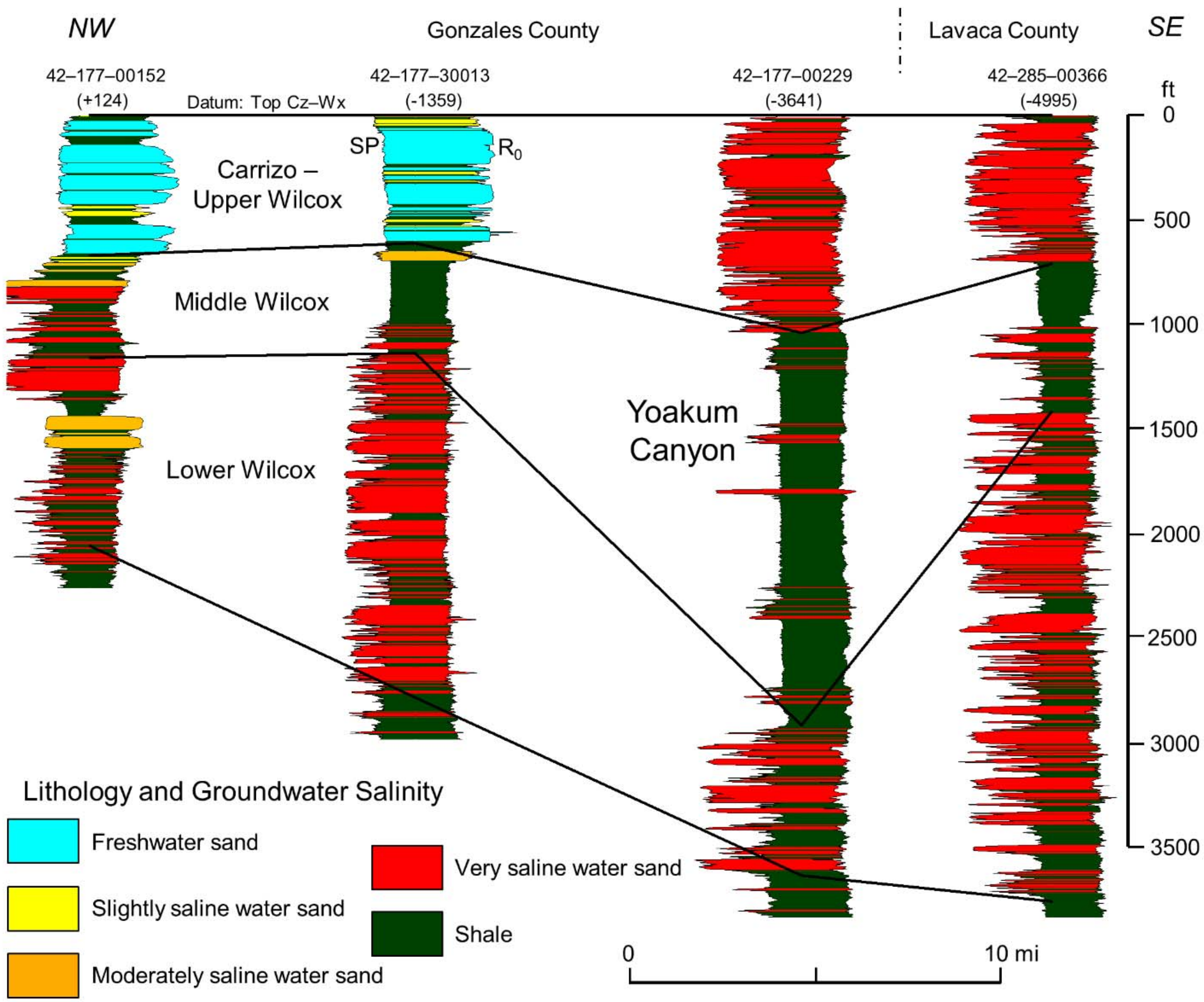


Figure 4-24. Stratigraphic cross section A showing lithologies and groundwater salinities. See Figure 4-1 for location. Well API numbers are shown at top. SP (left side) and resistivity (right side) logs are shown for each well. Subsea elevation of the datum (top Carrizo-Wilcox Aquifer) is also shown for each well.

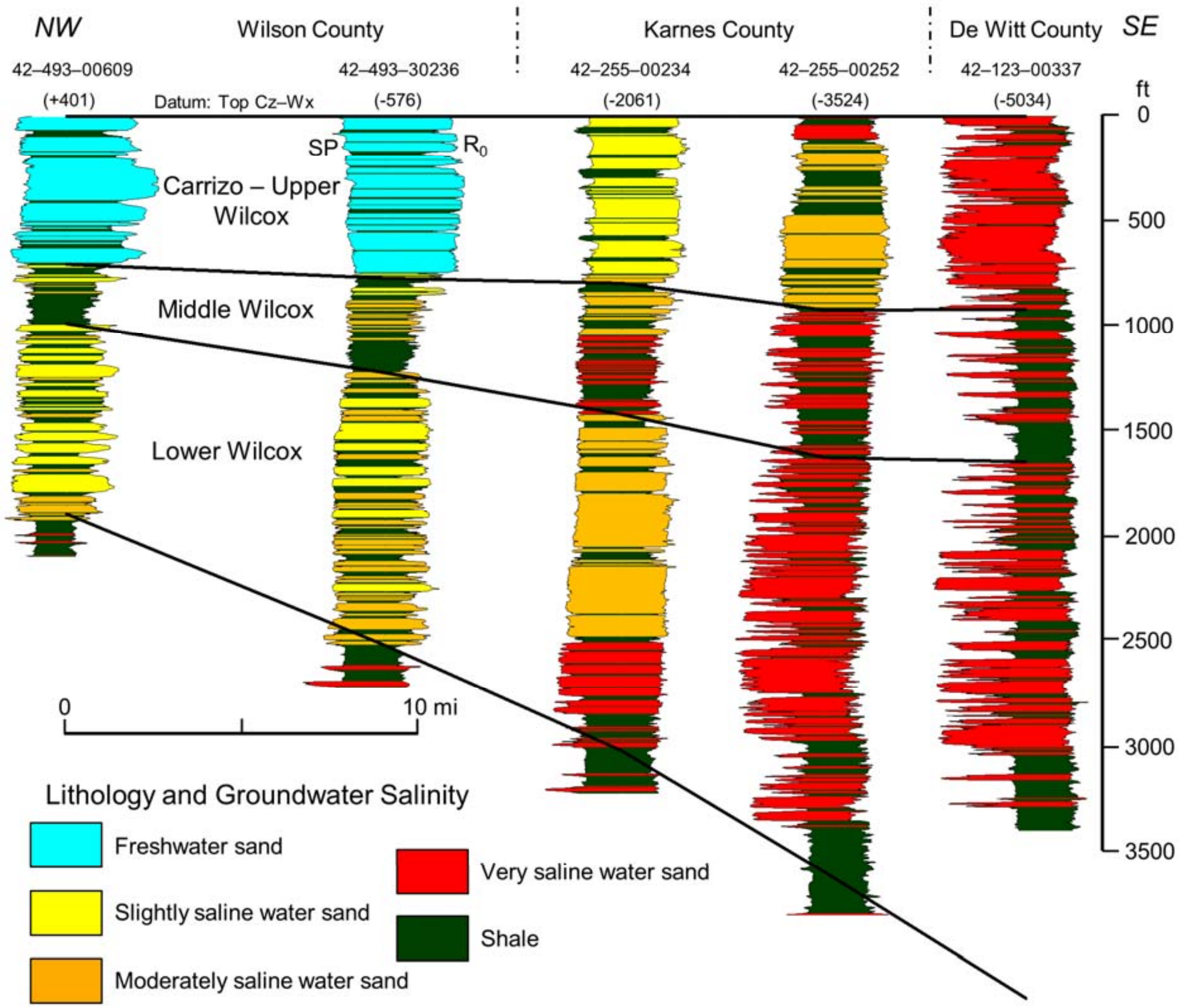


Figure 4-25. **Stratigraphic cross section B showing lithologies and groundwater salinities. See Figure 4-1 for location. Well API numbers are shown at top. SP (left side) and resistivity (right side) logs are shown for each well. Subsea elevation of the datum (top Carrizo-Wilcox Aquifer) is also shown for each well.**

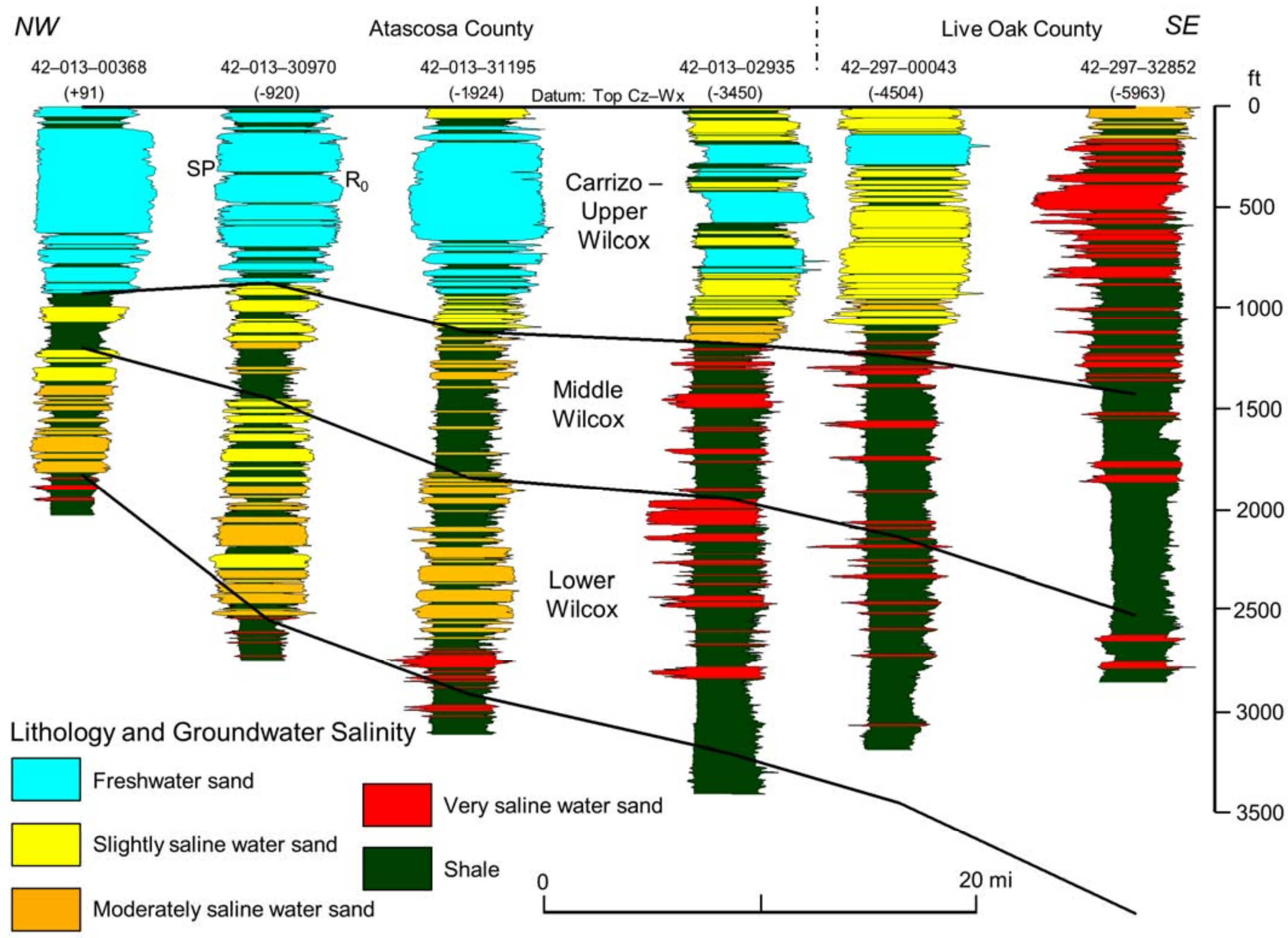


Figure 4-26. **Stratigraphic cross section C showing lithologies and groundwater salinities. See Figure 4-1 for location. Well API numbers are shown at top. SP (left side) and resistivity (right side) logs are shown for each well. Subsea elevation of the datum (top Carrizo-Wilcox Aquifer) is also shown for each well.**

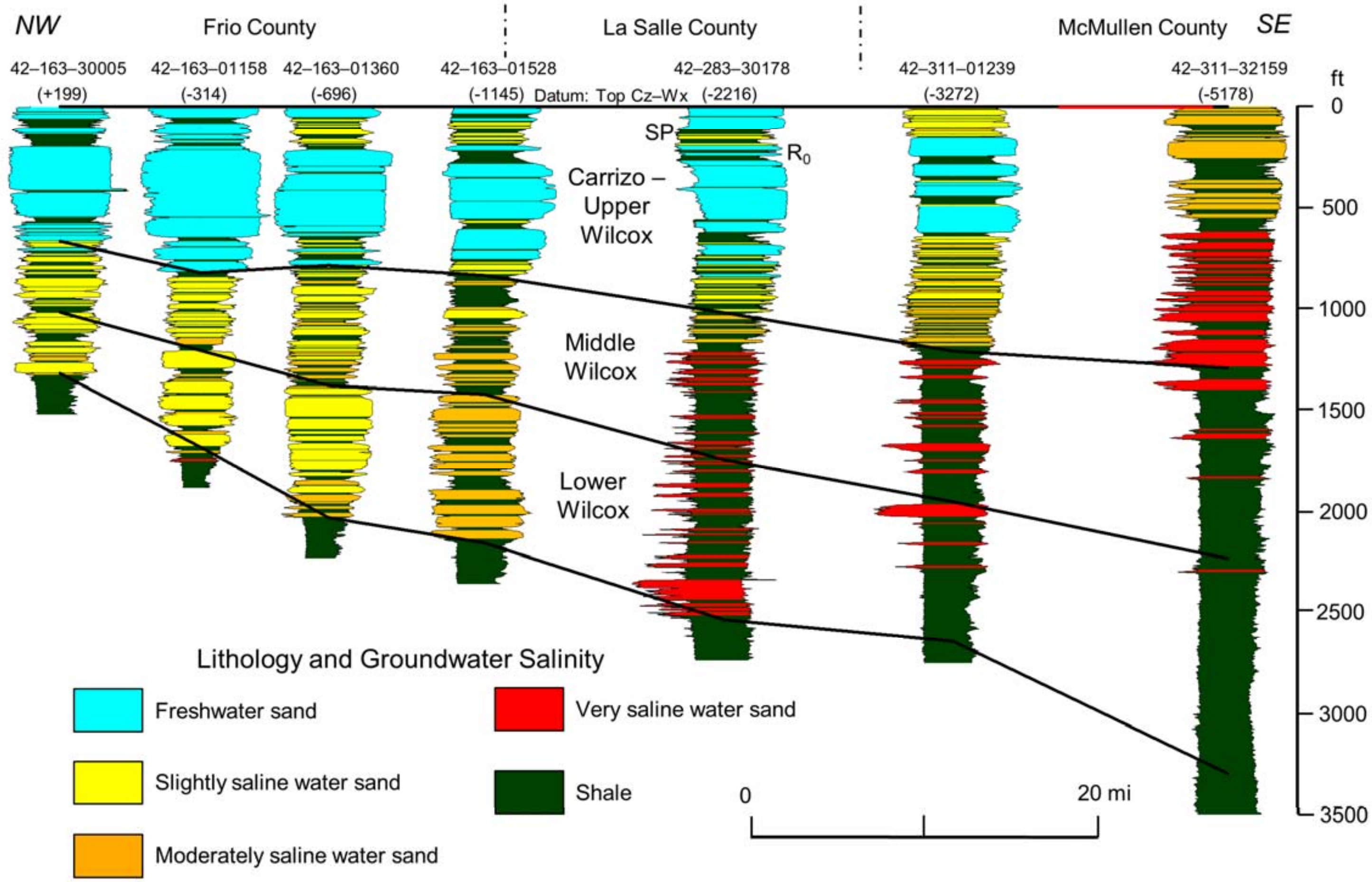


Figure 4-27. **Stratigraphic cross section D showing lithologies and groundwater salinities. See Figure 4-1 for location. Well API numbers are shown at top. SP (left side) and resistivity (right side) logs are shown for each well. Subsea elevation of the datum (top Carrizo-Wilcox Aquifer) is also shown for each well.**

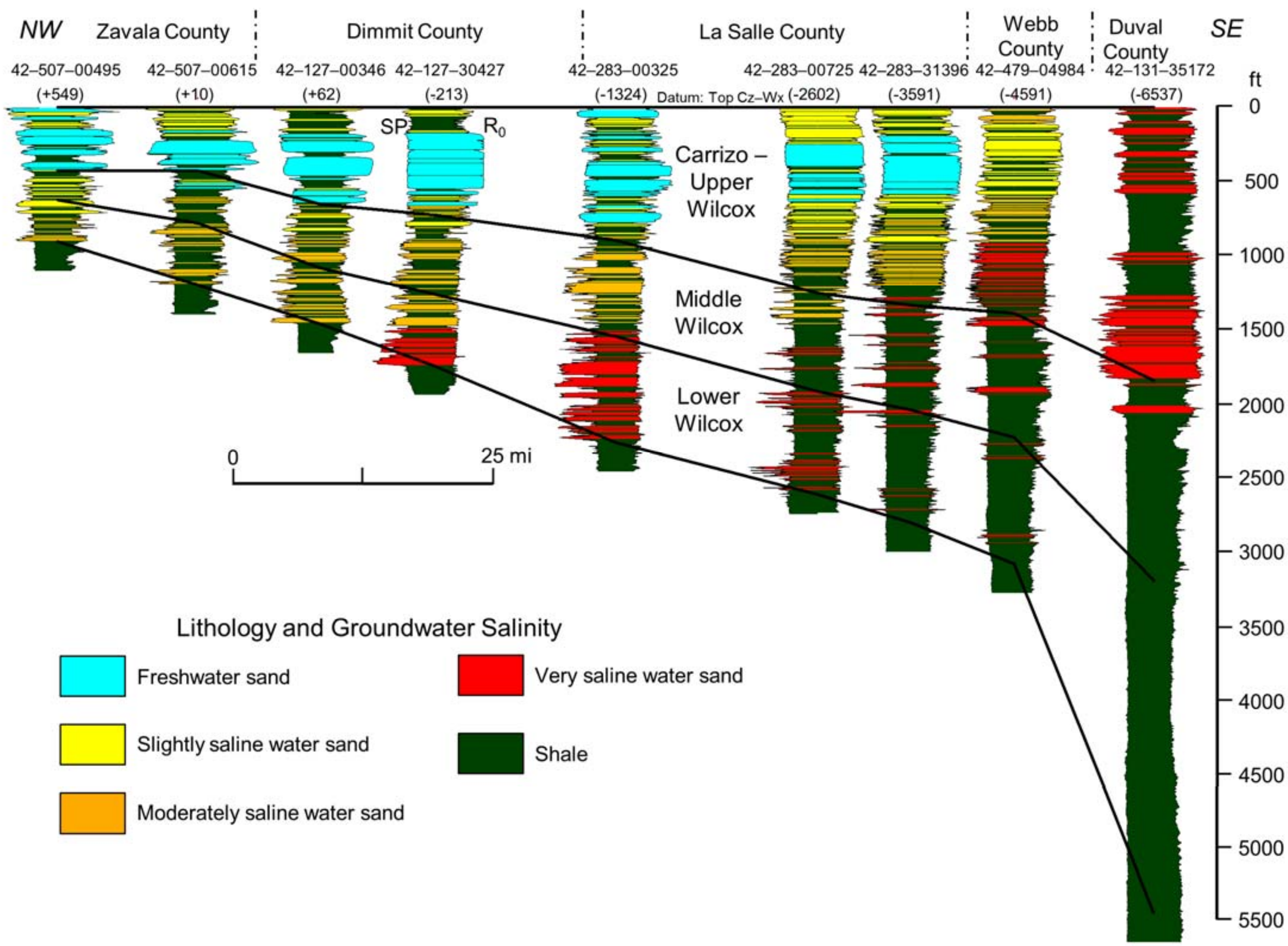


Figure 4-28. **Stratigraphic cross section E showing lithologies and groundwater salinities. See Figure 4-1 for location. Well API numbers are shown at top. SP (left side) and resistivity (right side) logs are shown for each well. Subsea elevation of the datum (top Carrizo-Wilcox Aquifer) is also shown for each well.**

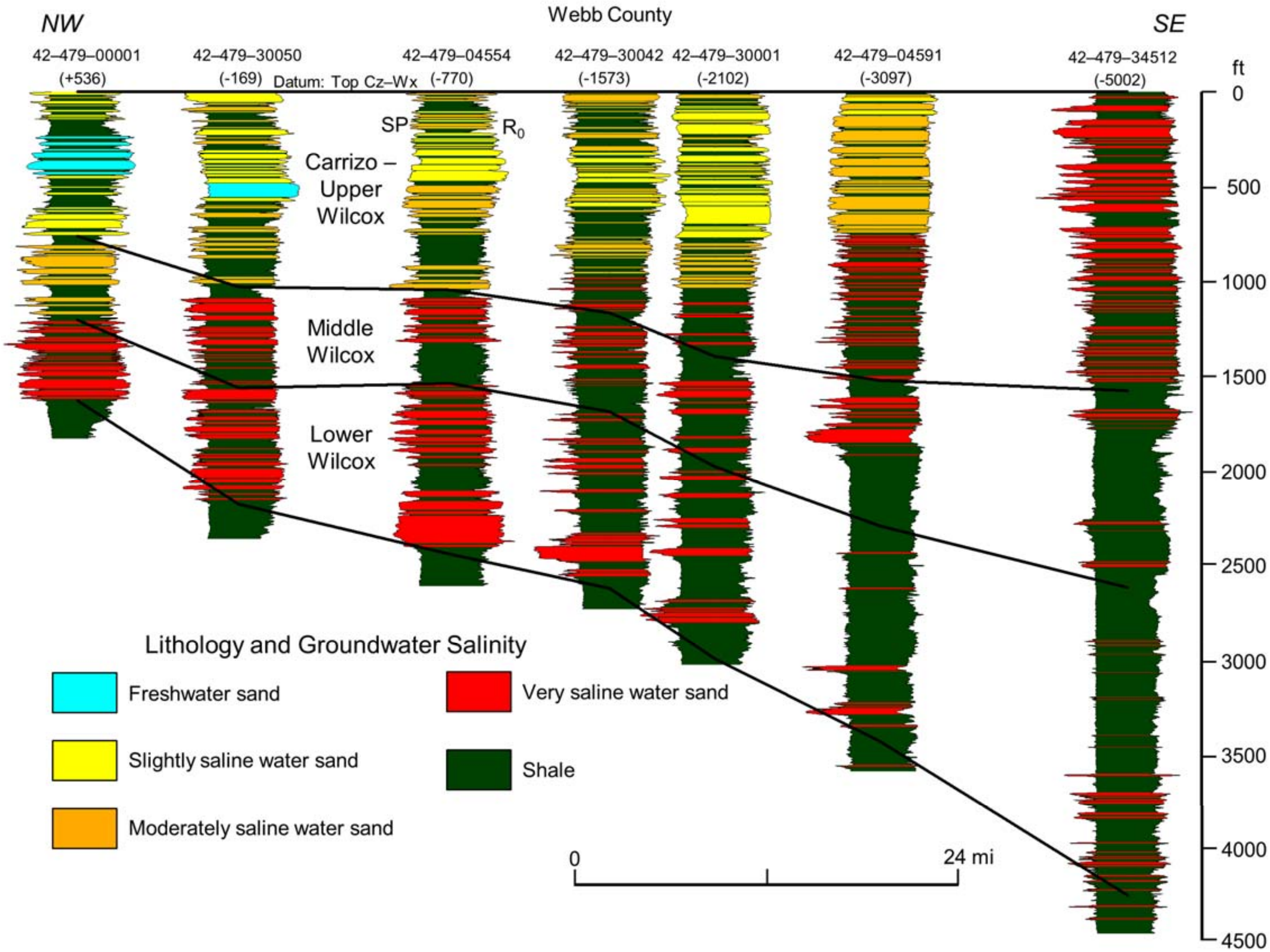


Figure 4-29. **Stratigraphic cross section F showing lithologies and groundwater salinities. See Figure 4-1 for location. Well API numbers are shown at top. SP (left side) and resistivity (right side) logs are shown for each well. Subsea elevation of the datum (top Carrizo-Wilcox Aquifer) is also shown for each well.**

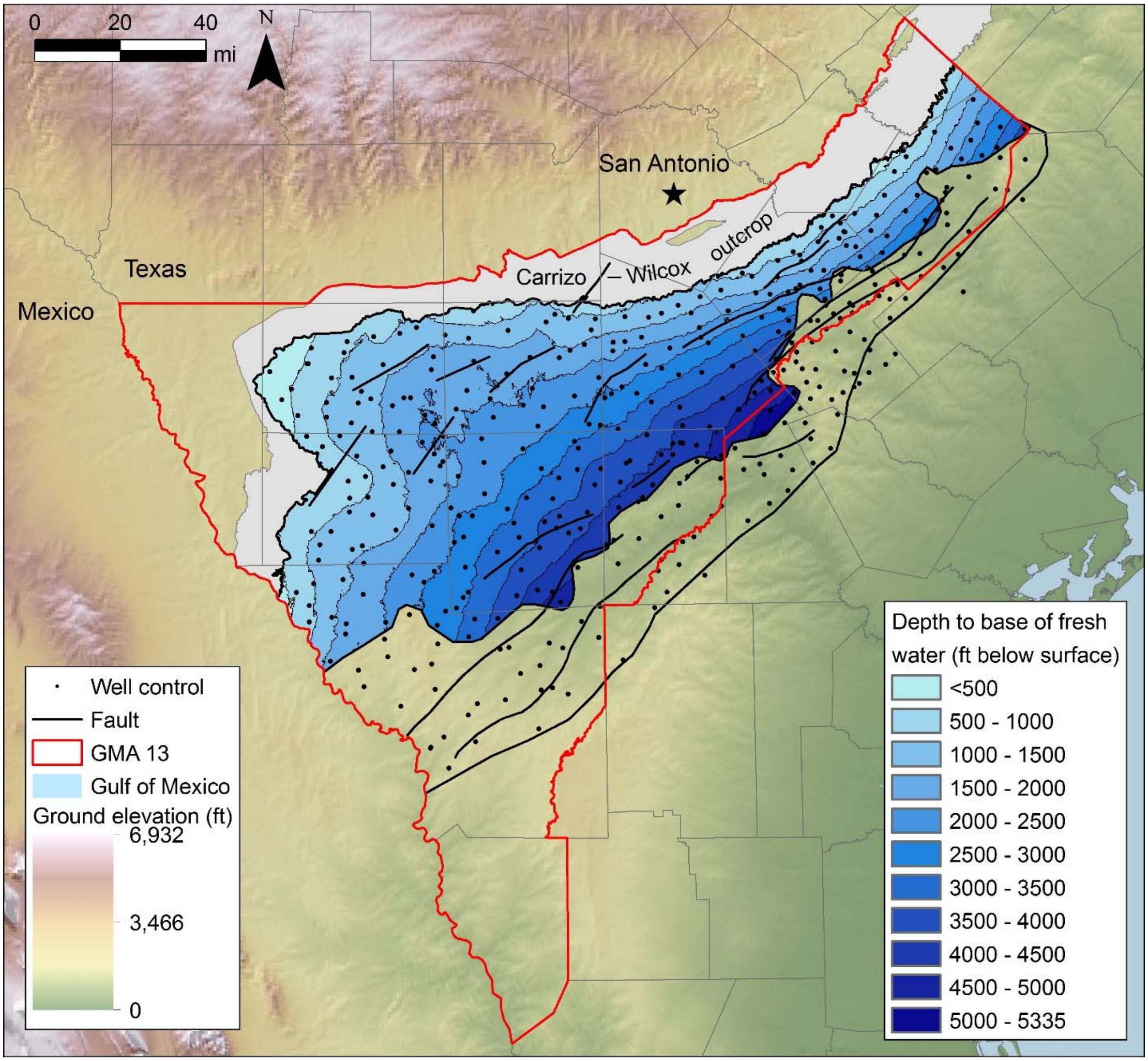


Figure 4-30. Depth from surface to base (deepest occurrence) of fresh groundwater in the Carrizo-Wilcox aquifer. Almost all fresh groundwater is in the Carrizo-upper Wilcox interval.

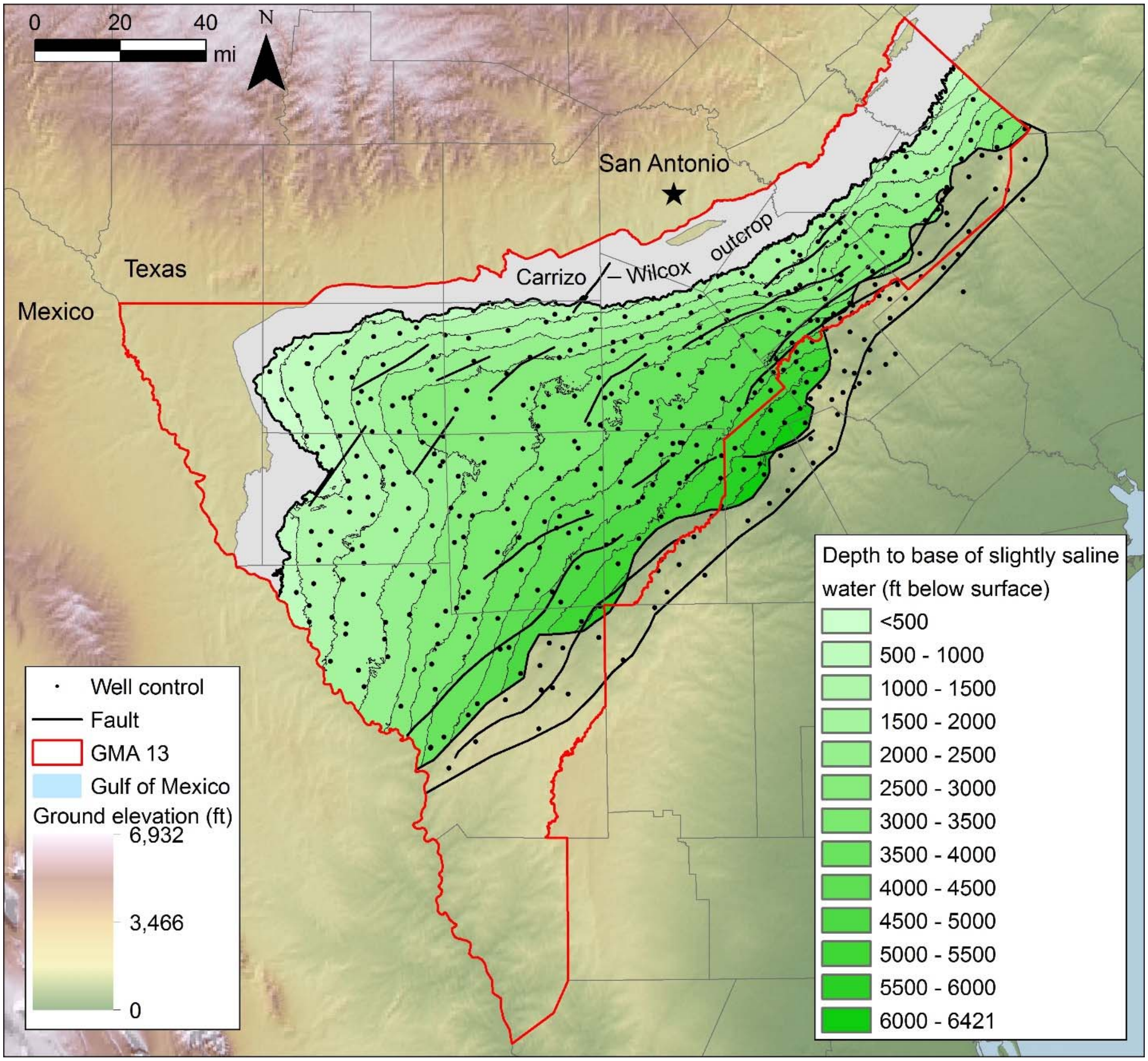


Figure 4-31. Depth from surface to base (deepest occurrence) of slightly saline groundwater in the Carrizo-Wilcox aquifer.

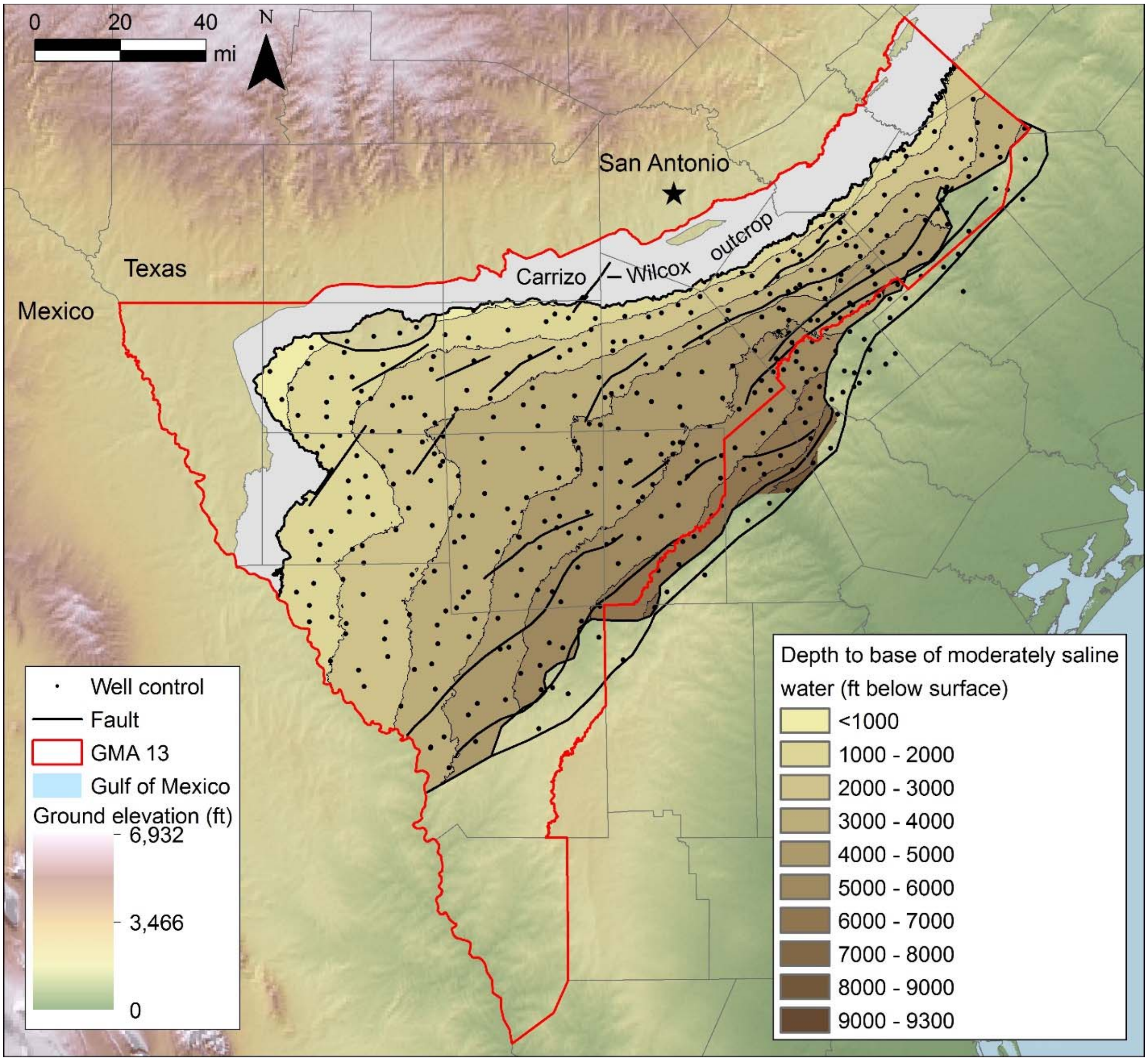


Figure 4-32. **Depth from surface to base (deepest occurrence) of moderately saline groundwater in the Carrizo-Wilcox aquifer.**

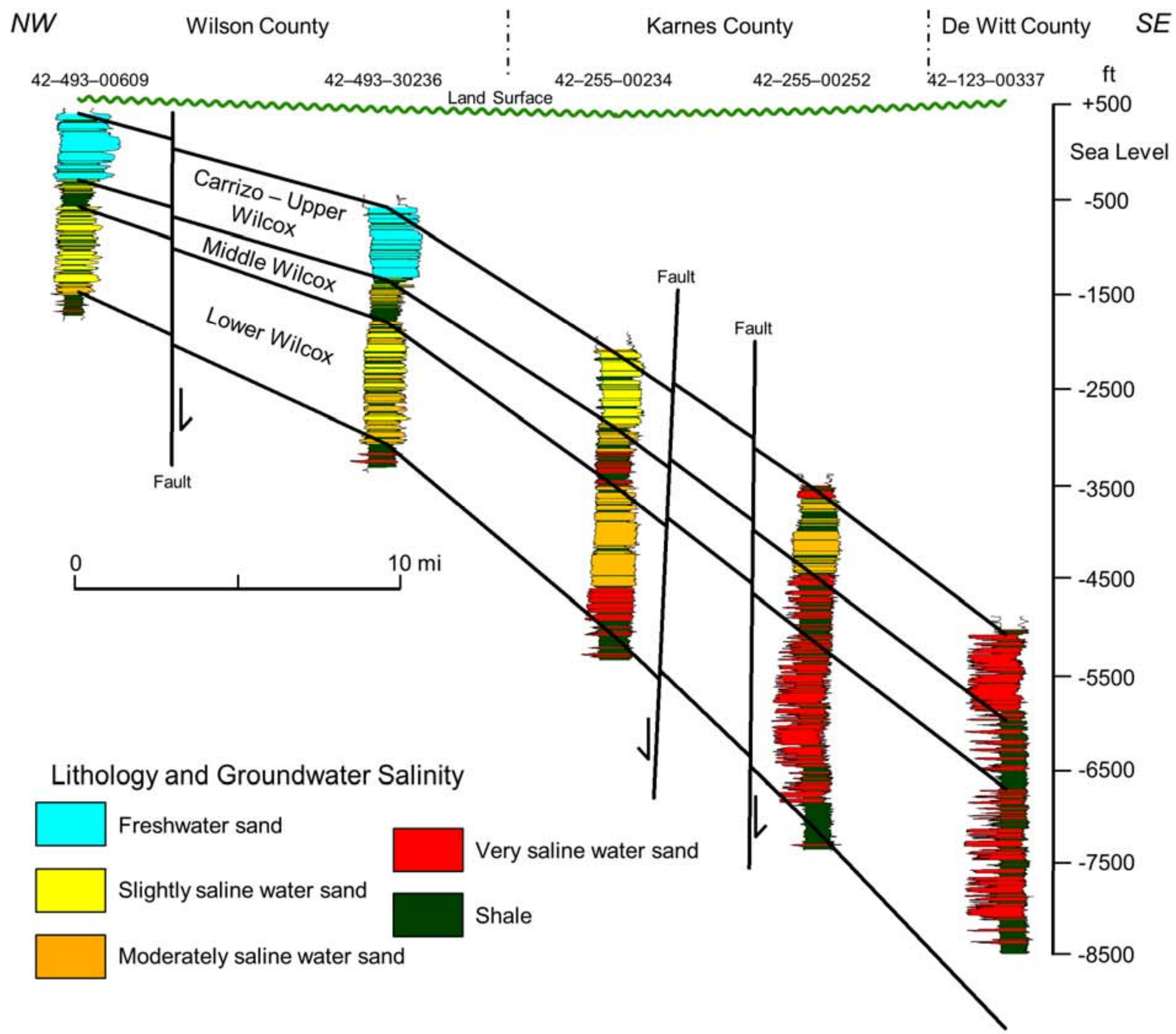


Figure 4-33. **Structural cross section B (sea-level datum) showing lithologies and groundwater salinities. Faults are also shown. See Figure 4-1 for location.**

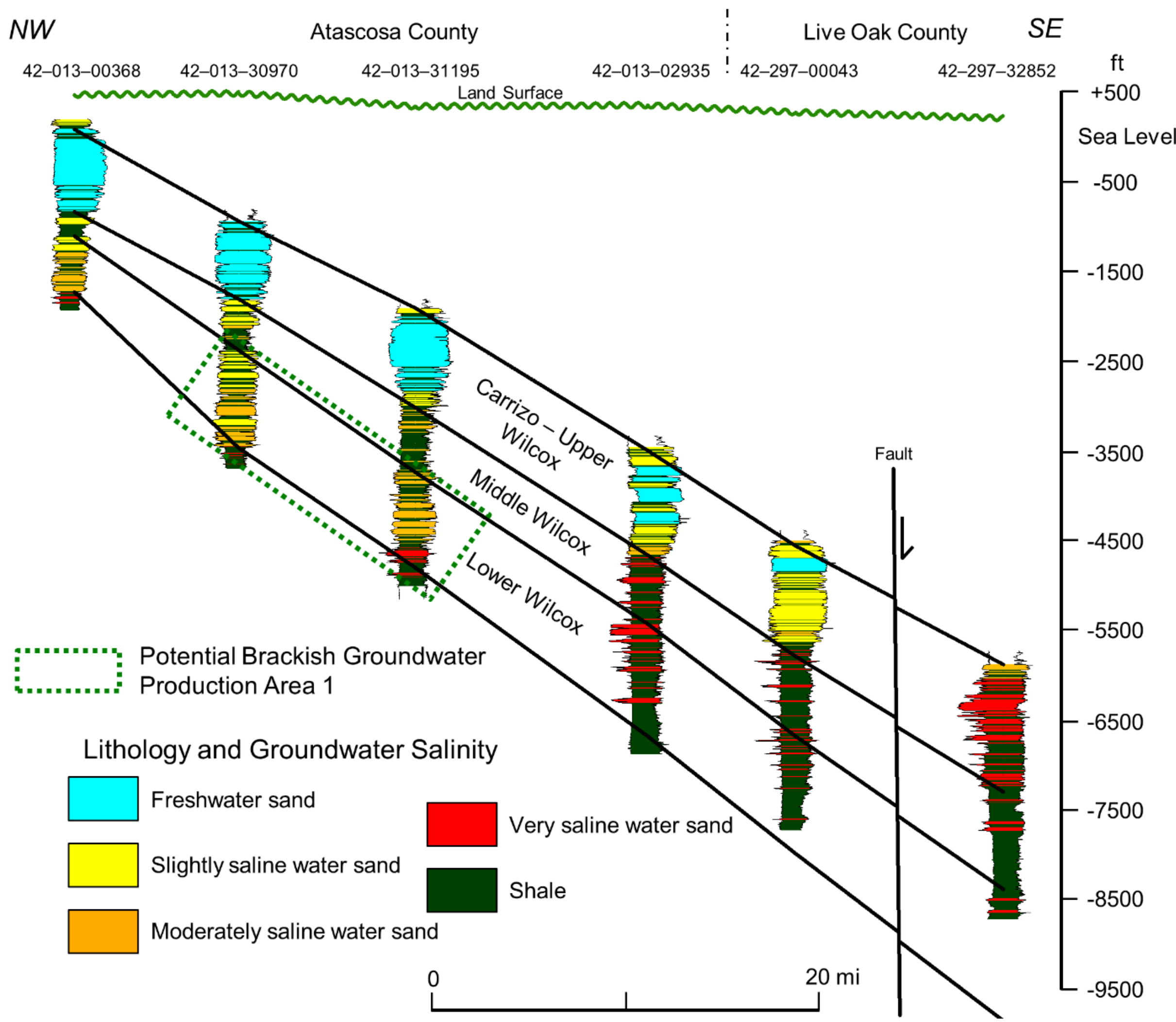


Figure 4-34. **Structural cross section C (sea-level datum) showing lithologies and groundwater salinities, and potential brackish groundwater production area 1. But although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. Absence of faults in the vicinity prevents groundwater mixing, and the shale-dominated middle Wilcox acts as a potential hydrogeologic barrier, but the presence of fresh groundwater in some parts of PPA #1 may still lead to significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers. See Figure 4-1 for location.**

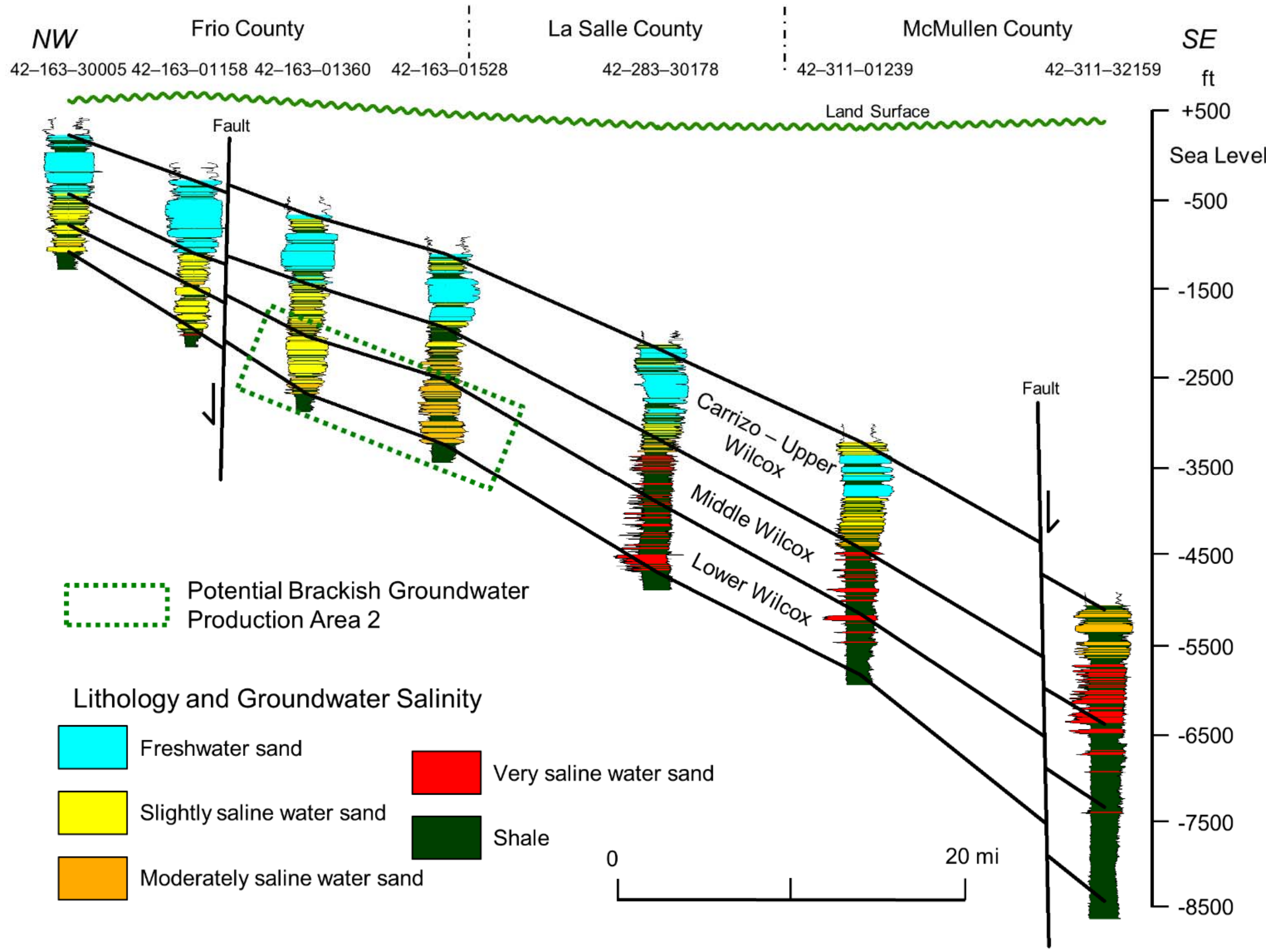


Figure 4-35. **Structural cross section D (sea-level datum) showing lithologies and groundwater salinities, and potential brackish groundwater production area 2. But although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30. PPA #2 contains some fresh groundwater, and the updip fault may facilitate groundwater mixing, while the locally sandy nature of the middle Wilcox forms an ineffective hydrogeologic barrier. So significant impacts to water availability or freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers may not be preventable. See Figure 4-1 for location.**

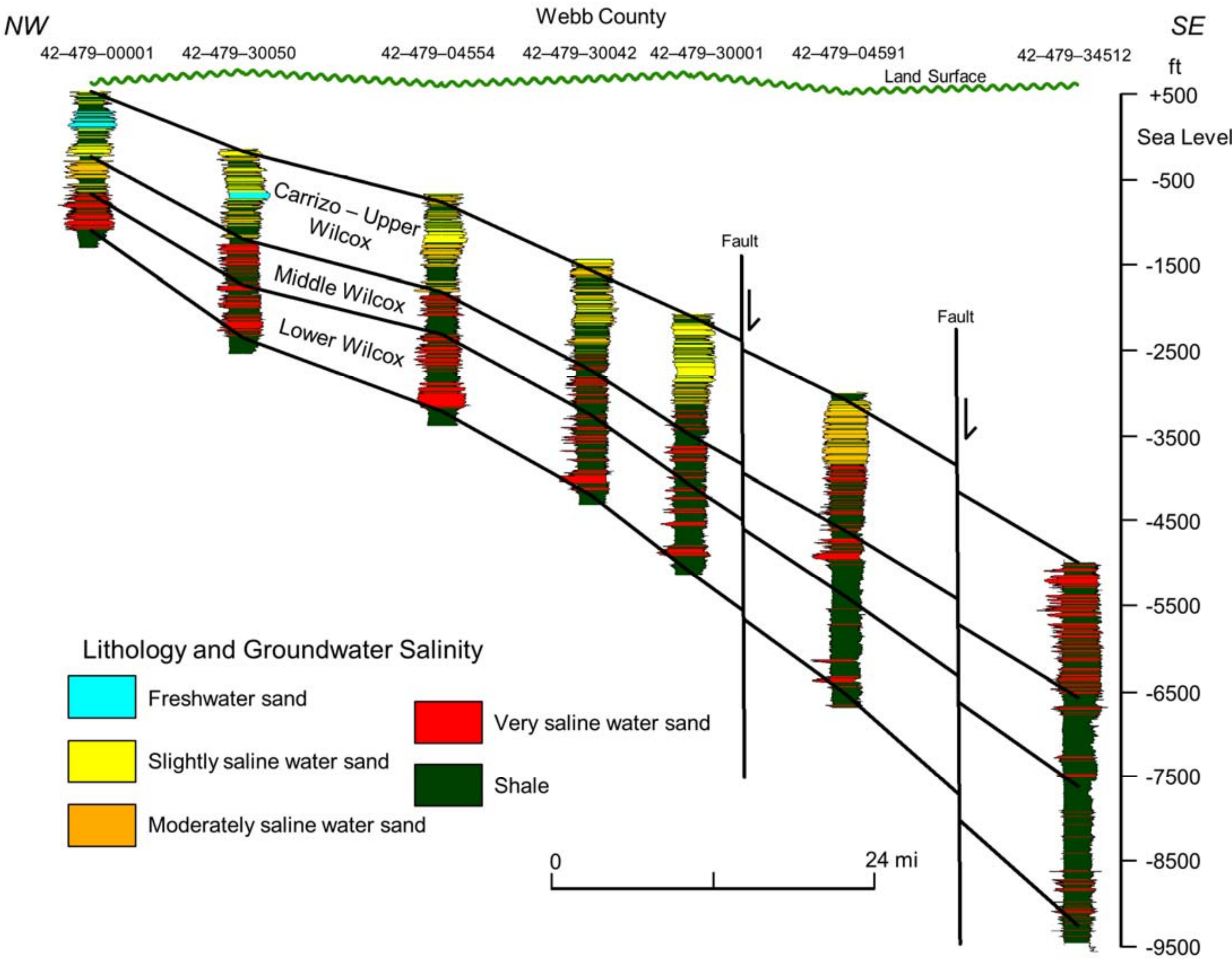


Figure 4-36. Structural cross section F (sea-level datum) showing lithologies and groundwater salinities. Faults are also shown. See Figure 4-1 for location.

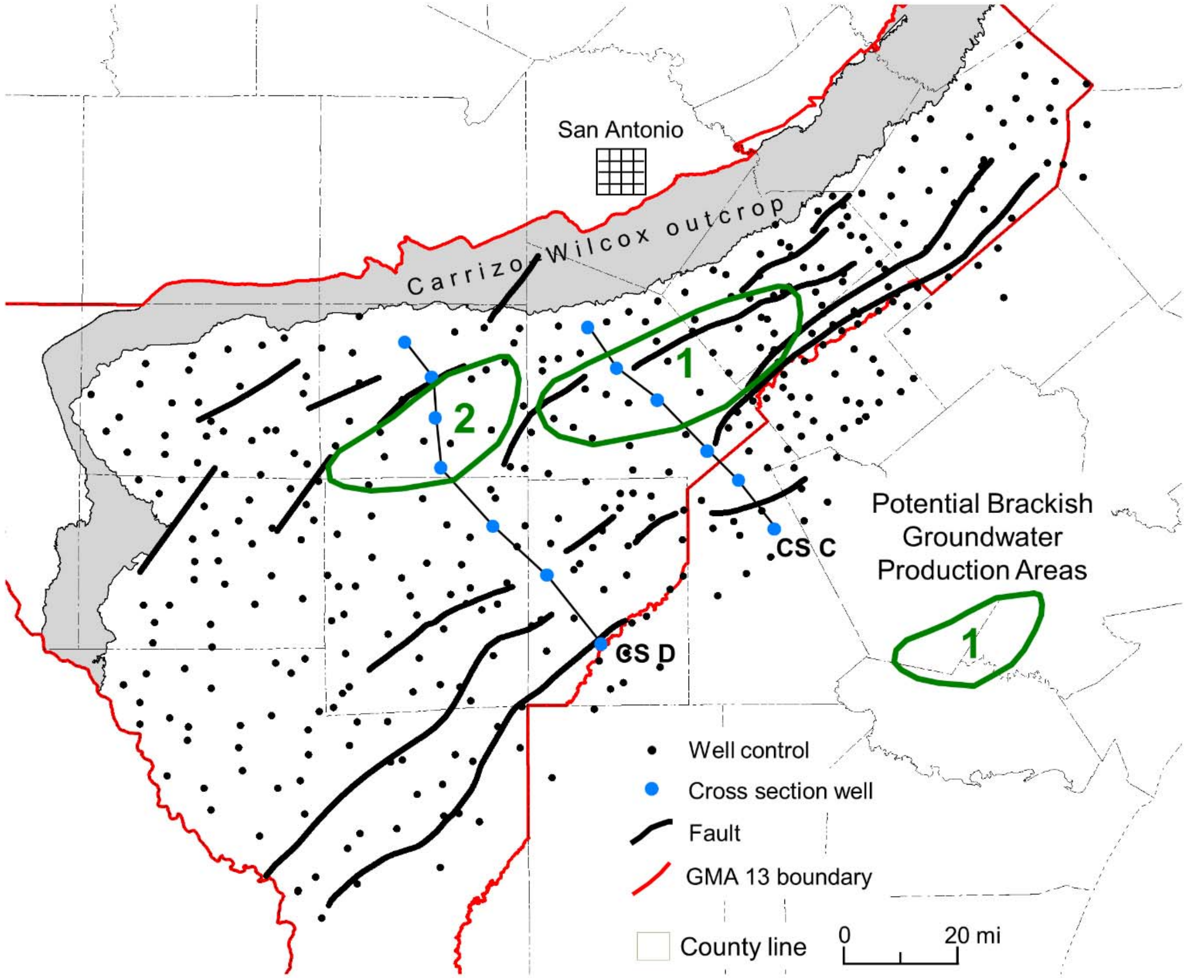


Figure 4-37. Potential brackish groundwater production areas in the Carrizo-Wilcox Aquifer in GMA 13. Both the PPAs were evaluated, and the analyses indicated that neither of the two met all required criteria of a PPA per House Bill 30. Presence of fresh groundwater in parts of both PPAs, in addition to the presence of a potentially leaky updip fault and the absence of effective hydrogeologic barriers in PPA #2 may not prevent significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers. Structural cross sections show the vertical location and stratigraphic setting of each production area (Figures 4-34, 4-35).

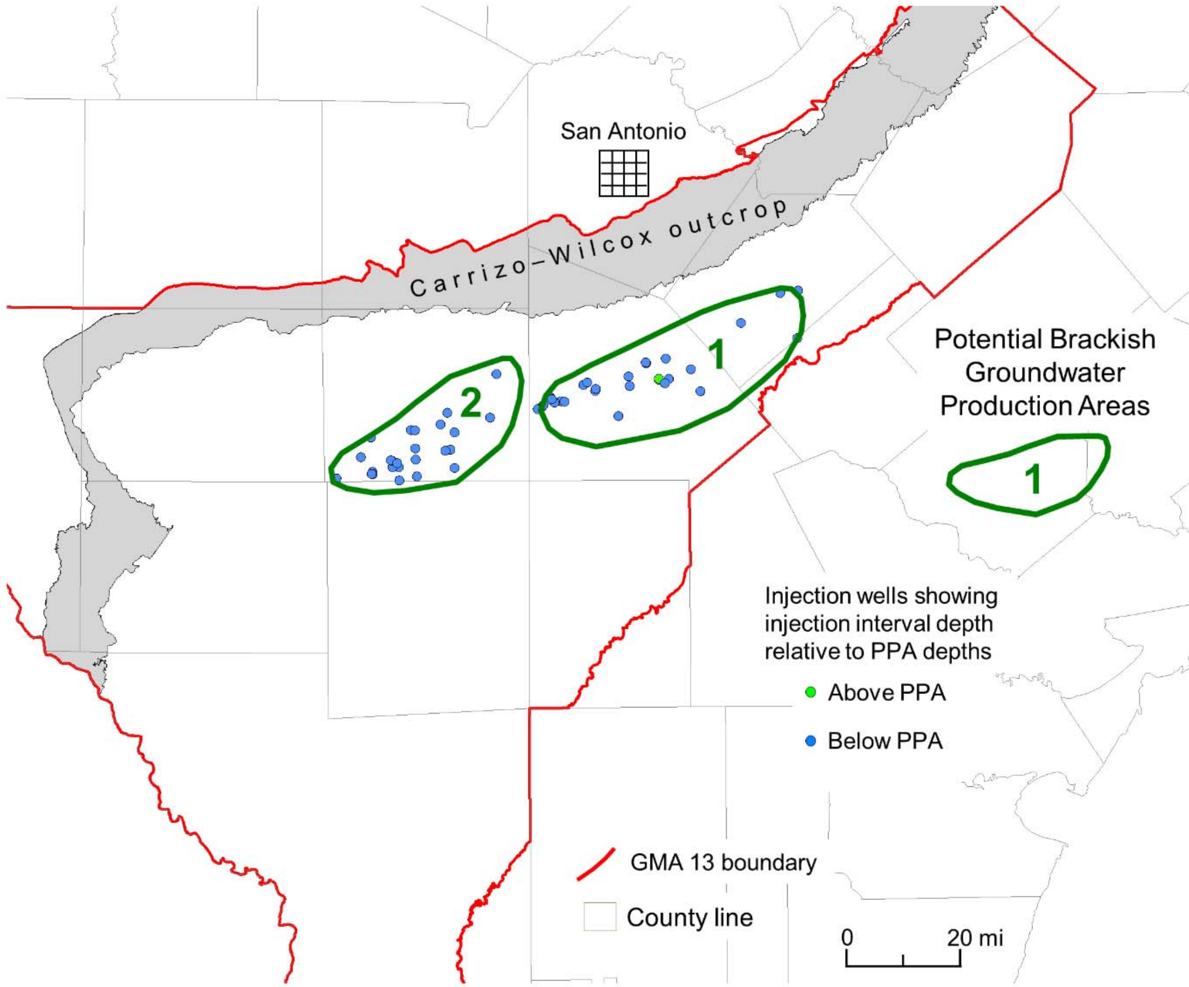


Figure 4-38. **Location of Class II injection wells within the potential brackish groundwater production areas. Injection intervals relative to the PPAs are also shown. Evaluation of both the PPAs indicated that neither of the two met all required criteria of a PPA per House Bill 30. Presence of fresh groundwater in parts of both PPAs, in addition to the presence of a potentially leaky updip fault and the absence of effective hydrogeologic barriers in PPA #2 may not prevent significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers.**

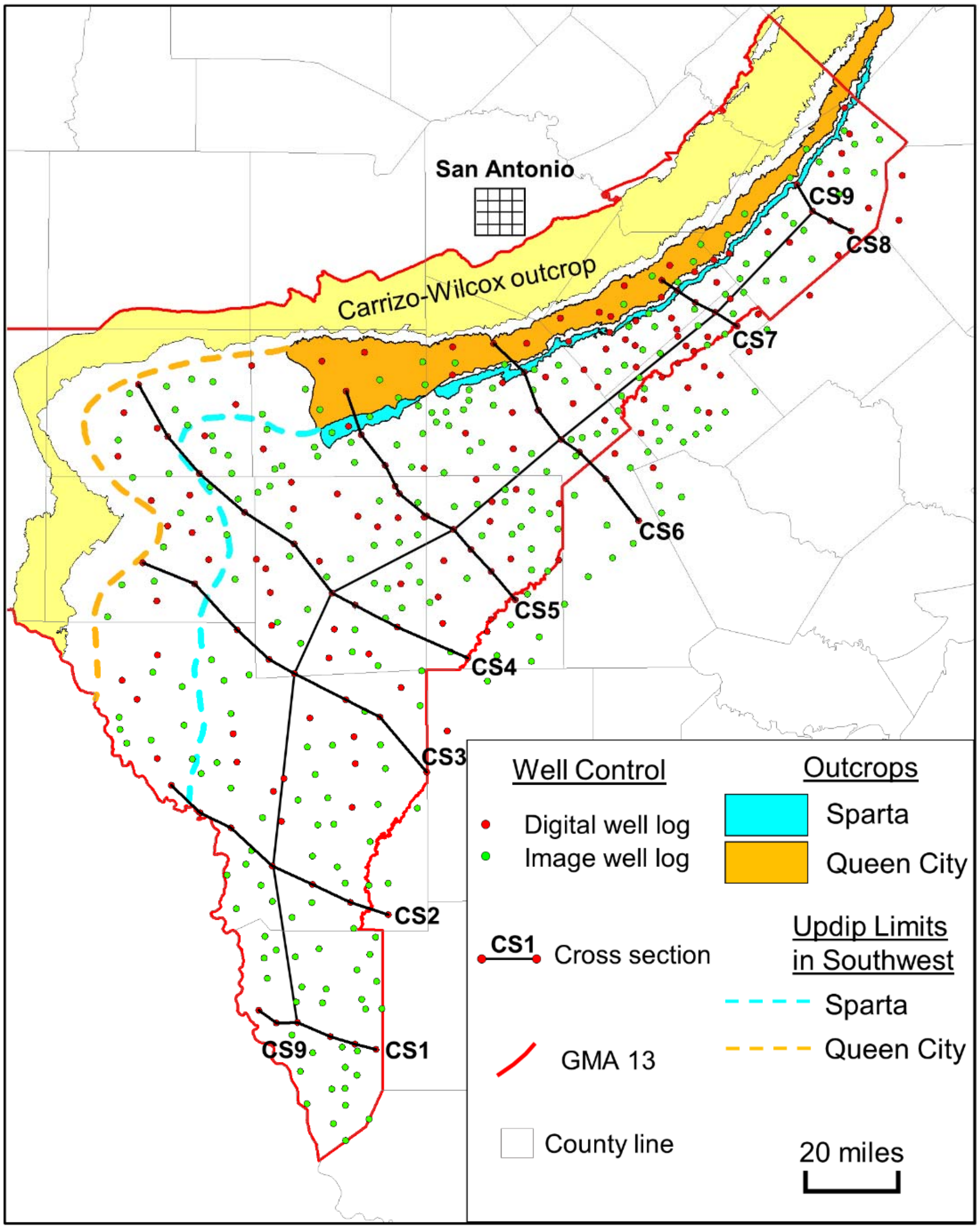


Figure 4-39. Location of Queen City and Sparta aquifers study area in GMA 13 showing electric log well control, cross sections lines and outcrops.

Geologic Formation Name Changes
South Texas Outcrop

<table>
<tr><th>Northeast of the Frio River</th><th>Southwest of the Frio River</th></tr>
<tr><td>Yegua</td><td>Yegua</td></tr>
<tr><td>Cook Mountain</td><td rowspan="2">Laredo</td></tr>
<tr><td>Sparta*</td></tr>
<tr><td>Weches*</td><td rowspan="2">El Pico Clay</td></tr>
<tr><td>Queen City*</td></tr>
<tr><td>Reklaw*</td><td>Bigford</td></tr>
<tr><td>Carrizo-Wilcox</td><td>Carrizo-Wilcox</td></tr>
</table>

*Names used throughout GMA 13 in this study

Figure 4-40. Stratigraphic chart showing geologic formation names in GMA 13. Surface formation names and contacts change at the Frio River, but the Queen City and Sparta aquifers in the subsurface are continuous across GMA 13. After Guevara and Garcia (1972), Ricoy and Brown (1977, and Hamlin (1988).

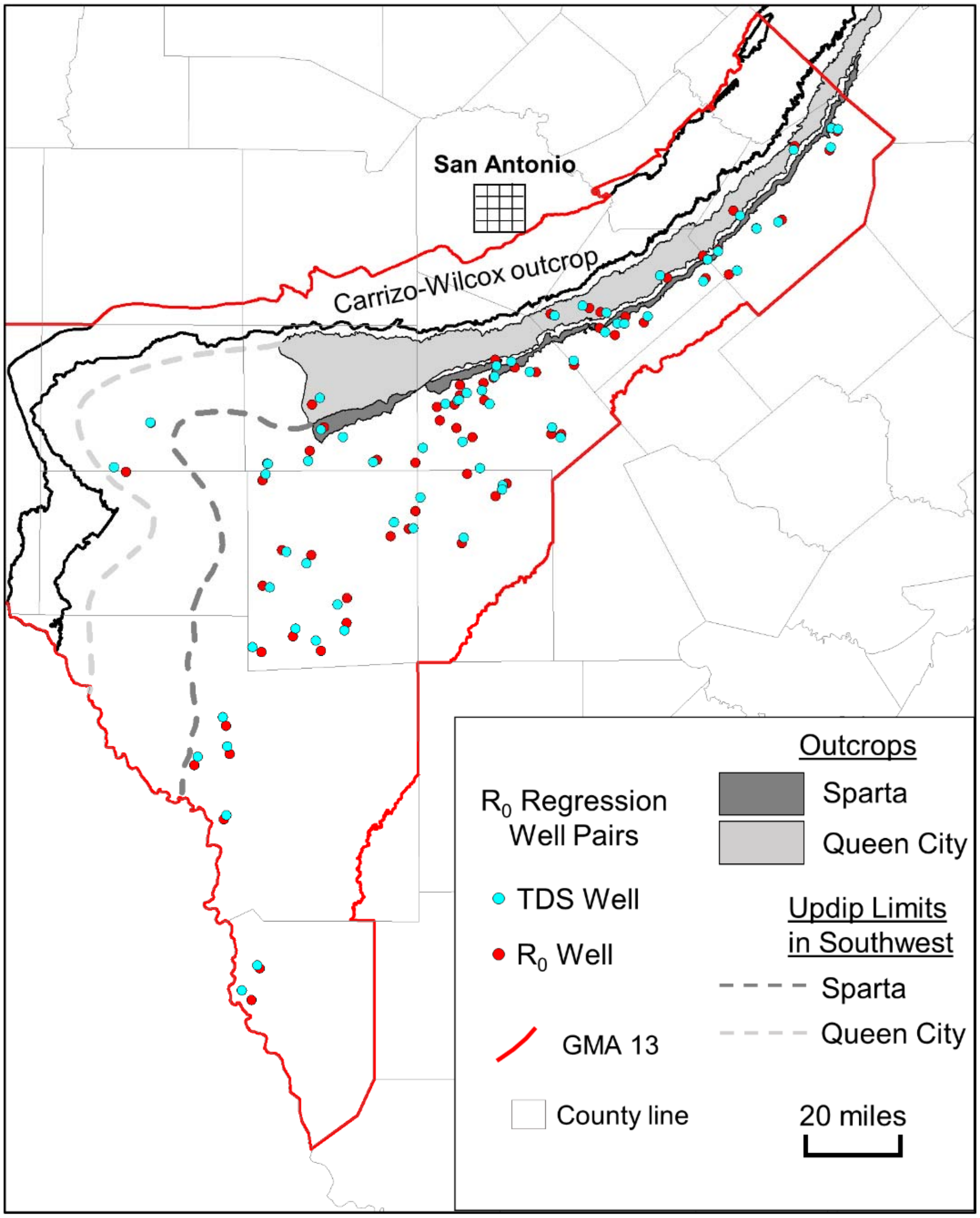


Figure 4-41. **Wells used to develop the TDS/R_0 regression for the Queen City and Sparta aquifers. Most TDS data (blue dots) come from water wells, whereas most resistivity data (red dots) come from petroleum wells. Well pairs that are very close together appear as a single blue dot.**

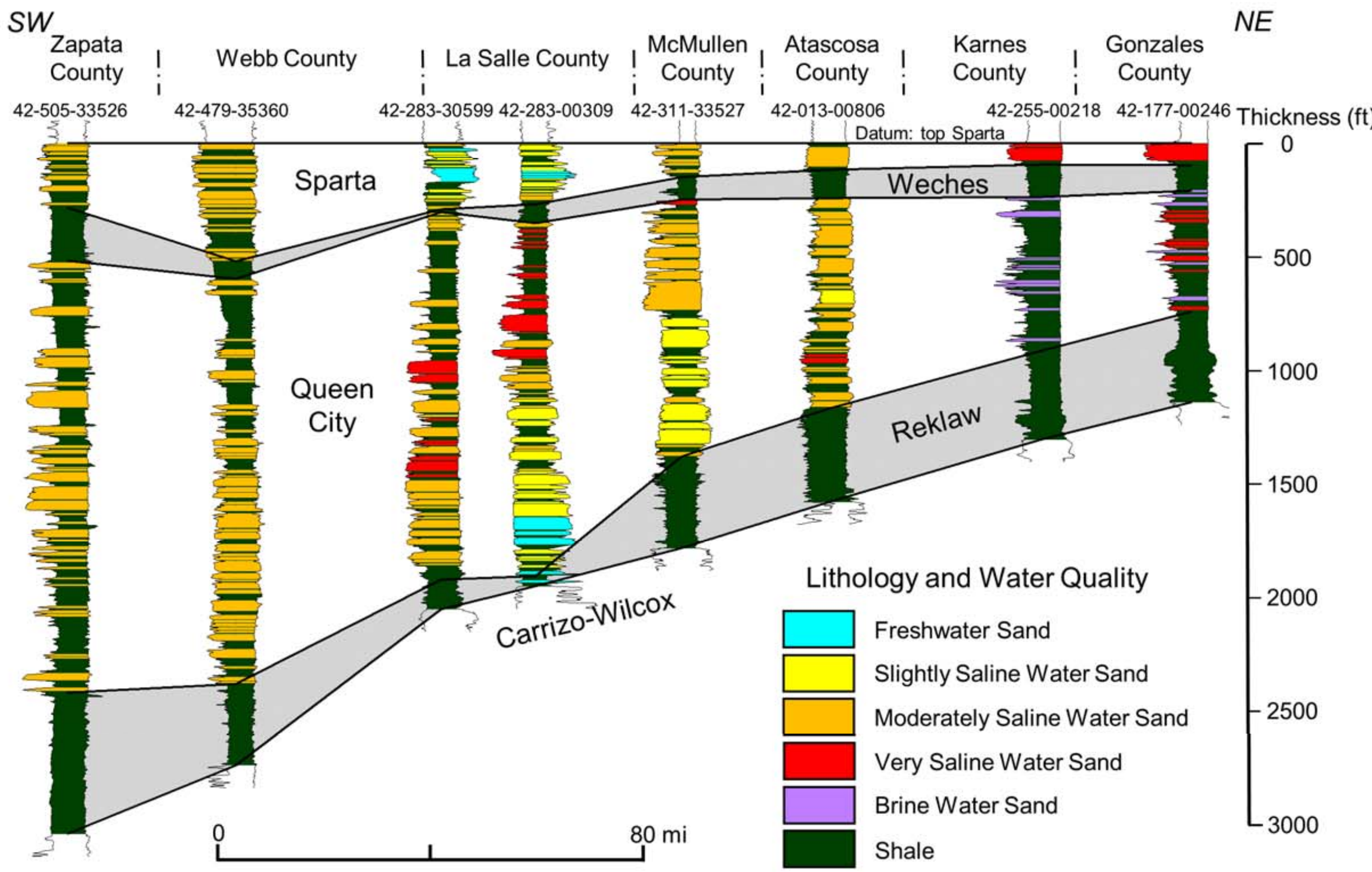


Figure 4-42. Stratigraphic cross section 9 (top Sparta datum) showing the geographic extent of the Queen City and Sparta aquifers in GMA 13. See Figure 4-39 for location. Electric logs (SP on the left and resistivity on the right) for each well are shown with color fill corresponding to lithology and groundwater salinity. The Reklaw and Weches shale aquitards are shaded gray.

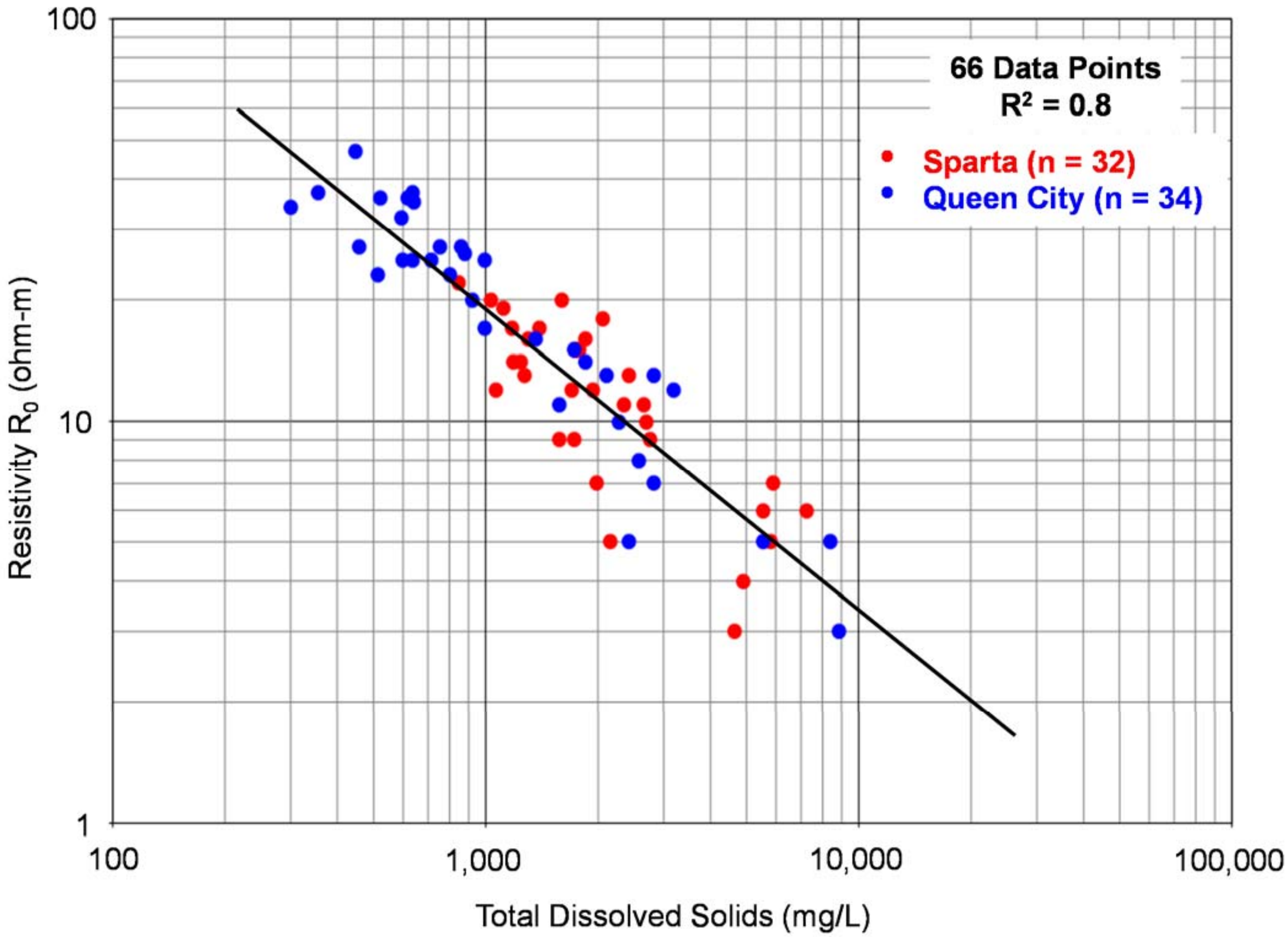


Figure 4-43. **Total dissolved solids (TDS) versus deep resistivity (R_0) for Queen City and Sparta well pairs in the study area. See Figure 4-41 for well locations.**

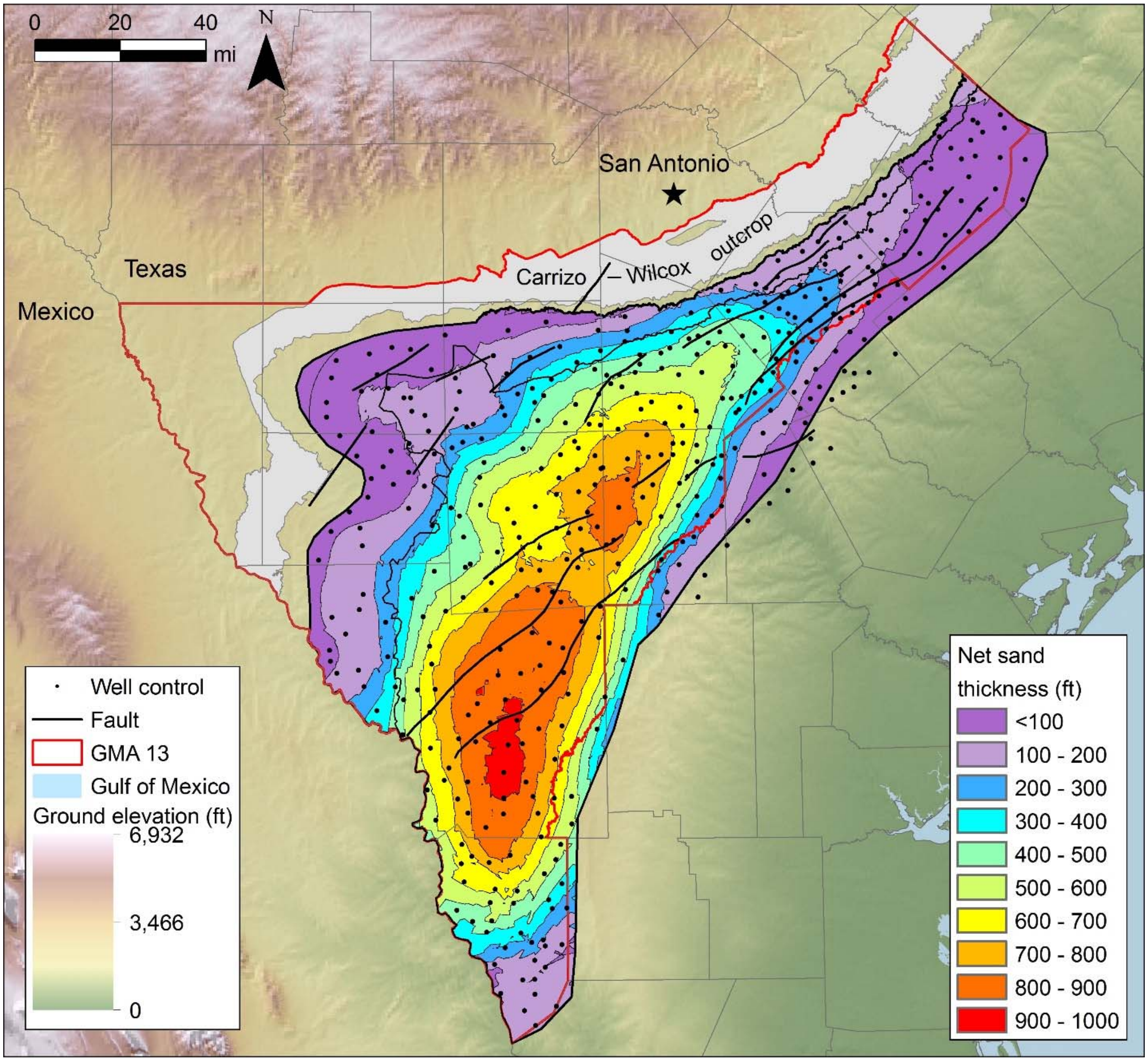


Figure 4-44. Queen City net sand thickness. A well-defined depocenter of maximum sand thickness is centered in Webb County.

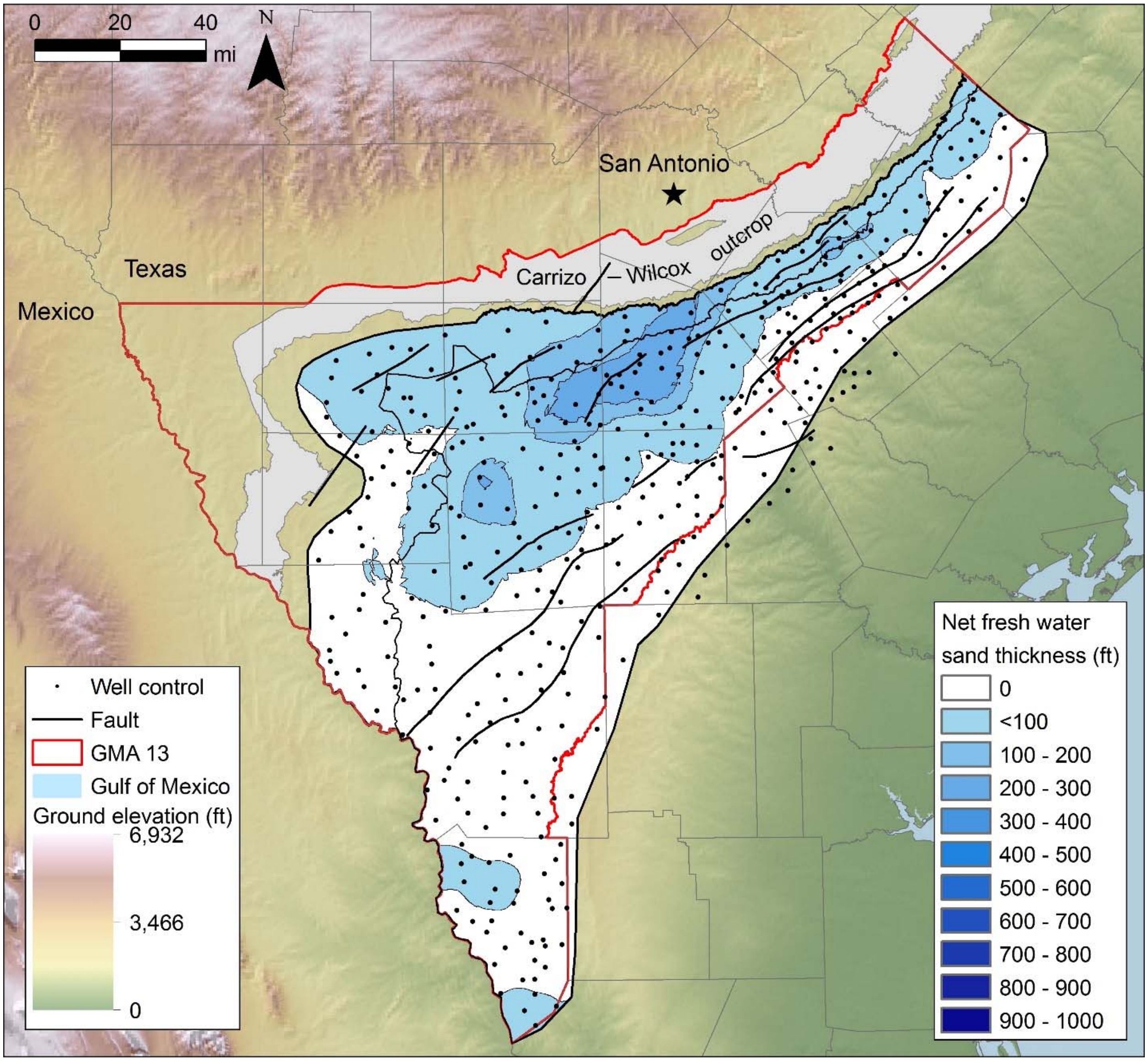


Figure 4-45. **Net thickness of sand containing fresh groundwater in the Queen City aquifer. The sands are concentrated in the north-central and northeastern parts of GMA 13. A handful of wells in Zapata County showing freshwater sands could have low TDS of anthropogenic origin, and require re-evaluation.**

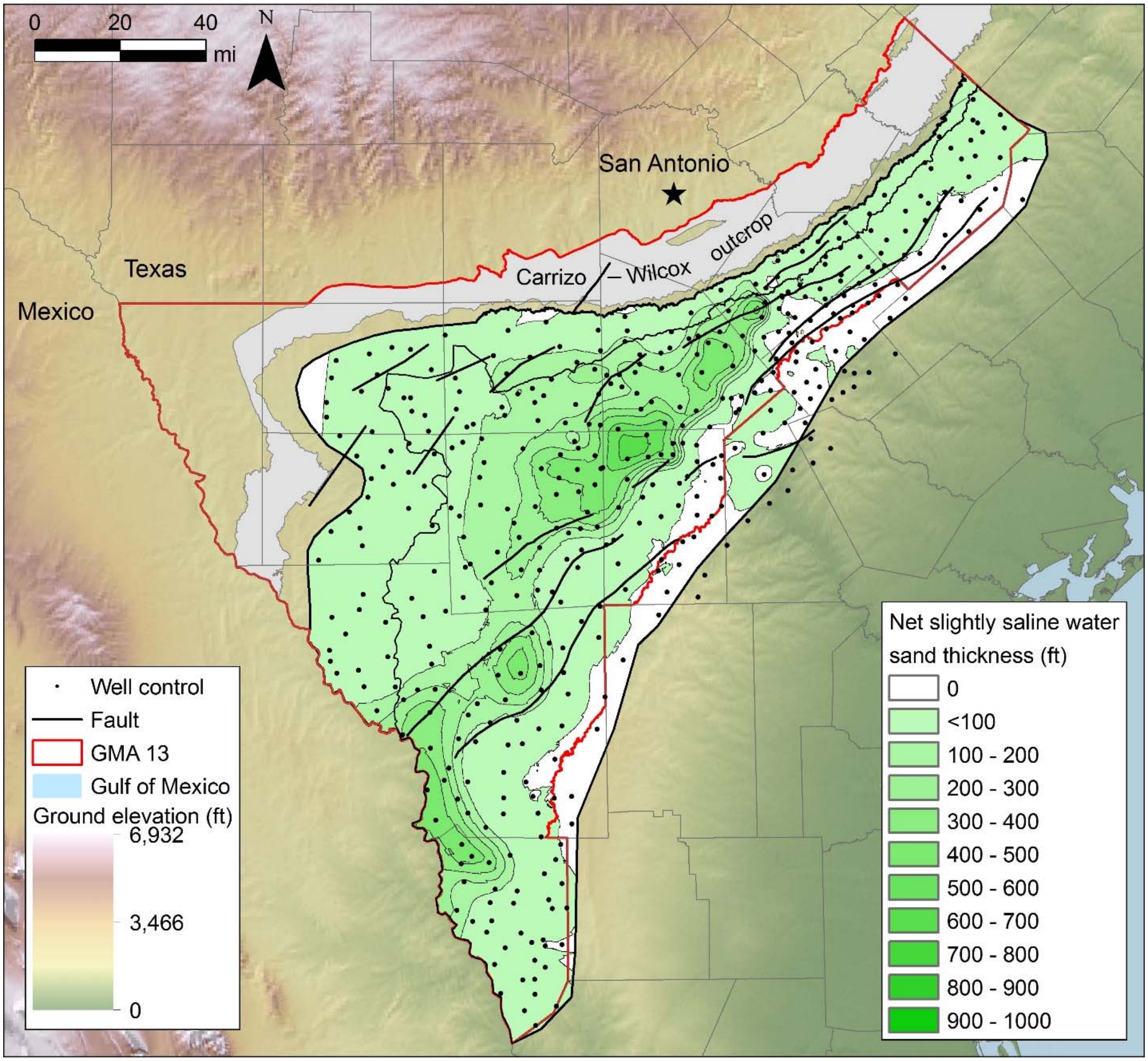


Figure 4-46. Net thickness of sand containing slightly saline groundwater in the Queen City aquifer.

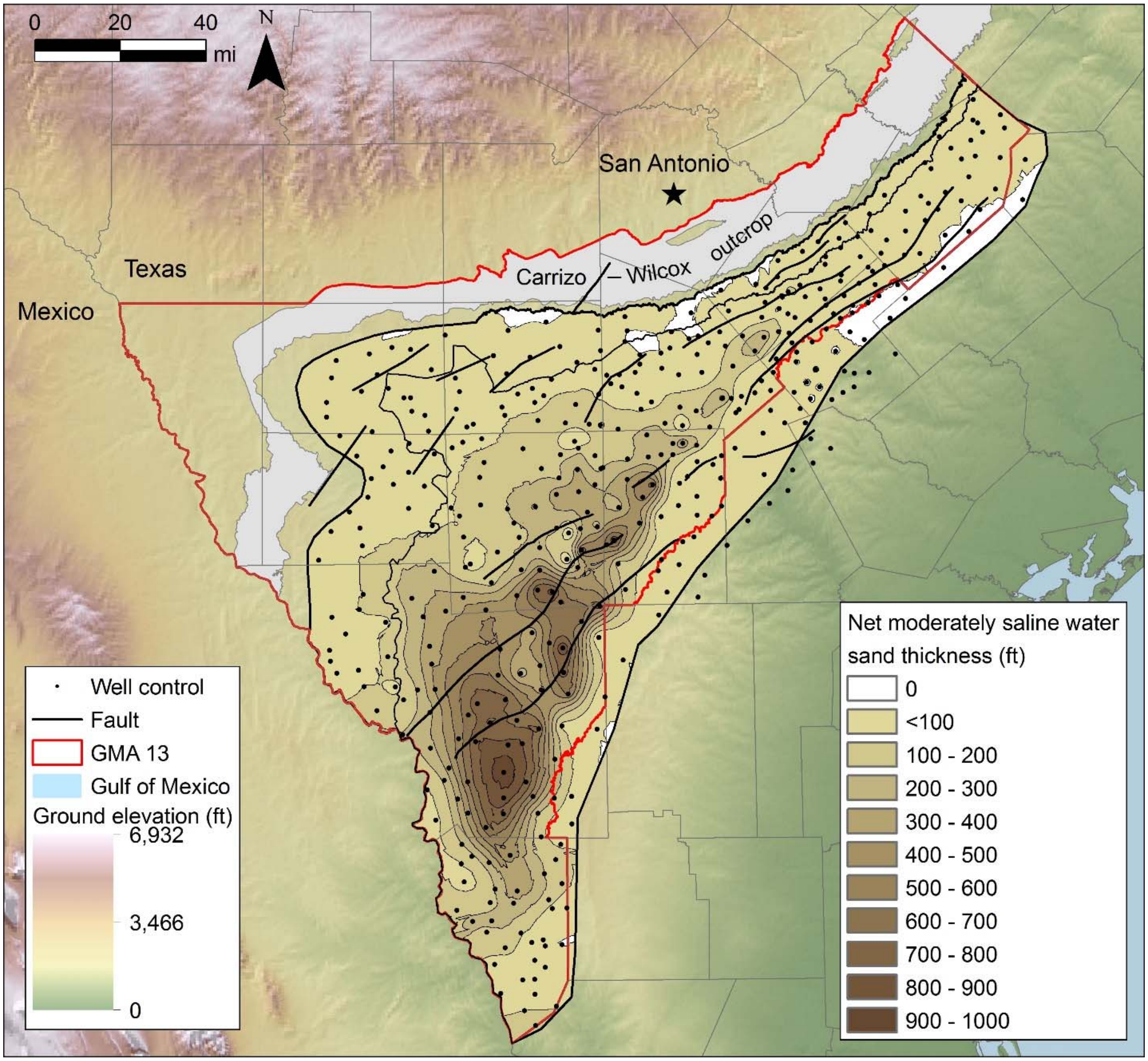


Figure 4-47. Net thickness of sand containing moderately saline groundwater in the Queen City aquifer.

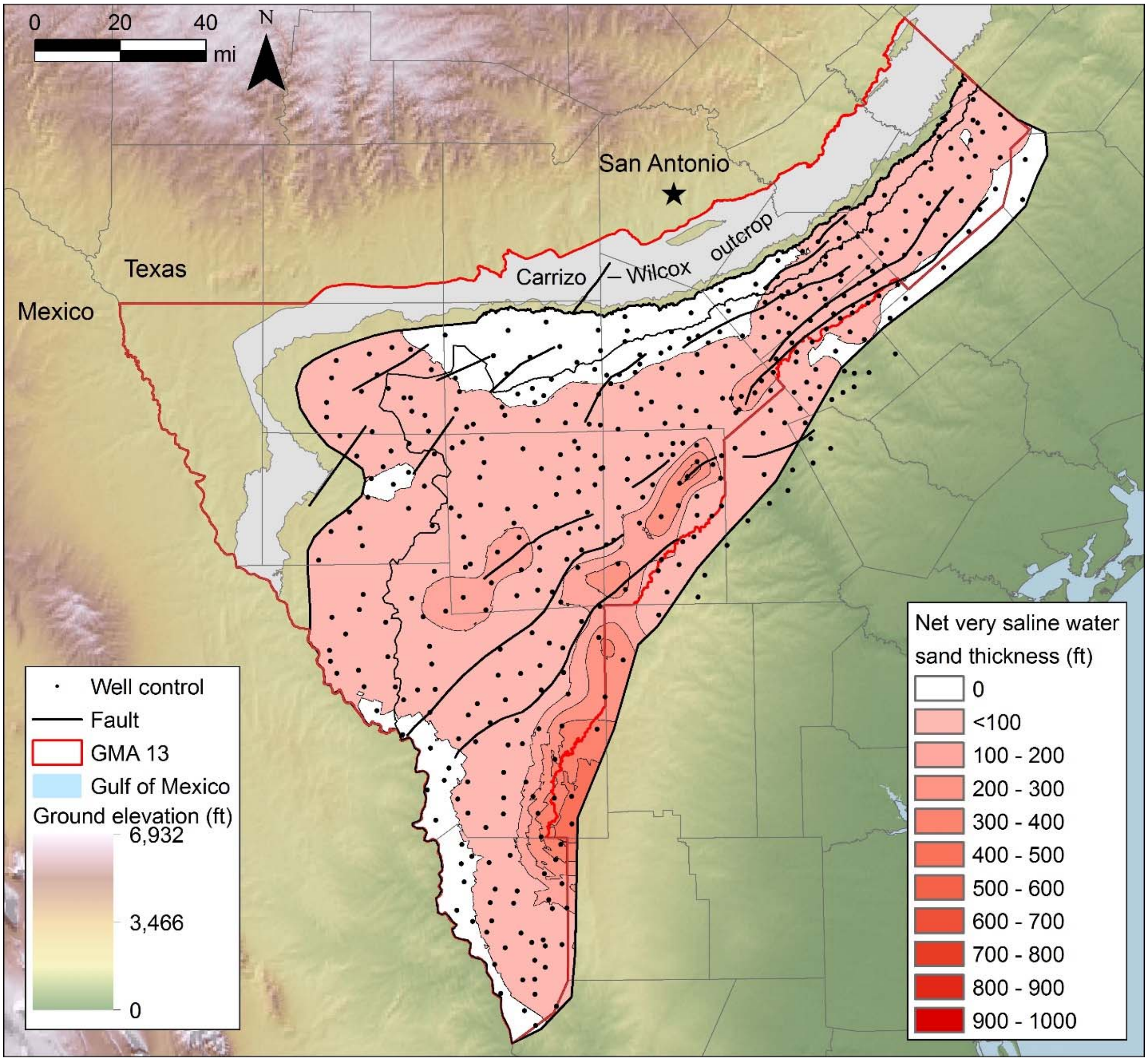


Figure 4-48. Net thickness of sand containing very saline groundwater in the Queen City aquifer.

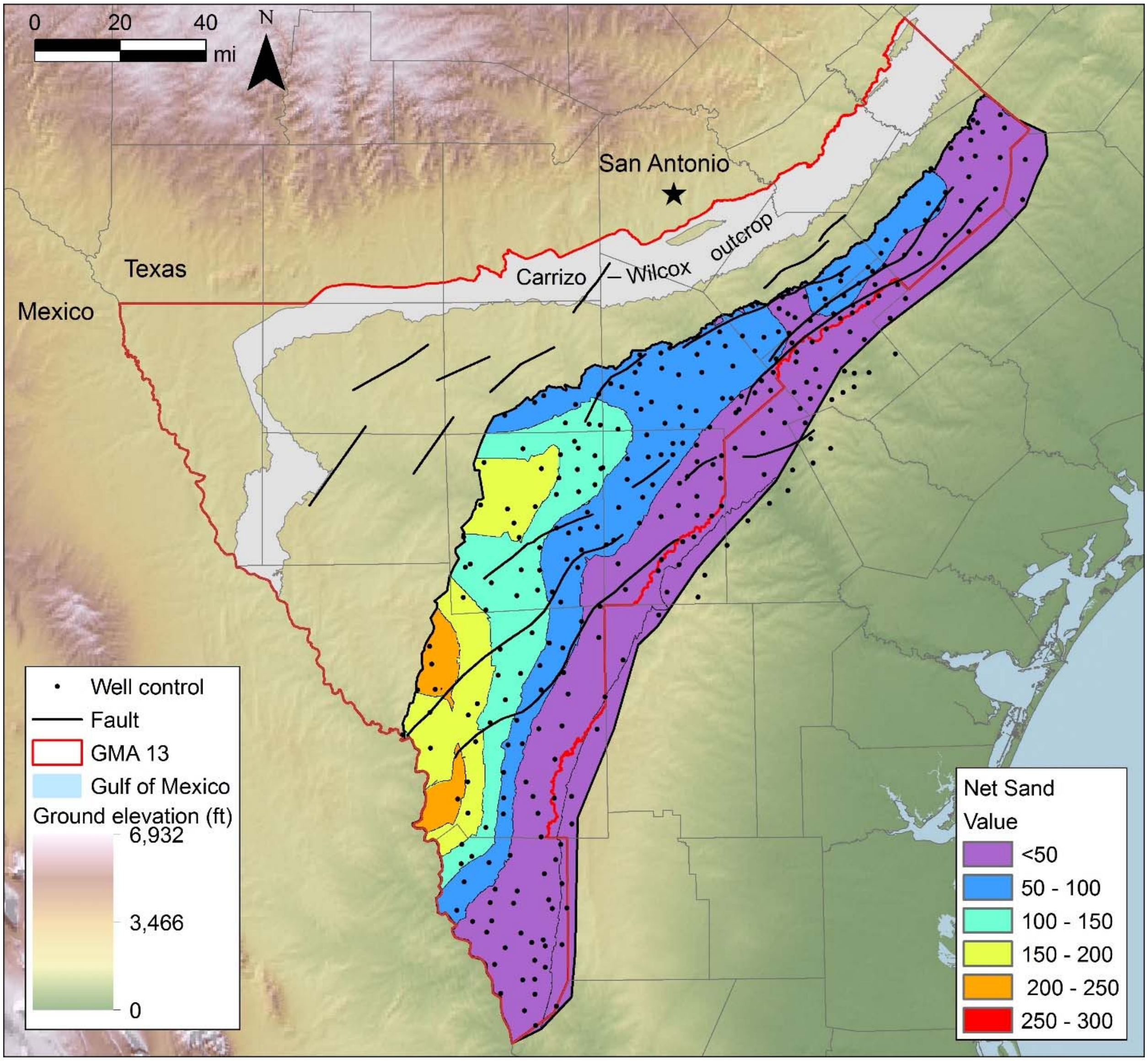


Figure 4-49. **Sparta net sand thickness. Sparta sands are thickest updip in the southwest and thin northeastward and downdip (southeast).**

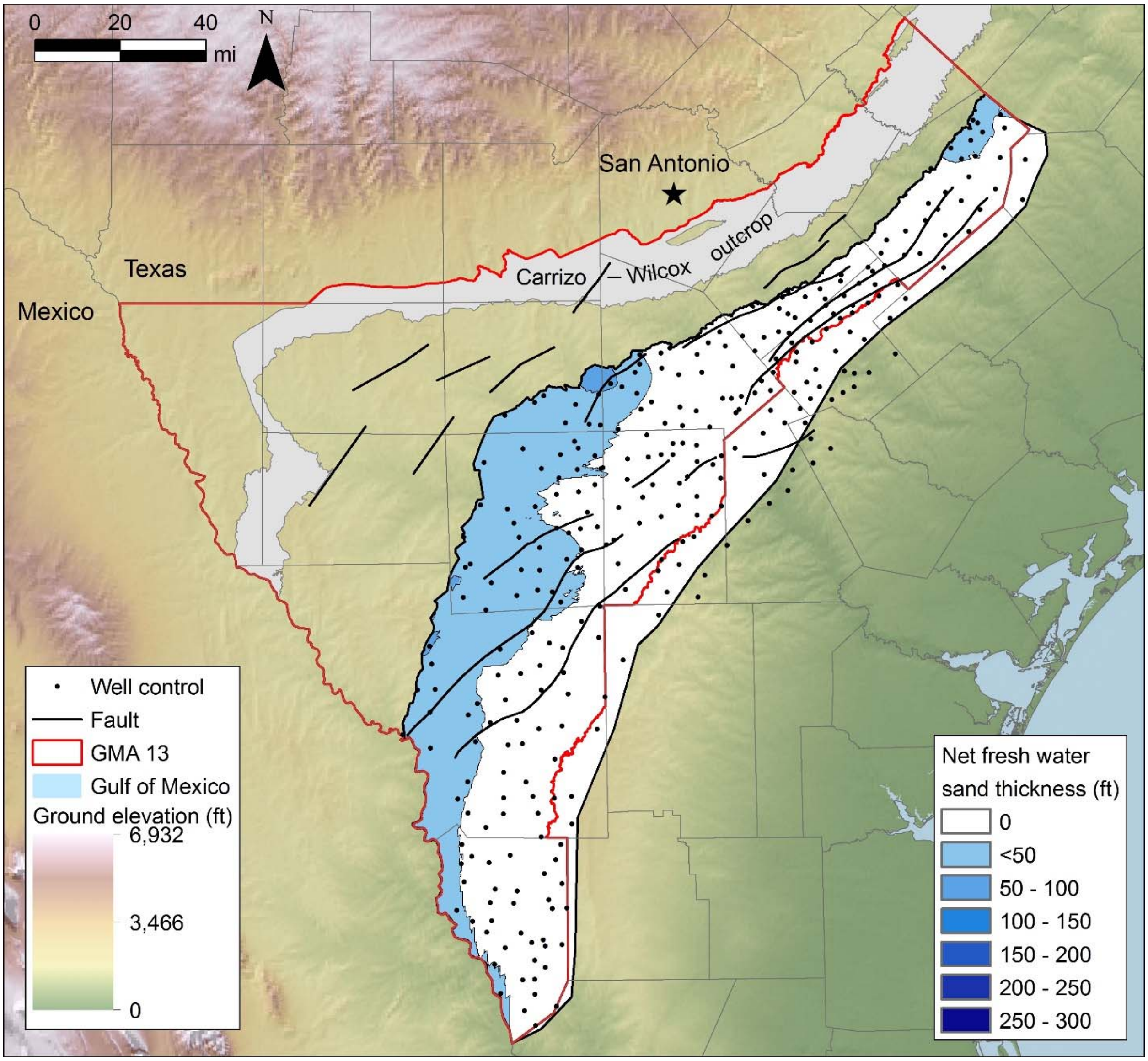


Figure 4-50. Net thickness of sand containing fresh groundwater in the Sparta aquifer.

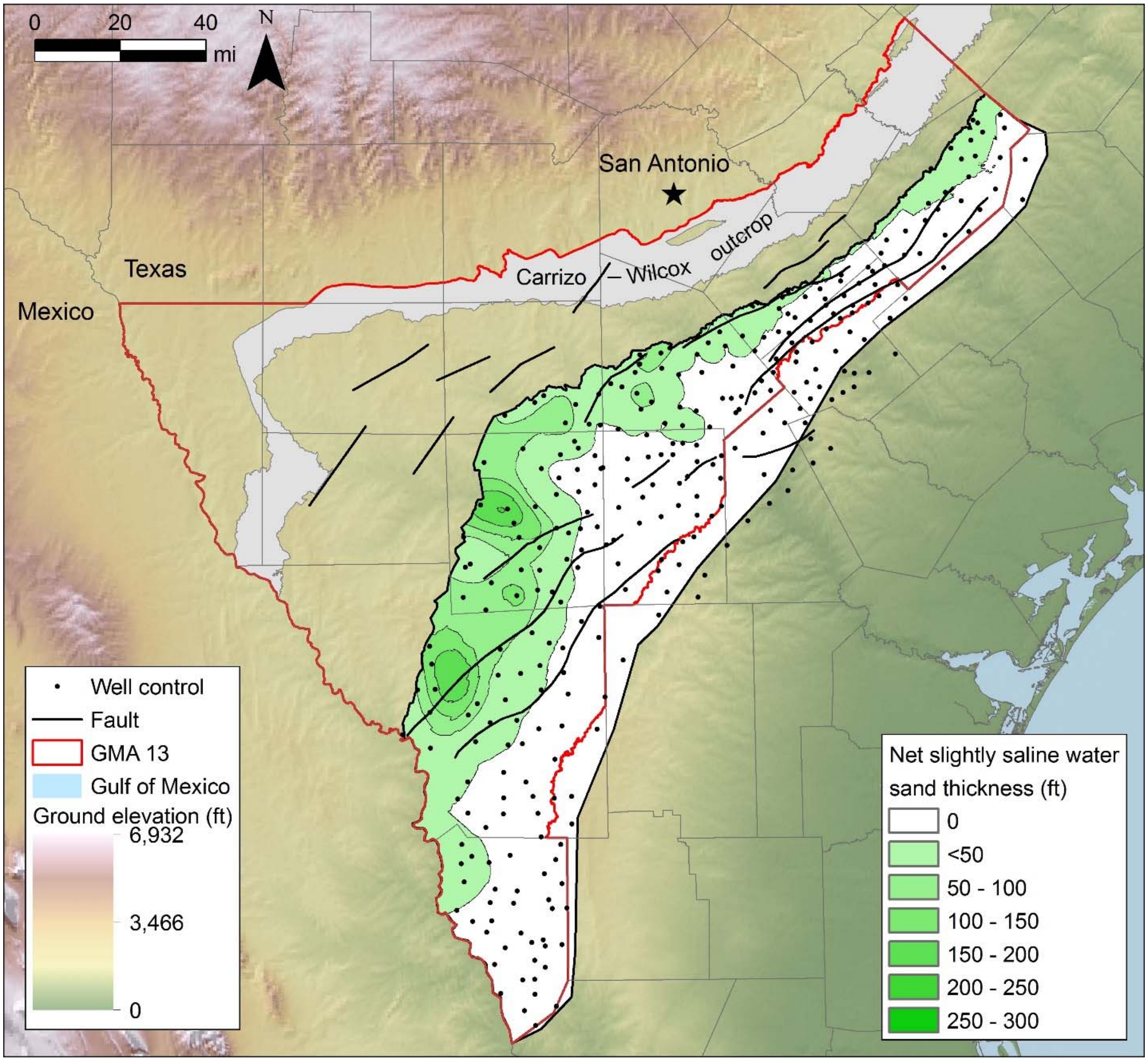


Figure 4-51. **Net thickness of sand containing slightly saline groundwater in the Sparta aquifer.**

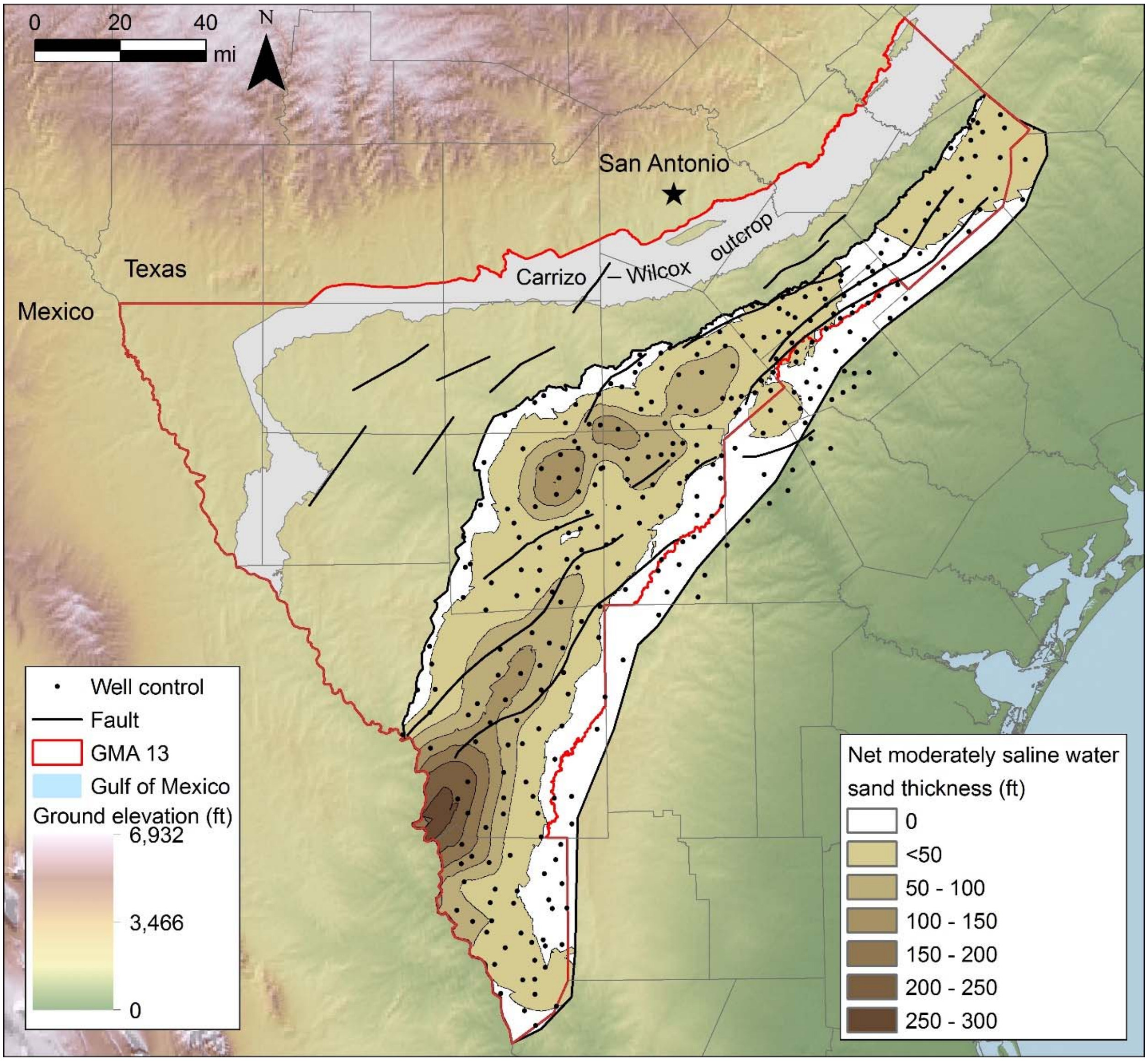


Figure 4-52. Net thickness of sand containing moderately saline groundwater in the Sparta aquifer.

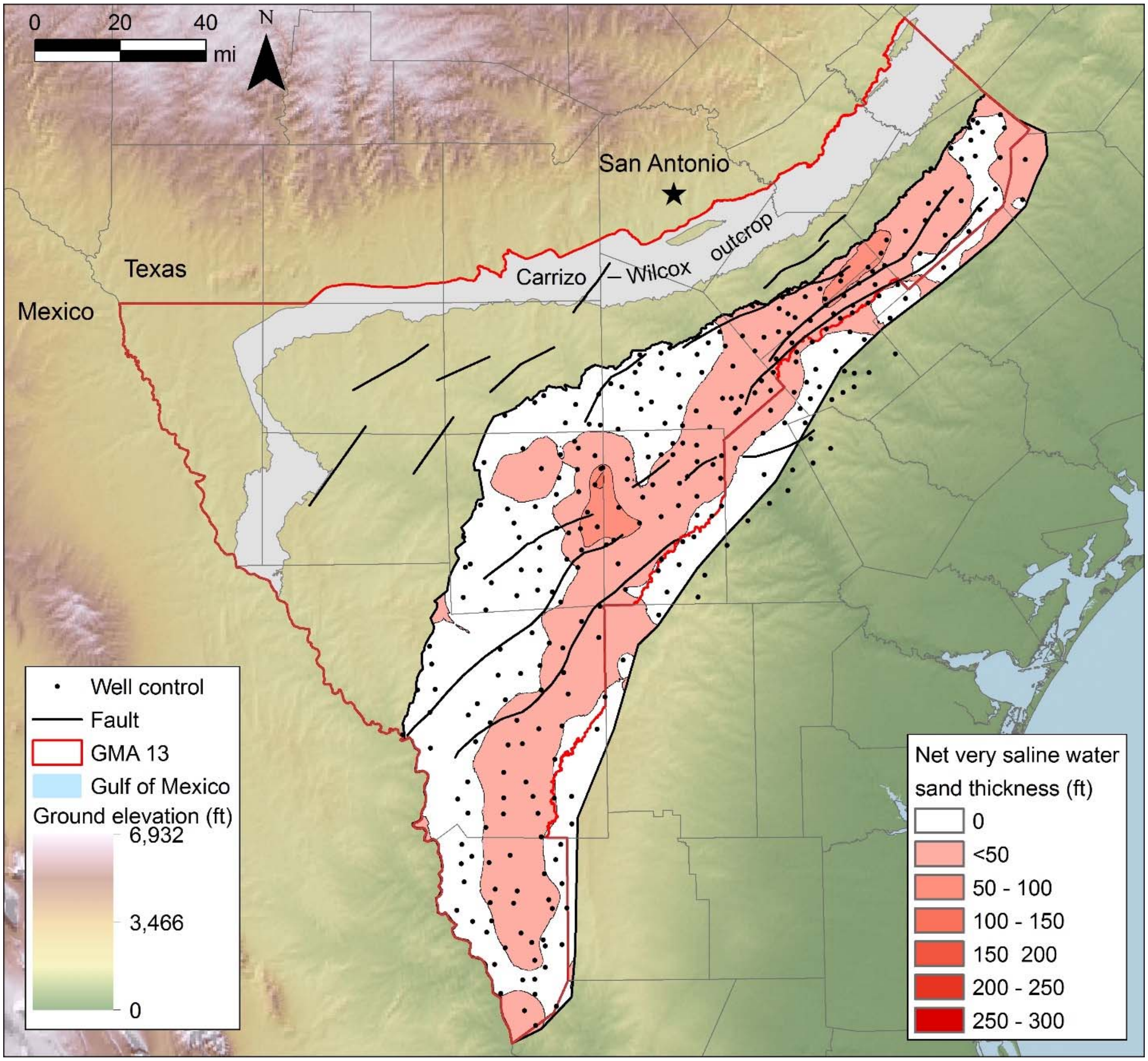


Figure 4-53. Net thickness of sand containing very saline groundwater in the Sparta aquifer.

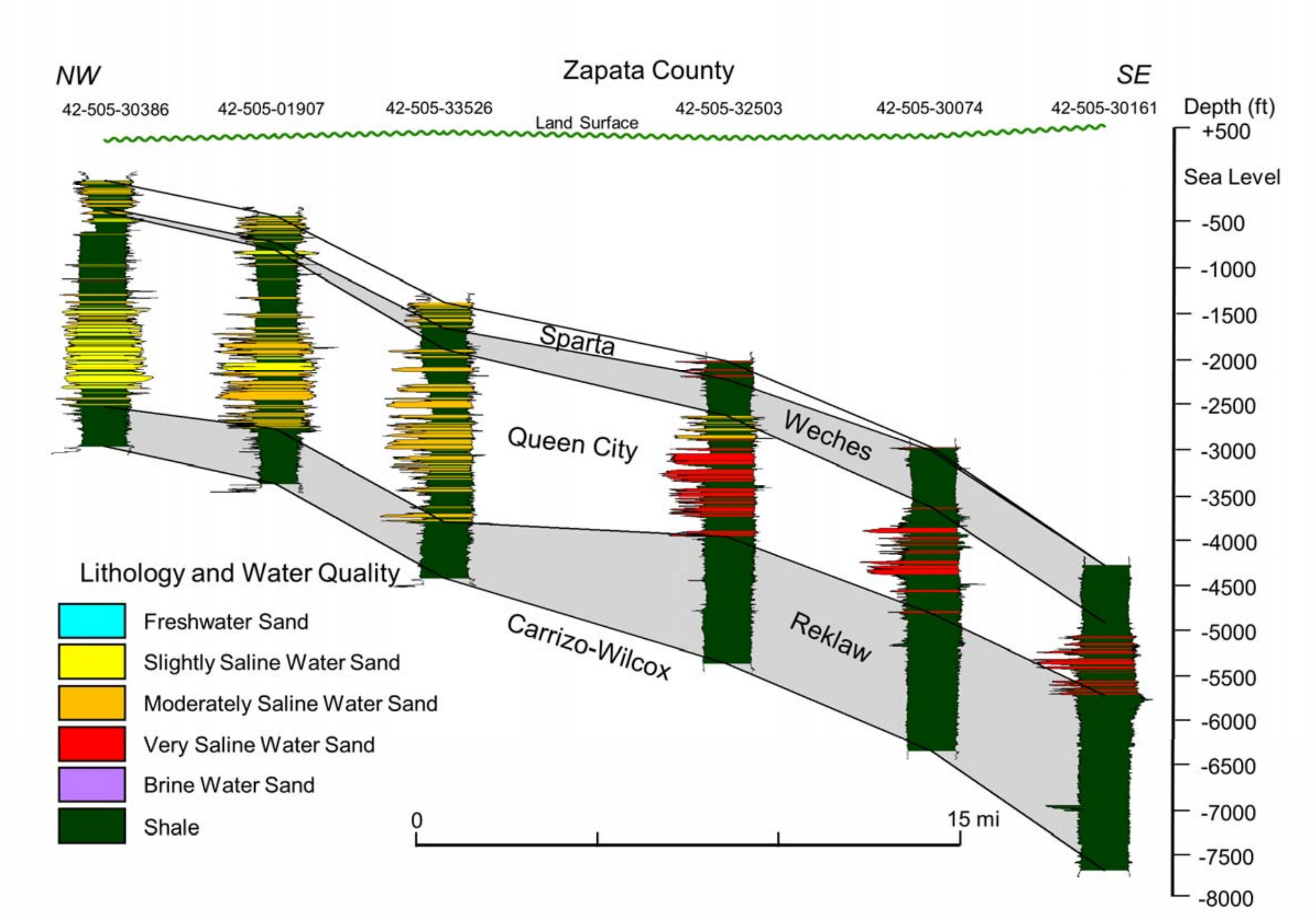


Figure 4-54. **Structural cross section 1 (sea-level datum) showing the Queen City and Sparta aquifers. Electric logs (SP on the left and resistivity on the right) for each well are shown with color fill corresponding to lithology and groundwater salinity. The Reklaw and Weches shale aquitards are shaded gray. See Figure 4-39 for location.**

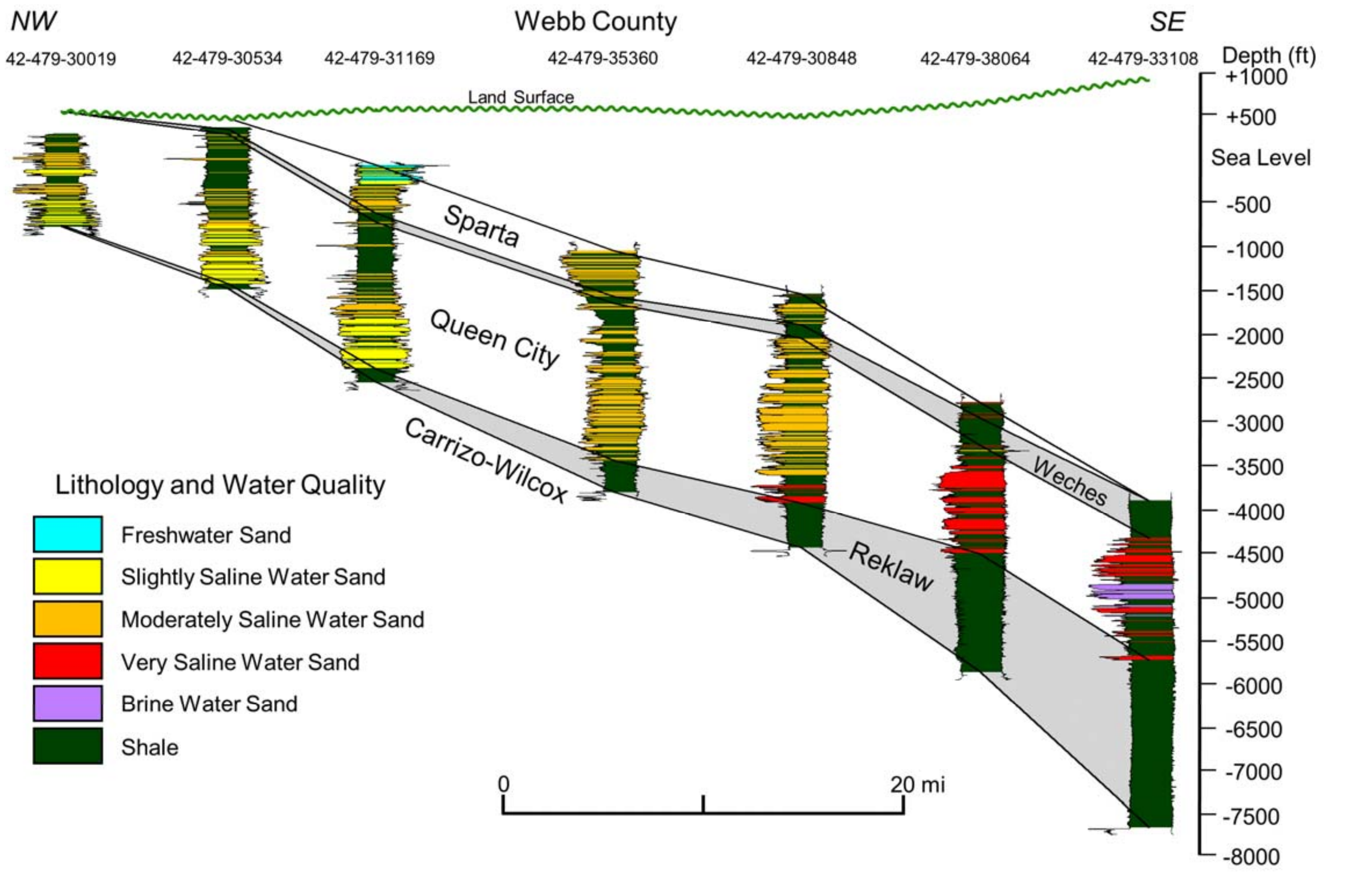


Figure 4-55. Structural cross section 2 (sea-level datum) showing the Queen City and Sparta aquifers. Electric logs (SP on the left and resistivity on the right) for each well are shown with color fill corresponding to lithology and groundwater salinity. The Reklaw and Weches shale aquitards are shaded gray. See Figure 4-39 for location.

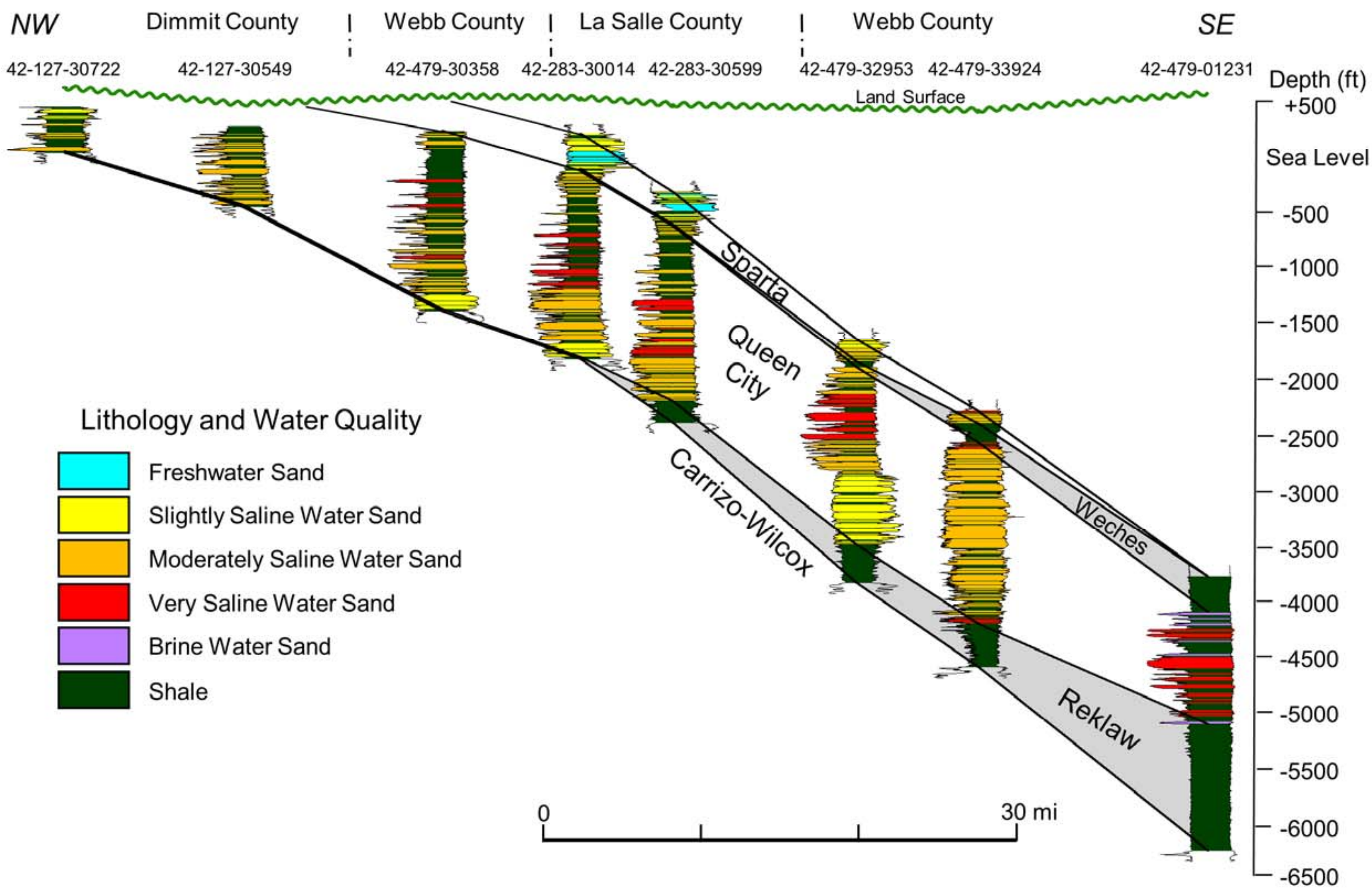


Figure 4-56. **Structural cross section 3 (sea-level datum) showing the Queen City and Sparta aquifers. Electric logs (SP on the left and resistivity on the right) for each well are shown with color fill corresponding to lithology and groundwater salinity. The Reklaw and Weches shale aquitards are shaded gray. See Figure 4-39 for location.**

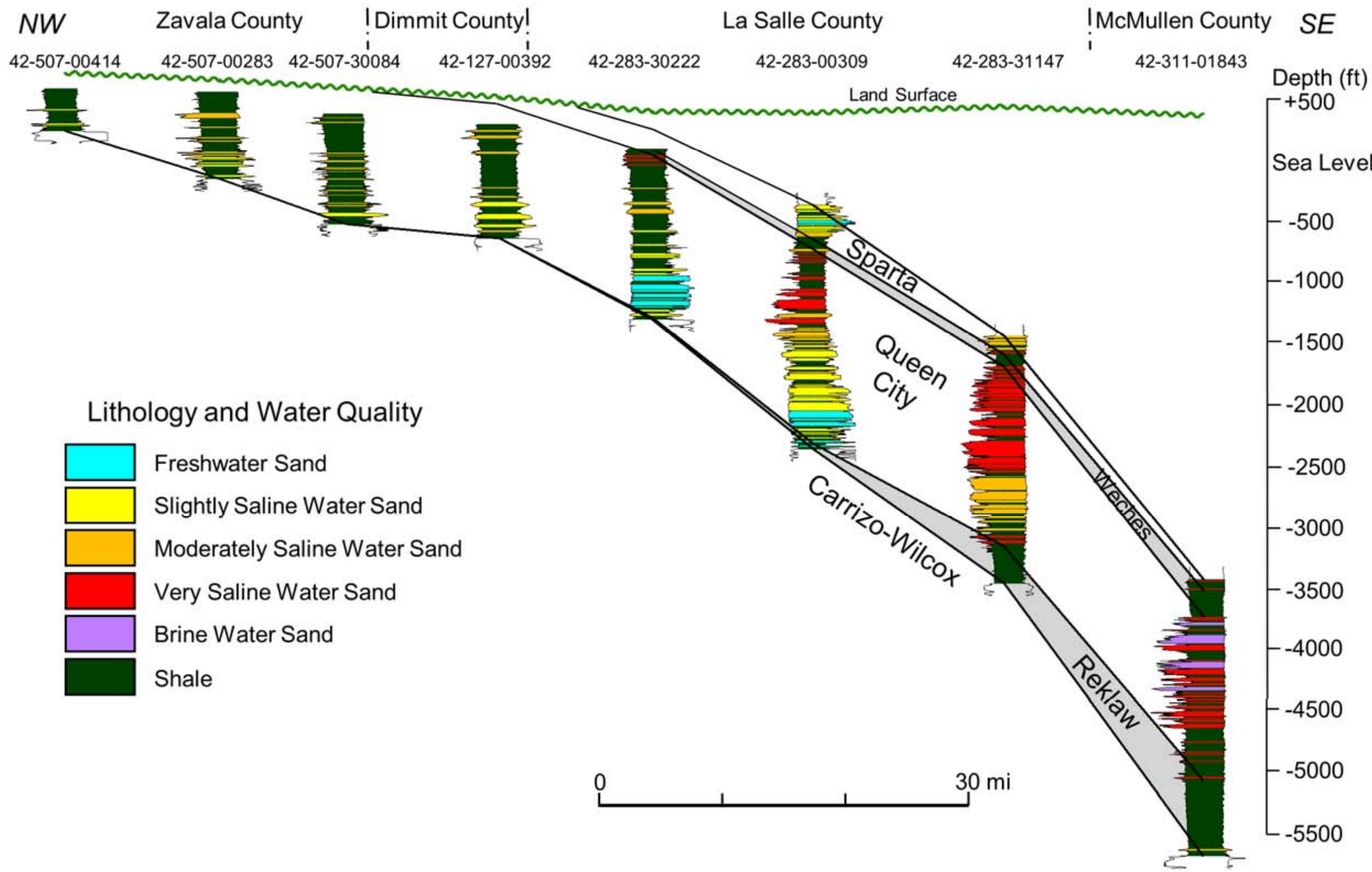


Figure 4-57. **Structural cross section 4 (sea-level datum) showing the Queen City and Sparta aquifers. Electric logs (SP on the left and resistivity on the right) for each well are shown with color fill corresponding to lithology and groundwater salinity. The Reklaw and Weches shale aquitards are shaded gray. See Figure 4-39 for location.**

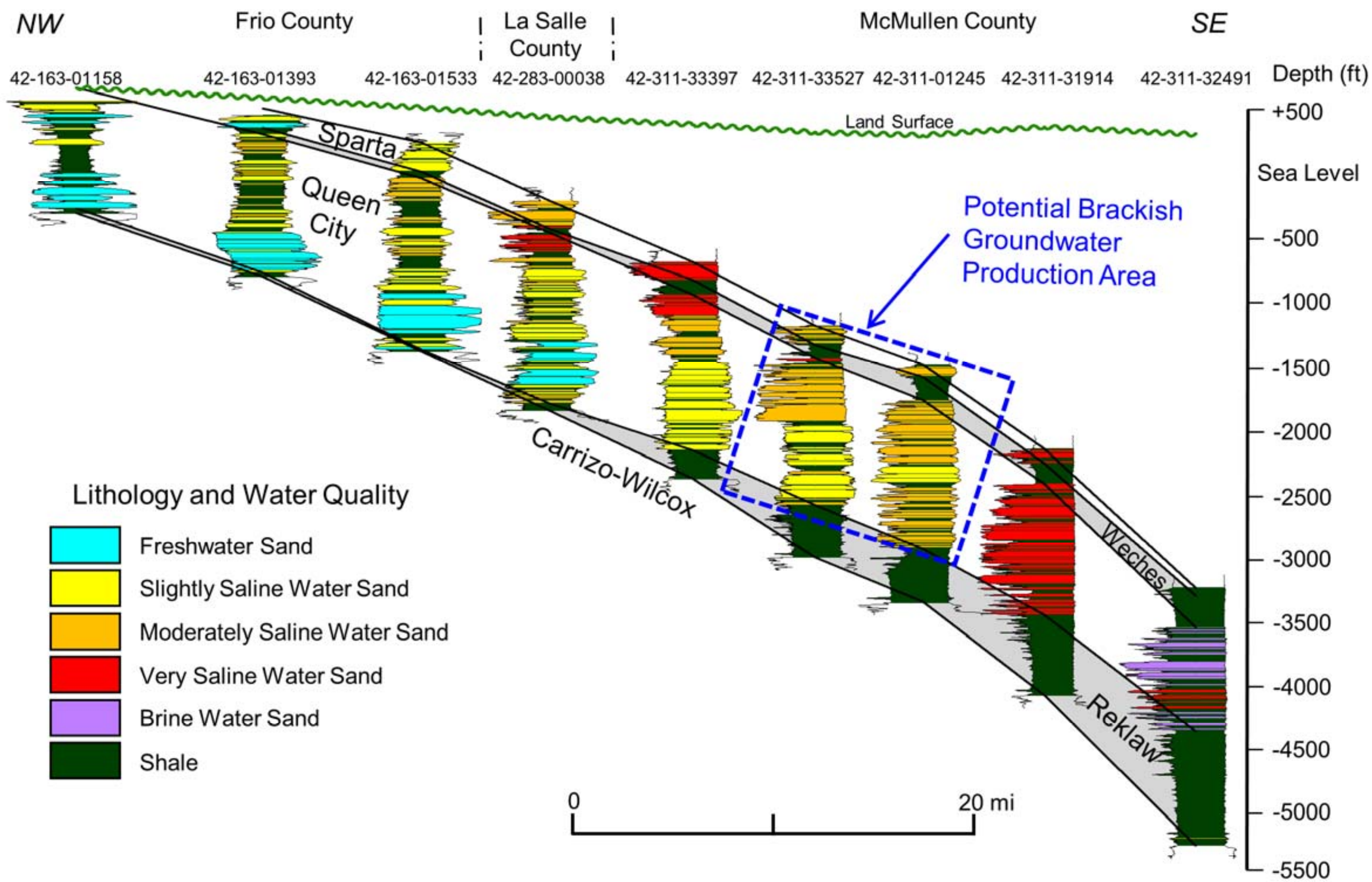


Figure 4-58. **Structural cross section 5 (sea-level datum) showing the Queen City and Sparta aquifers, and the potential brackish groundwater production area. Electric logs (SP on the left and resistivity on the right) for each well are shown with color fill corresponding to lithology and groundwater salinity. The Reklaw and Weches shale aquitards (shaded gray) form potential vertical hydrogeologic barriers, but barriers to lateral flow are more difficult to identify due to the interfingered nature of the brackish and freshwater sands. The PPA contains fresh groundwater in the Queen City Aquifer, and is also not separated by hydrogeologic barriers sufficient to prevent significant impacts to freshwater resource availability or quality in the Queen City-Sparta or adjacent aquifers, and thus, did not meet all required criteria of a PPA per House Bill 30. See Figure 4-39 for location.**

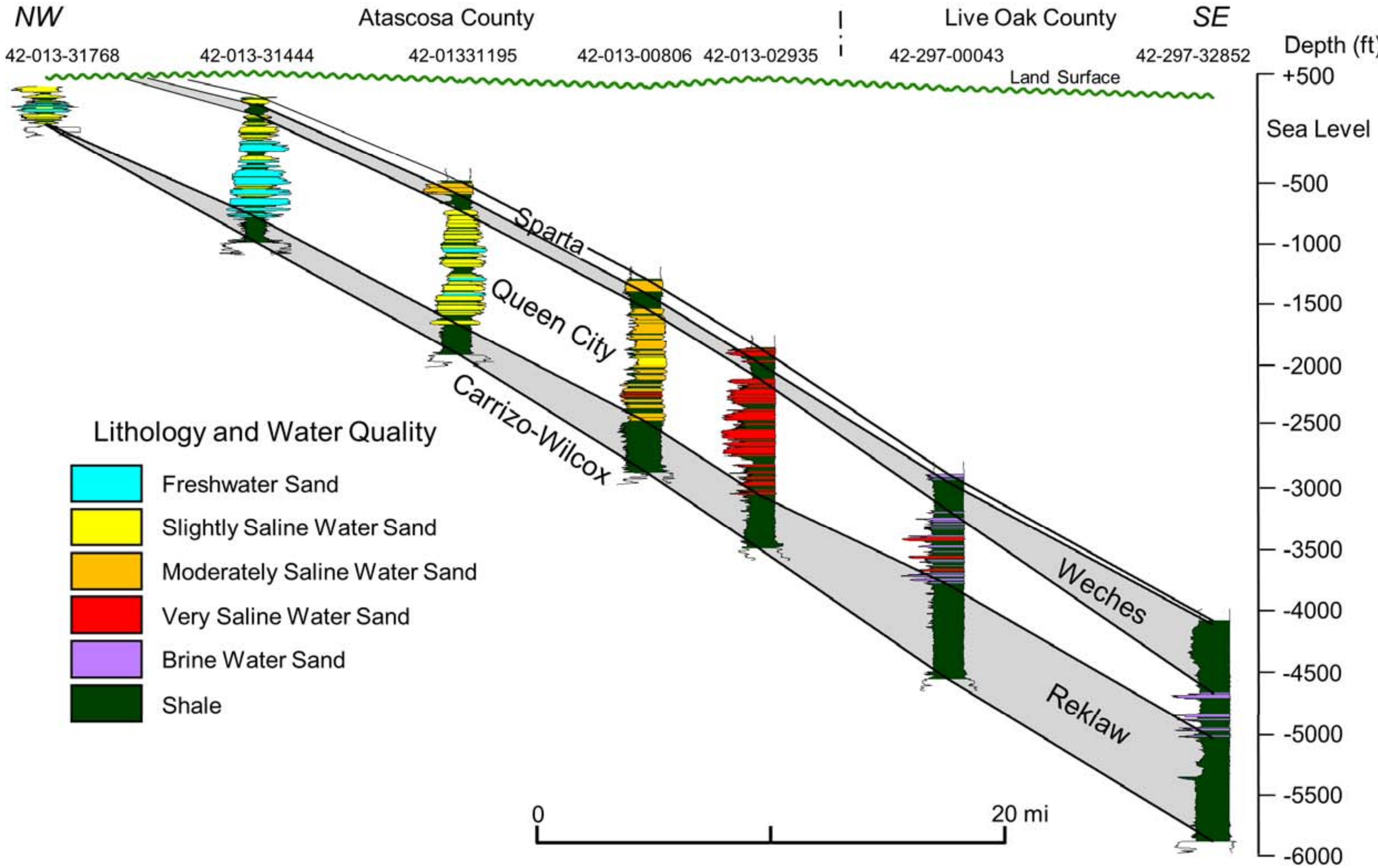


Figure 4-59. Structural cross section 6 (sea-level datum) showing the Queen City and Sparta aquifers. Electric logs (SP on the left and resistivity on the right) for each well are shown with color fill corresponding to lithology and groundwater salinity. The Reklaw and Weches shale aquitards are shaded gray. See Figure 4-39 for location.

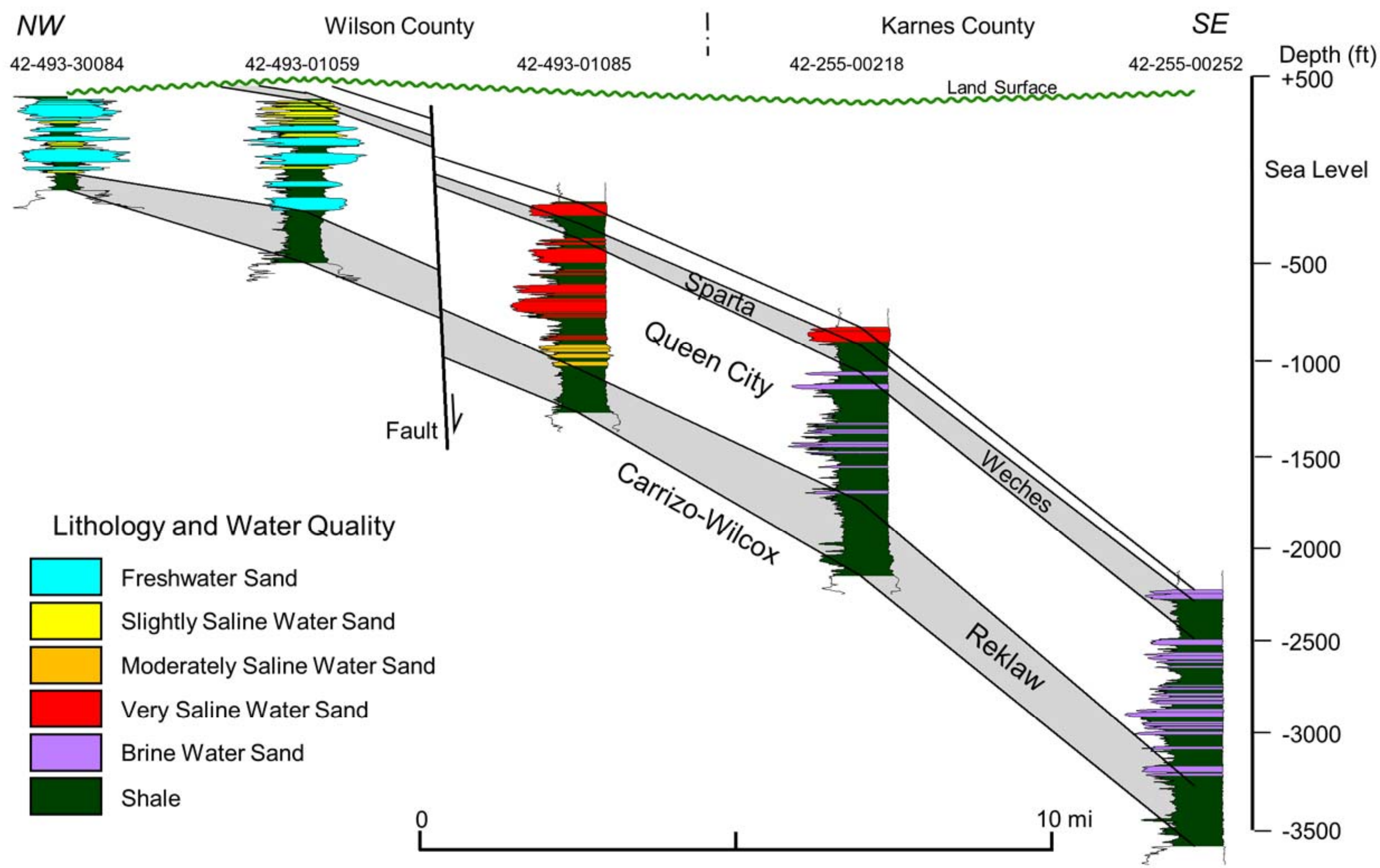


Figure 4-60. **Structural cross section 7 (sea-level datum) showing the Queen City and Sparta aquifers. Electric logs (SP on the left and resistivity on the right) for each well are shown with color fill corresponding to lithology and groundwater salinity. The Reklaw and Weches shale aquitards are shaded gray. See Figure 4-39 for location.**

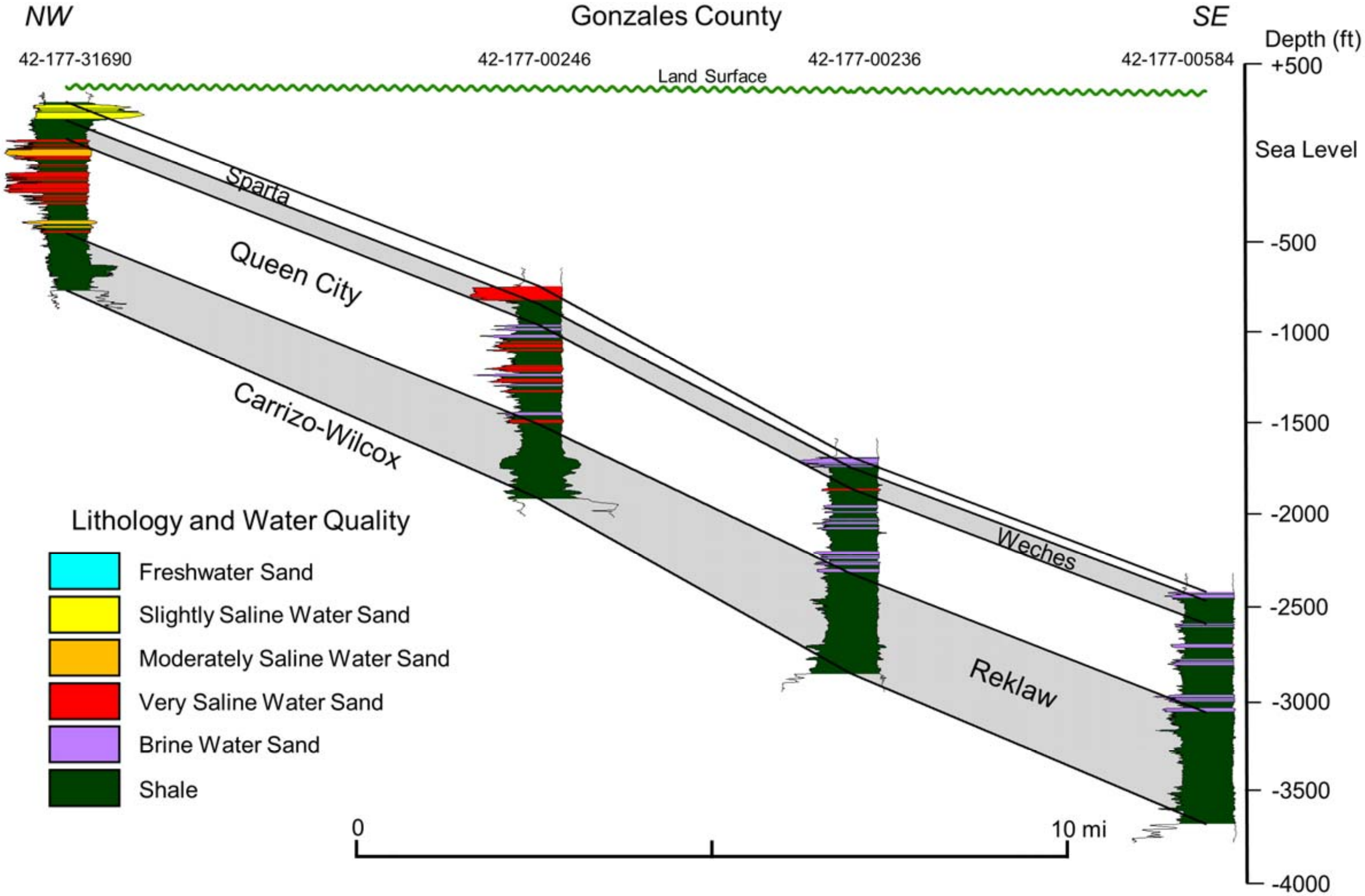


Figure 4-61. **Structural cross section 8 (sea-level datum) showing the Queen City and Sparta aquifers. Electric logs (SP on the left and resistivity on the right) for each well are shown with color fill corresponding to lithology and groundwater salinity. The Reklaw and Weches shale aquitards are shaded gray. See Figure 4-39 for location.**

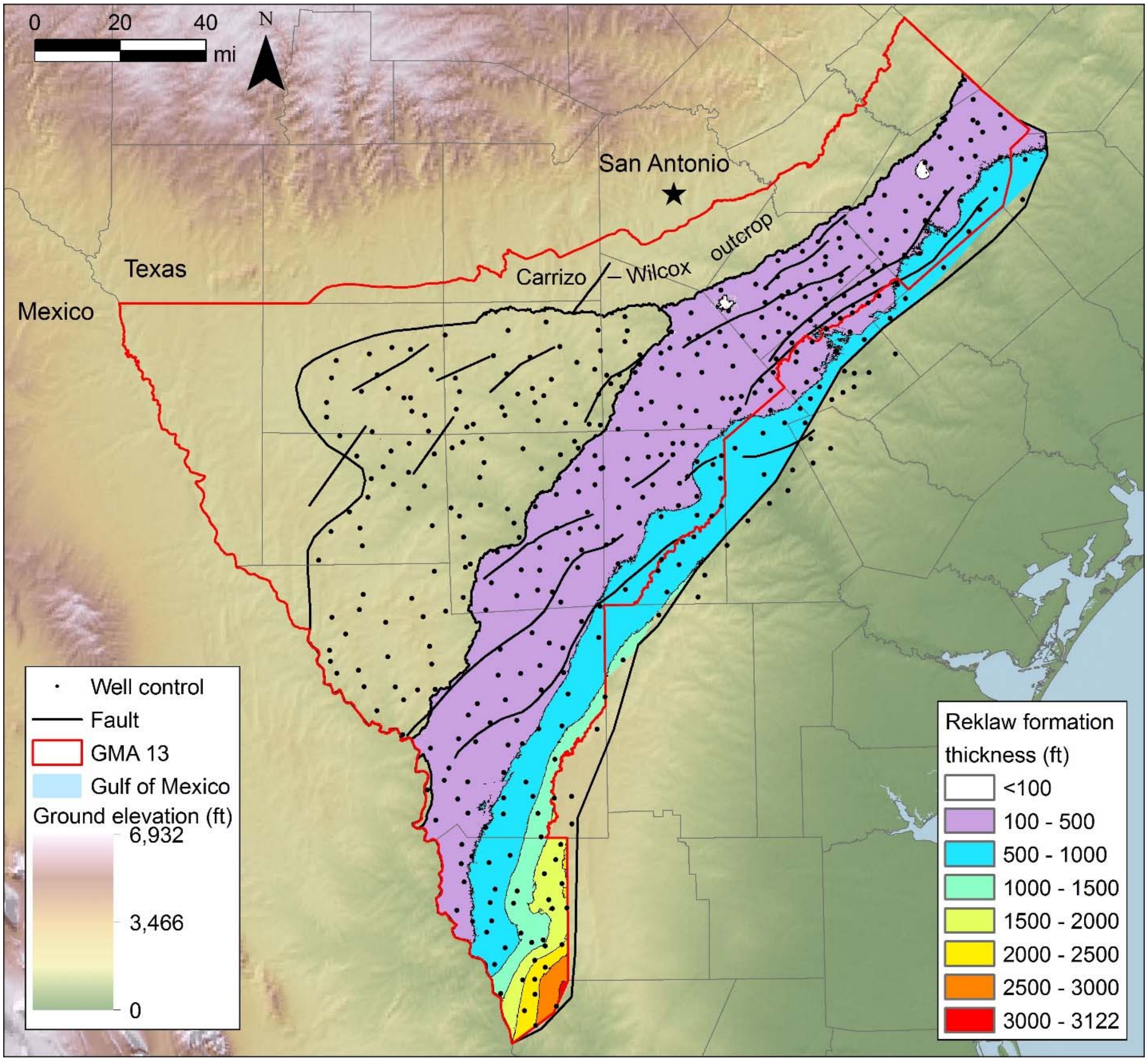


Figure 4-62. **Thickness of the Reklaw shale aquitard. The Reklaw thickens downdip, but updip from the 100 ft contour, the Reklaw is not shown on this figure being either very thin, or essentially missing. Minor and locally irregular shale thickness in the updip area (west) forms part of the Bigford Formation (Figure 4-40).**

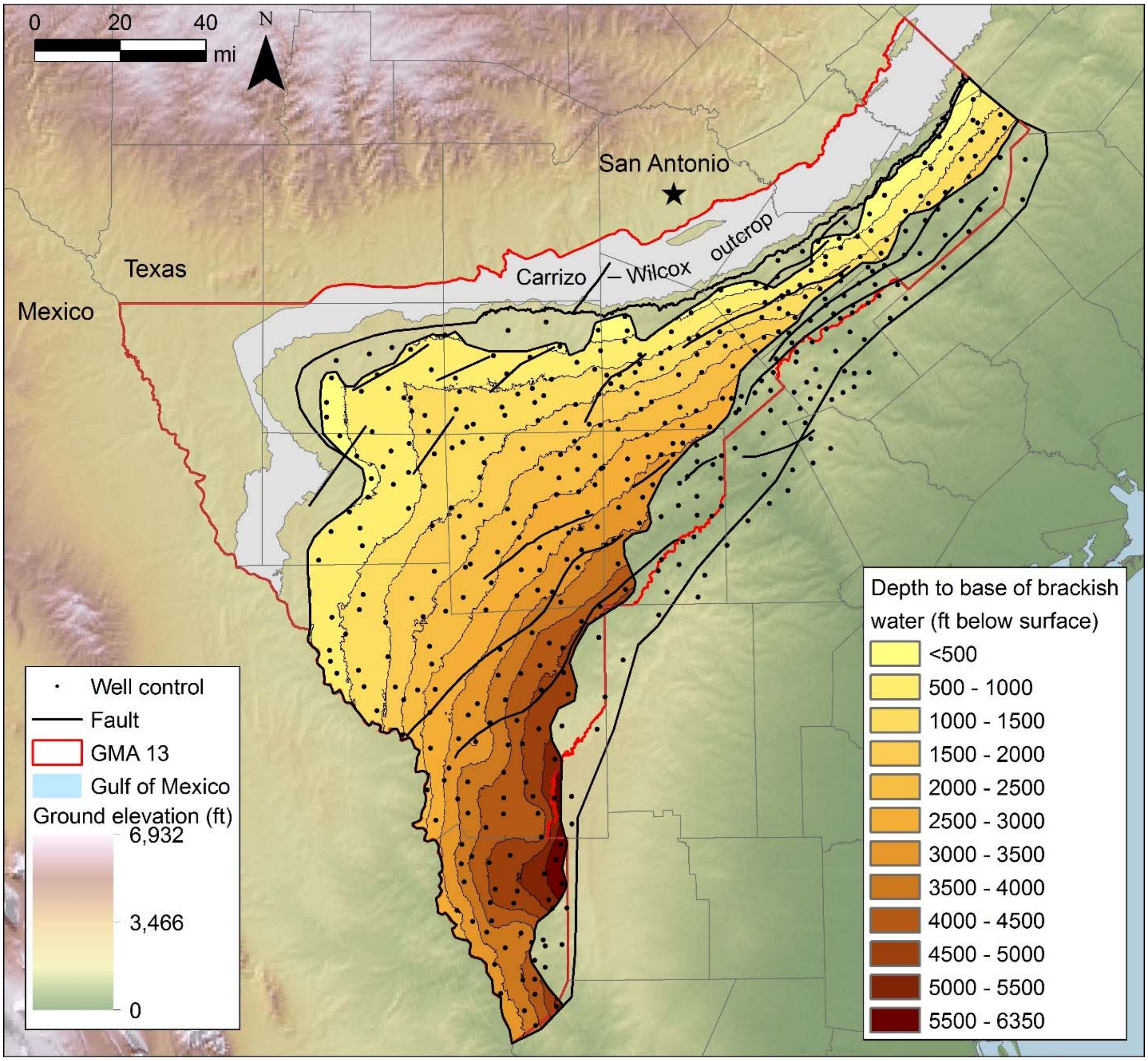


Figure 4-63. Depth from surface to base (deepest occurrence) of brackish groundwater in the Queen City and Sparta aquifers.

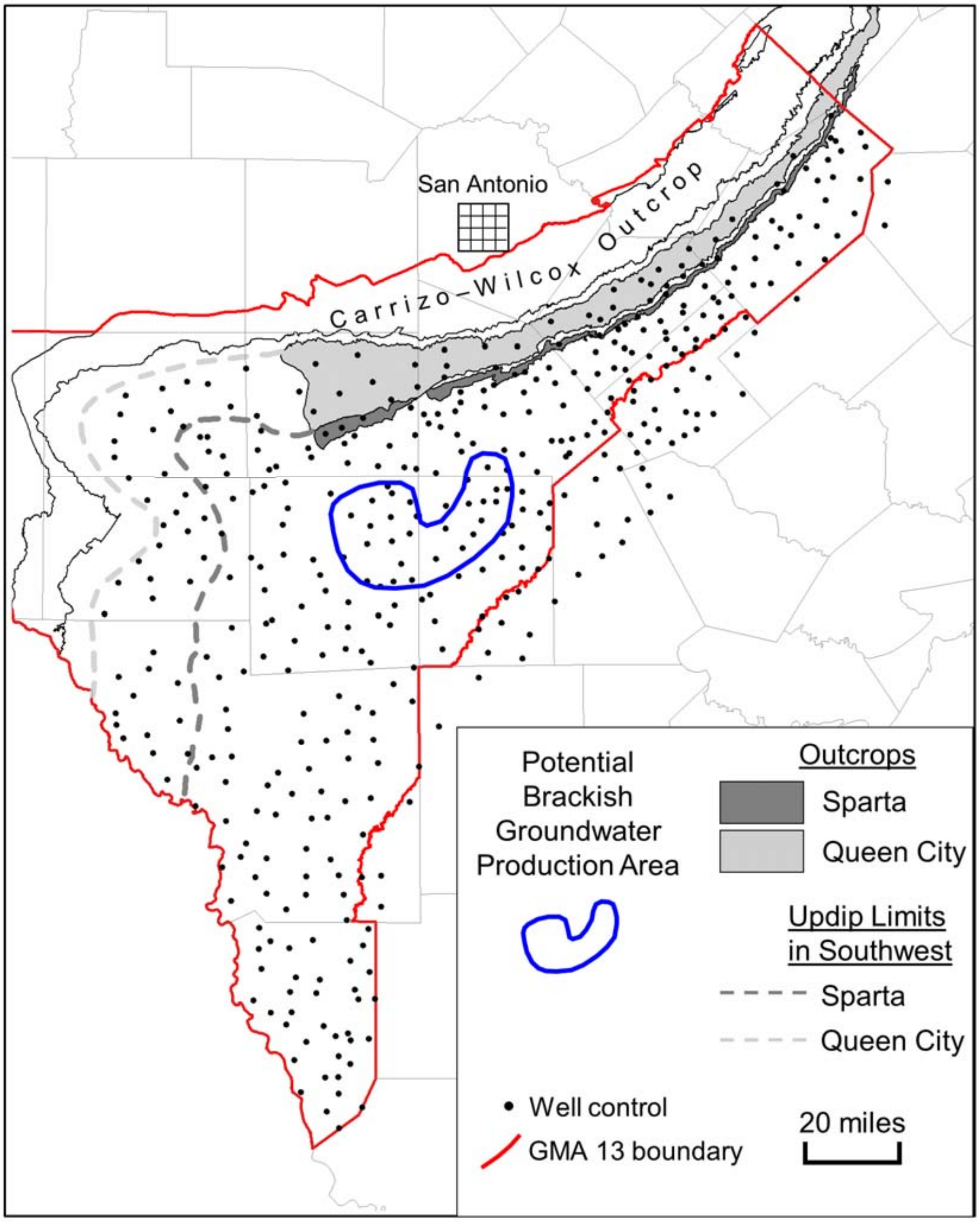


Figure 4-64. Potential brackish groundwater production area in the Queen City and Sparta aquifers in GMA 13. Structural cross section 5 shows the vertical location and stratigraphic setting of the PPA (Figure 4-58). The PPA was evaluated, and the analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. The PPA contains fresh groundwater in the Queen City Aquifer, and is also not separated by hydrogeologic barriers sufficient to prevent significant impacts to freshwater resource availability or quality in the Queen City-Sparta or adjacent aquifers.

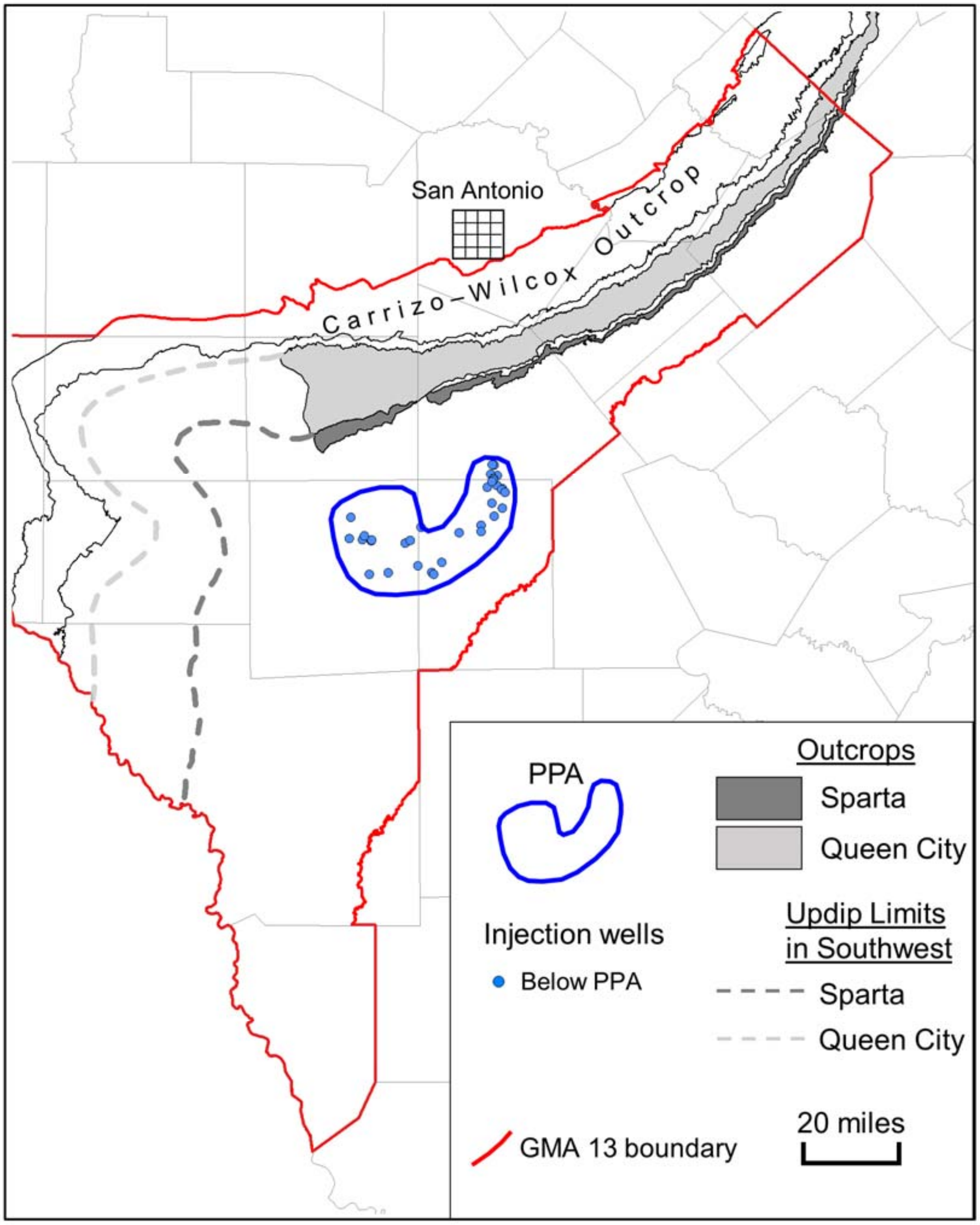


Figure 4-65. **Location of Class II injection wells within the potential brackish groundwater production area. Injection intervals relative to the PPA are also shown. Evaluation of the PPA indicated that it did not meet all required criteria of a PPA per House Bill 30. The PPA contains fresh groundwater in the Queen City Aquifer, and is also not separated by hydrogeologic barriers sufficient to prevent significant impacts to freshwater resource availability or quality in the Queen City-Sparta or adjacent aquifers.**

5 Volumes of Fresh, Brackish and Saline Groundwater

In this section, we provide estimates of groundwater volumes for different groundwater quality classifications in the Sparta, Queen City, and Carrizo-Wilcox aquifers. These estimates are based on the interpolation and extrapolation of the results of the geophysical log interpretations presented in Section 4.

5.1 Mechanics of Calculating Groundwater Volumes

Wade and Bradley (2013) provide a good overview of an approach for calculating the volume of groundwater in storage as part of their calculation of Total Estimated Recoverable Storage (TERS) for different aquifers in GMA 13. The approach we used to calculate aquifer groundwater volumes in the current study is essentially the same as the process used by the TWDB to estimate TERS (Wade and Bradley, 2013). However, while Wade and Bradley's (2013) TERS estimates provide the total storage for the Carrizo-Wilcox Aquifer, our estimates provide the storage values for Carrizo, Upper Wilcox, Middle Wilcox, and Lower Wilcox aquifers, as well as the Queen City and Sparta aquifers. In addition, we also provide storage estimates by groundwater quality type. We defined these groundwater quality types based on the water quality classifications developed by the United States Geological Survey (Winslow and Kister, 1956), presented in Section 1 and **Table 4-5**. We further provide estimates for how much groundwater of each groundwater quality type occurs in sands.

The method used to calculate groundwater volume in both Wade and Bradley (2013) and this report is dependent on whether the aquifer is confined or unconfined. The following section provides a general discussion about confined and unconfined aquifers and how storage is calculated differently in confined and unconfined aquifers. Because our calculations are similar to the TWDB calculation of TERS, much of the text in Section 5.1.1 mimics the discussions from Wade and Bradley (2013).

5.1.1 Confined and Unconfined Aquifers

In general, the Sparta, Queen City, and Carrizo-Wilcox aquifers are dipping aquifers that are unconfined up dip and confined down dip. **Figure 5-1** shows a schematic of idealized groundwater conditions in this kind of aquifer. The term "unconfined" refers to the portion of the aquifer where the water level occurs below the top of the aquifer. This generally coincides with the outcrop area and the area immediately downdip of the outcrop. In the Sparta, Queen City, and Carrizo-Wilcox aquifers, the formations generally dip southeast. Therefore, the unconfined portions of these aquifers fall along their northwestern edge in the outcrop area. The term "confined" refers to the portion of the aquifer where the water level occurs above the top of the aquifer. The Sparta, Queen City, and Carrizo-Wilcox aquifers become confined southeast of their outcrops, as the units dip deeper and are overlain by younger units.

As shown in the schematic provided in **Figure 5-2**, storage is conceptualized differently in confined and unconfined aquifers. For an unconfined aquifer, the total storage is equal to the volume of groundwater removed by pumping that makes the water level fall to the aquifer bottom.

In unconfined storage reduction, water is supplied through dewatering of pore space. The parameter used to calculate unconfined storage is either porosity or specific yield (also referred to as the drainable porosity), where specific yield is conceptualized as some fraction of total porosity. Specific yield values typically range from 0.01 to 0.3 for most unconfined aquifers. The TWDB makes a distinction between the total volume of groundwater in unconfined aquifer storage versus the portion of that total volume that is actually considered drainable. Therefore, we calculated the drainable unconfined storage based on specific yield separately from the total in-place unconfined storage based on porosity, according to the following equations:

For unconfined aquifers:

$$\text{Total Volume} = V_{\text{drainable}} = \text{Area} * S_y * (\text{Water Level} - \text{Bottom}) \quad \text{(Equation 5-1a)}$$

or

$$\text{Total Volume} = V_{\text{in place}} = \text{Area} * \theta * (\text{Water Level} - \text{Bottom}) \quad \text{(Equation 5-1b)}$$

where

$V_{drainable}$	=	storage volume due to water draining from the formation (acre-feet)
$V_{in\ place}$	=	storage volume due void spaces in the aquifer occupied by water (acre-feet)
Area	=	area of aquifer (acre)
Water Level	=	groundwater elevation (feet [ft] above mean sea level [amsl])
Bottom	=	elevation of aquifer bottom (ft amsl)
Sy	=	specific yield (unitless)
θ	=	porosity (unitless)

For a confined aquifer, the total storage comprises two parts. The first part is groundwater released from the aquifer when the water level falls from above the top of the aquifer to the top of the aquifer. The reduction of hydraulic head (which can be referred to as pressure head) in the aquifer due to pumping causes expansion of groundwater and deformation of aquifer solids. The aquifer is still fully saturated to this point. This portion of aquifer storage is referred to as the confined aquifer storage. In confined storage reduction, water is supplied through groundwater expansion and aquifer volume reduction. The parameters used to calculate confined storage are storativity (also referred to as storage coefficient) or specific storage, where specific storage is defined as storativity divided by aquifer thickness. Aquifer storativity typically ranges from 10^{-5} to 10^{-3} for most confined aquifers.

The second part of storage in confined aquifers is groundwater released from the aquifer due to actual dewatering of the aquifer as the water level in the aquifer falls below the top of the aquifer and ultimately to the bottom of the aquifer. This portion of aquifer storage is referred to as the unconfined aquifer storage and is similar to the storage reduction process that occurs in an unconfined aquifer. As with the calculation for unconfined aquifers, we calculated the drainable unconfined storage based on specific yield separately from the total in-place unconfined storage based on porosity (Equations 5-4a and 5-4b).

The total storage for confined aquifers is the sum of unconfined and confined storage. Given the same aquifer area and water level decline, the amount of water released from unconfined storage is much greater (orders of magnitude) than that released from confined storage due to the different physical processes occurring under unconfined versus confined conditions. This difference is reflected in the aquifer parameters used in the calculations, in that the specific yield values used to calculate unconfined storage are usually much larger than the storativity or specific storage values used to calculate confined storage. The equations for calculating the total groundwater volume are presented below:

For confined aquifers:

$$\text{Total Volume} = V_{\text{confined}} + V_{\text{drainable}} \qquad \text{(Equation 5-1c)}$$

- Volume for confined part

$$V_{\text{confined}} = \text{Area} * [S * (\text{Water level} - \text{Top})] \qquad \text{(Equation 5-2)}$$

or

$$V_{\text{confined}} = \text{Area} * [S_s * (\text{Top} - \text{Bottom}) * (\text{Water level} - \text{Top})] \qquad \text{(Equation 5-3)}$$

- Volume for unconfined part

$$V_{\text{drainable}} = \text{Area} * [S_y * (\text{Top} - \text{Bottom})] \qquad \text{(Equation 5-4a)}$$

or

$$V_{\text{in place}} = \text{Area} * [\theta * (\text{Top} - \text{Bottom})] \qquad \text{(Equation 5-4b)}$$

where

$V_{confined}$	=	storage volume due to elastic properties of the aquifer and water (acre-feet)
$V_{drainable}$	=	storage volume due to water draining from the formation (acre-feet)
$V_{in\ place}$	=	storage volume due void spaces in the aquifer occupied by water (acre-feet)
Area	=	area of aquifer (acre)
Water Level	=	groundwater elevation (ft amsl)
Top	=	elevation of aquifer top (ft amsl)
Bottom	=	elevation of aquifer bottom (ft amsl)
Sy	=	specific yield (unitless)
Ss	=	specific storage (1/ft)
S	=	storativity or storage coefficient (unitless)
θ	=	porosity (unitless)

It is important to note that the above equations can be used to provide two different values for the volume in unconfined storage: the drainable unconfined storage or the in-place unconfined storage. The drainable unconfined storage is calculated using Equation 5-1a for unconfined aquifers and using Equation 5-4a for confined aquifers. These calculations use specific yield, which is the methodology TWDB used to calculate TERS values in Wade and Bradley (2013).

The in-place unconfined storage is calculated using Equation 5-1b for unconfined aquifers and using Equation 5-4b for confined aquifers. These calculations use porosity. These calculated volumes are meant to represent the total groundwater in-place in an aquifer, rather than water that is actually drainable from the aquifer.

In this report, we provide total volumes calculated using drainable unconfined storage (based on specific yield), as well as total volumes calculated using in-place unconfined storage (based on porosity). As these values represent two different conceptualizations of storage, users should first determine which dataset is the most appropriate for their purposes before using these values.

5.1.2 Hydraulic and Physical Properties

The equations for calculating groundwater volumes (Equations 5-1 through 5-4) require input values of aquifer properties for each aquifer. For the purposes of this study, most of these aquifer properties are obtained from the Groundwater Availability Model for the Queen City and Sparta Aquifers (Kelley and others, 2004). **Table 5-1** lists the model layers that represent the Sparta, Queen City, and Carrizo-Wilcox aquifers in the Southern QCSP GAM. The model grid for this GAM provided the cell-by-cell values of specific yield, storage coefficient or specific storage, and elevations of aquifer tops and bottoms used in the volume calculations. The water level used in the groundwater volume calculations is the simulated GAM water level for 1999, which is the last year of the model calibration period.

The equations for in-place unconfined storage (Equations 5-1b and 5-4b) require input values of porosity rather than specific yield. Because porosity values are not provided in the QCSP model grid (Kelley and others, 2004), we developed a relationship of porosity versus depth as part of this study. We developed this relationship using porosity measurements for sand beds in the Queen City, Sparta, and Carrizo-Wilcox aquifers identified on neutron and density logs. These measurements are shown in **Figure 5-3.** These measurements include porosity measurements reported by McBride and others (1991). Based on this porosity/depth relationship, we calculated cell-by-cell values of porosity using the following equation:

$$\theta = 37.2 - 0.0022 * d \qquad \text{(Equation 5-5)}$$

where:

θ = porosity (unitless)
d = depth below ground surface (ft)

Table 5-1. Model layers that comprise the Sparta, Queen City, and Carrizo-Wilcox aquifers in the QCSP GAM (Kelley and others, 2004)

Model Layer	Aquifer
1	Sparta
2	Queen City
5	Carrizo
6	Upper Wilcox
7	Middle Wilcox
8	Lower Wilcox

5.1.3 Process for Calculating Groundwater Volumes Based on Water Quality

In the TWDB Total Estimated Recoverable Storage (TERS) calculation for GMA 13, Wade and Bradley (2013) first calculated a groundwater volume for each grid cell in the Southern QCSP GAM. They then selected all cells in the GAM that fell within the GMA 13 boundary and summed these cell groundwater volumes to provide an overall TERS value for the GAM as a whole. The GAM includes eight layers, which generally represents the Sparta Aquifer (Layer 1), the Weches Confining Unit (Layer 2), the Queen City Aquifer (Layer 3), the Reklaw Confining Unit (Layer 4), the Carrizo Aquifer (Layer 5), and the Upper Wilcox Formation (Layer 6), the Middle Wilcox Formation (Layer 7), and the Lower Wilcox Formation (Layer 8). To develop estimates of TERS, Wade and Bradley (2013) used Layer 1 (Sparta), Layer 3(Queen City Aquifer), and Layers 5 through 8 (Carrizo-Wilcox Aquifer system). They estimated groundwater volumes for individual counties and GCDs using the same process.

The current study follows the same methodology used in Wade and Bradley (2013), as described above, with a few modifications. Instead of treating the Carrizo-Wilcox Aquifer as a whole, we subdivided the aquifer and calculated a groundwater volume for each transmissive unit, including the Carrizo, Upper Wilcox, Middle Wilcox, and Lower Wilcox layers. Within each of these subdivisions, we also calculated groundwater volume estimates by groundwater quality type (listed in Section 1 and **Table 4-5**). In addition, we provide groundwater volume estimates for how much of the water in each groundwater quality type occurs in sands, rather than clays.

These additional subdivided groundwater volume calculations required information about the aquifers that was not available from the Southern QCSP GAM (Kelley and others, 2004). To generate the necessary aquifer-specific information, we first interpolated and extrapolated the results of the geophysical log interpretations presented in Section 4 and then spatially distributed this information to the model grid. Once assigned to the model grid cells, this information could be incorporated into the cell-wise groundwater volume calculations. We transferred the results of the geophysical log interpretations to the model grid cells and calculated the subdivided groundwater volumes using the following procedure:

Step 1. Assign sand layers to aquifer units. At every geophysical log location analyzed in Section 4, extract top and bottom surface elevations for each model layer in the Southern QCSP GAM, including the Sparta, Queen City, Carrizo, upper Wilcox, middle Wilcox, and lower Wilcox. Each of the sand layers were assigned to a model layer and an aquifer based on the on the location of the tops and bottoms of the model layers in the southern QCSP GAM. The extent of the formations that were included in the volume calculations are determined by the boundaries of the southern QCSP GAM, which are shown in Figure 5-4.

Step 2. Generate sand percentages for each grid cell. Use kriging to interpolate the point values of sand thickness from the geophysical log analyses and create a continuous map of sand percentages for each aquifer unit. Based on the resulting surface, assign a sand percent to each grid cell.

Note: If the geophysical logs did not provide adequate coverage to estimate sand percentages in the shallow regions of an aquifer unit, we used lithology profiles from driller logs in the TWDB Submitted Driller Reports database to fill in the gaps.

Step 3. Determine water quality percentages for each grid cell. Use kriging to interpolate the point values of water quality from the geophysical log analyses and create maps of fresh, slightly saline, moderately saline, and very saline water percentages for each aquifer unit. Based on the resulting surfaces, assign water quality sand percentages to each grid cell. **Figure 5-4** shows the location of the geophysical logs used in the calculations. Where the geophysical logs did not provide adequate coverage across the shallow portions of an aquifer, we used sand picks from driller logs whose locations are also shown in **Figure 5-4**. We assigned water quality to the sands identified in the driller logs based on water quality measurements from nearby wells in the TWDB groundwater database. The pairs used for the Carrizo-Wilcox and Queen City aquifers are shown in **Figure 5-5.** No pairs were created for the Sparta Aquifer because the spatial coverage provided by the geophysical log in the up-dip region near the outcrop was considered to be adequate.

Step 4. Calculate the groundwater volumes in each grid cell. For each aquifer unit, calculate the groundwater volume in the cell using the methodology for TERS calculations (Equations 5-1 through 5-4). To get groundwater volumes in sand by water quality type in each cell, multiply the total groundwater volume by the water quality sand percentage. To get total groundwater volumes by water quality type in each cell, calculate water quality percentages for the total volume that are proportional to the water quality percentage distribution for the sand volume. Multiply the total groundwater volume by these water quality percentages. For each grid cell, a volume is calculated for the confined and unconfined portion of the aquifer. Volume for the confined aquifer is calculated using Equation 5-2 or 5-3. These two equations are used only where the elevation of the water level (or hydraulic head) is higher the top of the formation. Volume for the unconfined aquifer is calculated using 5-4a or 5-4b. Equation 5-4a provides an estimate for the drainable water and using specific yield to estimate the fraction of the in-place water that will drain under the force of gravity. Equation 5-4b provides an estimate for the water in place and using porosity to estimate the in-place water.

5.2 Calculated Groundwater Volumes

Table 5-2 provides the total calculated volumes of groundwater in the Sparta, Queen City, and Carrizo-Wilcox aquifers in GMA 13. Because the total volume is the sum of confined storage and unconfined storage and we calculated unconfined storage two different ways, we also provide two different total volume estimates: the total volume calculated using drainable unconfined storage (based on specific yield) and the total volume calculated using in-place unconfined storage (based on porosity). The total Carrizo-Wilcox volume calculated using in-place unconfined storage is 4.9 billion acre-feet, or approximately 2.4 times greater than the total volume calculated using drainable unconfined storage (2.0 billion acre-feet). The total Sparta volume calculated using in-place unconfined storage is 1.5 billion acre-feet, or approximately 2.2 times greater than the total volume calculated using drainable unconfined storage (677 million acre-feet). The total Queen City volume calculated using in-place unconfined storage is 2.2 billion acre-feet, or approximately 2.2 times greater than the total volume calculated using drainable unconfined storage (974 million acre-feet).

The volumes of fresh, brackish (the sum of slightly saline and moderately saline water), and very saline groundwater in the Carrizo-Wilcox Aquifer calculated using drainable unconfined storage are 466 million, 834 million, and 744 million acre-feet respectively (**Table 5-2**). Of the Carrizo-Wilcox Aquifer units, the lower Wilcox Aquifer contains the most groundwater (35%). However, the majority of groundwater (66%) in this aquifer unit is very saline. Only about 23% of the groundwater in the Carrizo-Wilcox Aquifer is fresh water, and the majority of this fresh water occurs in the Carrizo Aquifer (73%). The upper Wilcox Aquifer contains the majority (30%) of the brackish water in the Carrizo-Wilcox Aquifer.

Brackish water (the sum of slightly saline and moderately saline water) makes up the majority of water in both the Sparta Aquifer (56%) and Queen City Aquifer (71%). Freshwater makes up very little of the remaining Sparta water (9%), whereas very saline accounts for 35% of the total groundwater. The Queen City is fresher, with freshwater accounting for slightly more (15%) of the total groundwater than very saline water (14%).

The sand fraction (groundwater contained in sand) is about 0.38 in the Carrizo-Wilcox Aquifer, 0.23 in the Sparta Aquifer and 0.33 in the Queen City Aquifer (**Table 5-2**). The sand fraction values vary among the Carrizo-Wilcox aquifer units, ranging from 0.63 in the Carrizo Aquifer to 0.27 in the middle Wilcox Aquifer. The sand fractions of fresh, slightly saline, moderately saline, and very saline groundwater in the Carrizo-Wilcox Aquifer are 0.57, 0.43, 0.37, and 0.24, respectively. The sand fractions of fresh, slightly saline, moderately saline, and very saline groundwater in the Sparta Aquifer are 0.29, 0.27, 0.24, and 0.18, respectively. The sand fractions of fresh, slightly saline, moderately saline, and very saline groundwater in the Queen City Aquifer are 0.28, 0.35, 0.34, and 0.29, respectively.

Tables 5-4 and **5-5** provide the volumes of fresh, slightly saline, moderately saline, and very saline groundwater for the counties in GMA 13. **Tables 5-6** and **5-7** provide the volume of fresh, slightly saline, moderately saline, and very saline groundwater for the GCDs in GMA 13. One of the underlying assumptions with using the geophysical logs is that the water quality has not changed over time. The dates associated with geophysical logs used in the analysis ranged between 1942 and 2013.

Table 5-2. **The volumes of fresh, moderately saline, slightly saline, very saline, and total groundwater volumes in the Sparta, Queen City, and Carrizo-Wilcox aquifers within GMA 13 based on totals that include either drainable unconfined storage (specific yield calculation) or total in-place unconfined storage (porosity calculation). The water levels were assumed from 1999 water level conditions.**

	Aquifer Unit	Total Volume (Millions of Acre-feet)					Total Volume in Sand (Millions of Acre-feet)				
		Fresh	Slightly saline	Moderately saline	Very saline	Total	Fresh	Slightly saline	Moderately saline	Very saline	Total
Use of Specific Yield in Calculating the Groundwater Volume in an Unconfined Aquifer											
	Sparta	61.6	117.6	263.5	234.1	676.7	17.9	31.5	62.9	42.6	154.8
	Queen City	150.5	305.9	384.9	132.6	973.8	41.7	106.3	130.8	38.8	317.7
	Carrizo	341.1	105.8	44.0	12.1	503.0	223.0	61.0	23.8	6.9	314.8
Wilcox	Upper Wilcox	70.2	120.1	127.9	34.1	352.2	27.5	44.9	45.0	10.9	128.2
Wilcox	Middle Wilcox	37.6	68.8	148.1	225.2	479.7	11.0	23.8	44.5	50.3	129.7
Wilcox	Lower Wilcox	17.4	73.6	146.7	472.2	709.9	3.2	28.3	57.5	108.2	197.2
	Carrizo-Wilcox	466.3	368.3	466.7	743.6	2044.8	264.7	158	170.8	176.3	769.9
	Total	678.3	791.7	1115.1	1110.3	3695.4	324.2	295.8	364.5	257.8	1242.4
Use of Porosity in Calculating the Groundwater Volume in an Unconfined Aquifer											
	Sparta	140.2	265.9	583.0	512.2	1501.3	40.6	71.0	139.2	93.0	343.7
	Queen City	346.5	677.5	843.6	292.4	2160.0	96.4	231.1	280.6	84.2	692.3
	Carrizo	737.3	206.9	84.4	23.0	1051.6	481.1	119.0	45.4	13.1	658.6
Wilcox	Upper Wilcox	151.1	234.1	238.8	59.8	683.8	58.6	86.8	82.8	18.9	247.2
Wilcox	Middle Wilcox	128.7	216.9	422.6	583.1	1351.3	37.1	74.6	128.9	132.8	373.4
Wilcox	Lower Wilcox	61.3	226.4	420.6	1126.3	1834.5	11.0	85.1	161.4	274.6	532.1
	Carrizo-Wilcox	1078.4	884.3	1166.4	1792.2	4921.2	587.8	365.5	418.5	439.4	1811.3
	Total	1565.1	1827.7	2592.9	2596.8	8582.6	724.7	667.6	838.4	616.6	2847.3

Table 5-3. **The volume of fresh, slightly saline, moderately saline, very saline, and total groundwater in the Carrizo-Wilcox Aquifer within GMA 13 calculated using specific yield by county and by aquifer unit. The water levels were assumed from 1999 water level conditions.**

Aquifer Unit		Total Volume (Millions of AF)					Total Volume in Sand (Millions of AF)				
		Fresh	Slightly saline	Moderately saline	Very saline	Total	Fresh	Slightly saline	Moderately saline	Very saline	Total
Atascosa											
Sparta		5.8	14.0	27.5	23.6	71.0	1.1	1.7	2.7	1.3	6.8
Queen City		30.5	36.5	19.4	10.2	96.7	12.2	15.3	8.1	3.8	39.4
Carrizo		75.4	13.0	0.9	0.0	89.2	53.0	8.9	0.6	0.0	62.4
Wilcox	Upper Wilcox	3.7	4.9	2.1	0.1	10.8	2.0	2.7	1.2	0.0	6.0
Wilcox	Middle Wilcox	6.2	14.9	15.3	9.2	45.6	2.2	4.7	4.2	2.1	13.1
Wilcox	Lower Wilcox	0.2	21.8	33.5	32.0	87.5	0.0	8.8	12.7	7.9	29.5
Carrizo-Wilcox		85.5	54.6	51.8	41.3	233.1	57.2	25.1	18.7	10	111
Total		121.8	105.1	98.7	75.2	400.7	70.5	42.1	29.5	15.1	157.1
Bexar											
Carrizo		1.7	0.0	0.0	0.0	1.7	0.9	0.0	0.0	0.0	0.9
Wilcox	Upper Wilcox	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Wilcox	Middle Wilcox	1.5	0.9	0.2	0.0	2.6	0.3	0.2	0.0	0.0	0.5
Wilcox	Lower Wilcox	0.8	2.1	1.8	0.1	4.8	0.1	0.3	0.2	0.0	0.7
Carrizo-Wilcox		2.6	24.8	35.5	32.1	95	0.4	9.3	12.9	7.9	30.7
Total		4.1	2.9	2.1	0.1	9.2	1.3	0.5	0.3	0.0	2.0
Caldwell											
Queen City		0.4	0.0	0.0	0.0	0.4	0.1	0.0	0.0	0.0	0.1
Carrizo		2.5	0.3	0.0	0.0	2.9	0.5	0.1	0.0	0.0	0.6
Wilcox	Upper Wilcox	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
Wilcox	Middle Wilcox	4.1	0.8	0.8	2.5	8.3	0.6	0.1	0.1	0.4	1.2
Wilcox	Lower Wilcox	4.1	0.0	2.1	4.3	10.5	0.4	0.0	0.2	0.4	1.0
Carrizo-Wilcox		10.9	1.1	2.9	6.8	21.9	1.5	0.2	0.3	0.8	2.8
Total		11.3	1.2	2.9	6.9	22.2	1.6	0.2	0.3	0.8	2.9
Dimmit											
Sparta		0.1	0.1	0.1	0.0	0.3	0.0	0.0	0.0	0.0	0.0

Aquifer Unit		Total Volume (Millions of AF)					Total Volume in Sand (Millions of AF)				
		Fresh	Slightly saline	Moderately saline	Very saline	Total	Fresh	Slightly saline	Moderately saline	Very saline	Total
Queen City		6.9	20.8	28.3	13.7	69.7	1.3	4.1	5.8	2.9	14.1
Carrizo		21.4	2.2	0.4	0.0	23.9	14.3	1.3	0.2	0.0	15.7
Wilcox	Upper Wilcox	18.0	12.9	7.2	0.0	38.2	6.1	4.2	2.2	0.0	12.5
	Middle Wilcox	2.2	2.4	15.7	9.7	30.0	0.6	0.7	4.8	3.1	9.2
	Lower Wilcox	0.0	0.1	10.6	32.9	43.6	0.0	0.1	3.7	12.1	15.8
Carrizo-Wilcox		41.6	17.6	33.9	42.6	135.7	21	6.3	10.9	15.2	53.2
Total		48.7	38.5	62.2	56.3	205.7	22.3	10.4	16.7	18.1	67.5
Frio											
Sparta		0.6	3.1	2.7	0.3	6.8	0.2	1.0	0.8	0.1	2.1
Queen City		31.6	32.3	15.5	2.0	81.3	8.5	8.4	4.1	0.4	21.4
Carrizo		48.4	1.2	0.0	0.0	49.6	32.9	0.8	0.0	0.0	33.7
Wilcox	Upper Wilcox	3.3	2.7	0.4	0.0	6.3	1.6	1.4	0.2	0.0	3.3
	Middle Wilcox	4.2	14.4	10.8	0.4	29.9	1.8	6.4	4.6	0.2	12.9
	Lower Wilcox	1.8	18.0	11.6	2.2	33.7	0.7	8.8	6.1	1.2	16.8
Carrizo-Wilcox		57.7	36.3	22.8	2.6	119.5	37	17.4	10.9	1.4	66.7
Total		89.9	71.7	41.1	4.9	207.6	45.8	26.8	15.9	1.9	90.3
Gonzales											
Sparta		2.1	11.0	28.4	63.7	105.2	0.2	1.2	3.3	8.0	12.7
Queen City		28.3	8.6	10.8	14.3	62.1	4.2	1.2	1.4	1.7	8.5
Carrizo		36.4	9.6	10.7	10.7	67.5	21.8	5.6	6.1	6.1	39.6
Wilcox	Upper Wilcox	1.1	0.1	0.8	0.9	2.9	0.5	0.0	0.4	0.5	1.3
	Middle Wilcox	3.2	9.7	25.5	47.3	85.7	1.0	3.3	10.3	17.7	32.3
	Lower Wilcox	0.4	4.4	19.8	63.1	87.7	0.1	1.3	7.0	26.4	34.7
Carrizo-Wilcox		41.1	23.8	56.8	122	243.8	23.4	10.2	23.8	50.7	107.9
Total		71.6	43.4	96.0	200.1	411.0	27.7	12.7	28.4	60.4	129.2
Guadalupe											
Queen City		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Carrizo		2.1	0.0	0.0	0.0	2.1	1.1	0.0	0.0	0.0	1.1
Wilcox	Upper Wilcox	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
	Middle Wilcox	3.7	2.3	0.5	0.0	6.6	0.8	0.4	0.1	0.0	1.2
	Lower Wilcox	5.3	1.5	2.3	0.1	9.2	0.9	0.2	0.3	0.0	1.5

	Aquifer Unit	Total Volume (Millions of AF)					Total Volume in Sand (Millions of AF)				
		Fresh	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**	**Fresh**	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**
	Carrizo-Wilcox	11.3	3.8	2.8	0.1	18.1	2.8	0.6	0.4	0	3.8
	Total	11.3	3.8	2.9	0.1	18.1	2.8	0.6	0.4	0.0	3.9
	Karnes										
	Sparta	0.0	0.0	6.4	27.9	34.3	0.0	0.0	0.8	3.6	4.4
	Queen City	6.8	1.2	2.4	4.8	15.1	0.9	0.2	0.5	0.8	2.4
	Carrizo	2.3	5.5	6.5	0.4	14.7	1.5	3.6	4.1	0.3	9.4
Wi lc	Upper Wilcox	0.0	0.3	0.3	0.1	0.8	0.0	0.2	0.2	0.1	0.5
	Middle Wilcox	0.0	1.8	3.5	3.3	8.6	0.0	0.9	1.5	1.4	3.7
	Lower Wilcox	0.0	0.1	4.7	16.8	21.6	0.0	0.1	2.5	9.0	11.6
	Carrizo-Wilcox	2.3	7.7	15	20.6	45.7	1.5	4.8	8.3	10.8	25.2
	Total	9.2	9.0	23.7	53.3	95.2	2.5	5.0	9.6	15.0	32.0
	La Salle										
	Sparta	21.3	33.6	52.6	28.5	136.1	7.5	11.4	17.8	9.4	46.1
	Queen City	14.9	71.9	93.9	24.8	205.5	5.5	29.6	40.1	9.8	85.0
	Carrizo	50.9	17.3	2.0	0.0	70.3	33.5	10.6	1.2	0.0	45.3
Wilcox	Upper Wilcox	12.0	37.0	30.0	1.7	80.7	4.6	13.5	10.4	0.5	29.0
	Middle Wilcox	0.1	1.1	33.8	33.3	68.2	0.0	0.4	8.6	6.6	15.6
	Lower Wilcox	0.0	0.8	7.3	92.2	100.3	0.0	0.4	3.5	21.0	24.8
	Carrizo-Wilcox	63	56.2	73.1	127.2	319.5	38.1	24.9	23.7	28.1	114.7
	Total	99.2	161.7	219.6	180.5	661.0	51.1	65.9	81.6	47.3	245.8
	Maverick										
	Carrizo	0.3	0.0	0.0	0.0	0.3	0.2	0.0	0.0	0.0	0.2
Wilcox	Upper Wilcox	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1
	Middle Wilcox	0.1	0.0	0.2	0.1	0.4	0.0	0.0	0.0	0.0	0.1
	Lower Wilcox	0.0	0.1	0.2	0.9	1.2	0.0	0.0	0.0	0.2	0.2
	Carrizo-Wilcox	0.5	0.1	0.4	1	2	0.3	0	0	0.2	0.6
	Total	0.6	0.2	0.3	1.0	2.1	0.3	0.0	0.0	0.2	0.5
	McMullen										
	Sparta	6.8	14.6	96.9	73.3	191.6	1.7	3.6	23.1	17.4	45.9
	Queen City	2.9	50.5	54.7	15.1	123.1	1.4	24.8	26.7	6.7	59.5
	Carrizo	22.1	20.8	5.0	0.3	48.1	13.8	12.2	2.9	0.1	29.1

	Aquifer Unit	Total Volume (Millions of AF)					Total Volume in Sand (Millions of AF)				
		Fresh	Slightly saline	Moderately saline	Very saline	Total	Fresh	Slightly saline	Moderately saline	Very saline	Total
Wilcox	Upper Wilcox	5.4	16.2	24.7	6.5	52.8	2.9	8.3	12.6	3.0	26.9
Wilcox	Middle Wilcox	0.1	1.6	15.4	35.0	52.1	0.0	0.4	3.0	5.6	9.0
Wilcox	Lower Wilcox	0.0	0.1	1.2	91.9	93.1	0.0	0.0	0.3	4.7	4.9
	Carrizo-Wilcox	27.6	38.7	46.3	133.7	246.1	16.7	20.9	18.8	13.4	69.9
	Total	37.2	103.8	197.8	222.0	560.7	19.8	49.4	68.6	37.6	175.3
	Medina										
	Carrizo	1.2	0.0	0.0	0.0	1.2	0.5	0.0	0.0	0.0	0.5
Wilcox	Upper Wilcox	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.1
Wilcox	Middle Wilcox	1.4	0.5	0.1	0.0	2.0	0.4	0.1	0.0	0.0	0.5
Wilcox	Lower Wilcox	1.5	1.3	0.1	0.0	2.9	0.2	0.2	0.0	0.0	0.4
	Carrizo-Wilcox	4.3	1.8	0.2	0	6.4	1.2	0.3	0	0	1.5
	Total	4.4	1.9	0.2	0.0	6.5	1.2	0.3	0.0	0.0	1.5
	Uvalde										
	Carrizo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wilcox	Upper Wilcox	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Wilcox	Middle Wilcox	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.1
Wilcox	Lower Wilcox	0.4	0.3	0.0	0.0	0.7	0.1	0.0	0.0	0.0	0.1
	Carrizo-Wilcox	0.8	0.3	0	0	1.1	0.2	0	0	0	0.2
	Total	0.8	0.3	0.0	0.0	1.1	0.2	0.1	0.0	0.0	0.3
	Webb										
	Sparta	24.8	41.1	40.5	3.9	110.3	7.1	12.6	13.2	1.3	34.2
	Queen City	5.1	61.7	143.9	35.5	246.2	1.2	18.6	40.9	9.7	70.4
	Carrizo	12.2	28.9	17.2	0.5	58.7	5.6	13.3	7.7	0.3	26.9
Wilcox	Upper Wilcox	14.6	41.9	61.8	24.8	143.1	4.5	12.6	17.5	6.8	41.4
Wilcox	Middle Wilcox	0.0	0.1	10.7	83.3	94.0	0.0	0.0	2.0	12.9	14.9
Wilcox	Lower Wilcox	0.0	0.0	0.1	131.1	131.2	0.0	0.0	0.0	23.2	23.2
	Carrizo-Wilcox	26.8	70.9	89.8	239.7	427	10.1	25.9	27.2	43.2	106.4
	Total	56.7	173.7	274.2	279.0	783.6	18.4	57.0	81.4	54.2	211.0
	Wilson										
	Sparta	0.0	0.0	8.3	12.7	21.0	0.0	0.0	1.2	1.5	2.7
	Queen City	16.1	5.0	5.4	8.4	34.9	5.5	1.8	1.8	2.5	11.6
	Carrizo	43.3	5.5	1.4	0.2	50.3	31.1	3.9	0.9	0.1	36.1
Wilcox	Upper Wilcox	2.0	0.8	0.2	0.0	3.0	0.9	0.4	0.1	0.0	1.4
Wilcox	Middle Wilcox	5.3	11.8	13.6	1.0	31.8	1.5	4.0	4.7	0.4	10.5

Aquifer Unit		Total Volume (Millions of AF)					Total Volume in Sand (Millions of AF)				
		Fresh	Slightly saline	Moderately saline	Very saline	Total	Fresh	Slightly saline	Moderately saline	Very saline	Total
	Lower Wilcox	0.7	13.9	42.0	4.4	61.1	0.1	5.4	18.2	2.2	25.8
Carrizo-Wilcox		51.3	32	57.2	5.6	146.2	33.6	13.7	23.9	2.7	73.8
Total		67.3	37.1	70.9	26.8	202.1	39.2	15.4	26.9	6.7	88.1
Zavala											
Sparta		0.0	0.0	0.1	0.1	0.2	0.0	0.0	0.0	0.0	0.0
Queen City		7.0	17.3	10.6	3.8	38.7	0.9	2.3	1.4	0.5	5.2
Carrizo		21.1	1.4	0.0	0.0	22.5	12.5	0.8	0.0	0.0	13.3
Wilcox	Upper Wilcox	9.1	3.2	0.4	0.0	12.6	4.0	1.4	0.1	0.0	5.6
Wilcox	Middle Wilcox	5.1	6.4	2.1	0.0	13.6	1.8	2.2	0.7	0.0	4.7
Wilcox	Lower Wilcox	2.1	9.1	9.4	0.2	20.9	0.5	2.8	2.7	0.1	6.1
Carrizo-Wilcox		37.4	20.1	11.9	0.2	69.6	18.8	7.2	3.5	0.1	29.7
Total		44.4	37.4	22.5	4.1	108.5	19.7	9.5	4.9	0.6	34.8
Grand Total											
Sparta		61.6	117.6	263.5	234.1	676.7	17.9	31.5	62.9	42.6	154.8
Queen City		150.5	305.9	384.9	132.6	973.8	41.7	106.3	130.8	38.8	317.7
Carrizo		341.1	105.8	44.0	12.1	503.0	223.0	61.0	23.8	6.9	314.8
Wilcox	Upper Wilcox	70.2	120.1	127.9	34.1	352.2	27.5	44.9	45.0	10.9	128.2
Wilcox	Middle Wilcox	37.6	68.8	148.1	225.2	479.7	11.0	23.8	44.5	50.3	129.7
Wilcox	Lower Wilcox	17.4	73.6	146.7	472.2	709.9	3.2	28.3	57.5	108.2	197.2
Carrizo-Wilcox		466.3	368.3	466.7	743.6	2044.8	264.7	158	170.8	176.3	769.9
Total		676.8	678.3	791.7	1115.1	1110.3	3695.4	324.2	295.8	364.5	257.8

Table 5-4. The volume of fresh, slightly saline, moderately saline, very saline, and total groundwater in the Carrizo-Wilcox Aquifer within GMA 13 calculated using porosity by county and by aquifer unit. The water levels were assumed from 1999 water level conditions.

Aquifer Unit		Total Volume (AF)					Total Volume in Sand (AF)				
		Fresh	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**	**Fresh**	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**
Atascosa											
	Sparta	13.9	32.9	62.5	53.0	162.2	2.6	3.9	6.3	2.9	15.7
	Queen City	70.9	82.3	42.9	21.5	217.6	28.3	34.4	17.9	8.0	88.6
	Carrizo	159.9	24.8	1.7	0.0	186.4	112.2	17.0	1.1	0.0	130.2
Wilcox	Upper Wilcox	7.5	8.9	3.9	0.1	20.5	4.0	5.0	2.2	0.1	11.2
Wilcox	Middle Wilcox	20.4	44.6	41.5	22.6	129.0	7.2	14.3	11.4	5.1	38.0
Wilcox	Lower Wilcox	0.6	63.2	89.0	72.9	225.7	0.1	25.4	34.0	18.5	78.0
	Carrizo-Wilcox	45.9	190.3	281.1	567.8	1085.1	14.5	73	105.1	131.9	324.4
	Total	273.2	256.6	241.4	170.2	941.4	154.3	99.9	72.9	34.6	361.8
Bexar											
	Carrizo	4.0	0.0	0.0	0.0	4.0	2.1	0.0	0.0	0.0	2.2
Wilcox	Upper Wilcox	0.3	0.1	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.1
Wilcox	Middle Wilcox	5.4	3.1	0.8	0.0	9.2	1.0	0.5	0.1	0.0	1.7
Wilcox	Lower Wilcox	3.1	7.2	6.5	0.3	17.1	0.4	1.1	0.9	0.1	2.4
	Carrizo-Wilcox	12.8	10.4	7.3	0.3	30.6	3.5	1.6	1	0.1	6.4
	Total	12.7	10.4	7.3	0.3	30.8	3.6	1.6	1.0	0.1	6.2
Caldwell											
	Queen City	1.0	0.0	0.0	0.0	1.1	0.2	0.0	0.0	0.0	0.2
	Carrizo	6.0	0.7	0.0	0.1	6.9	1.2	0.1	0.0	0.0	1.4
Wilcox	Upper Wilcox	0.4	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
Wilcox	Middle Wilcox	14.7	2.9	2.9	8.8	29.3	2.3	0.5	0.4	1.3	4.5
Wilcox	Lower Wilcox	14.4	0.1	7.0	14.4	36.0	1.3	0.0	0.7	1.3	3.4
	Carrizo-Wilcox	35.5	3.7	9.9	23.3	72.7	4.8	0.6	1.1	2.6	9.3
	Total	36.6	3.8	10.0	23.4	73.7	5.0	0.6	1.2	2.6	9.4
Dimmit											
	Sparta	0.3	0.3	0.1	0.0	0.7	0.1	0.0	0.0	0.0	0.1

	Aquifer Unit	Total Volume (AF)					Total Volume in Sand (AF)				
		Fresh	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**	**Fresh**	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**
	Queen City	16.5	49.9	67.7	32.8	167.0	3.1	9.9	13.8	6.9	33.7
	Carrizo	49.2	4.9	0.9	0.0	54.9	32.9	2.8	0.4	0.0	36.1
Wilcox	Upper Wilcox	41.3	28.8	15.8	0.0	85.8	13.9	9.4	4.8	0.0	28.2
	Middle Wilcox	7.9	8.0	51.2	30.8	97.8	2.1	2.4	15.5	9.9	29.9
	Lower Wilcox	0.0	0.4	33.8	102.1	136.2	0.0	0.2	11.5	36.8	48.5
	Carrizo-Wilcox	98.4	42.1	101.7	132.9	374.7	48.9	14.8	32.2	46.7	142.7
	Total	115.2	92.2	169.4	165.8	542.6	52.1	24.7	46.1	53.6	176.6
	Frio										
	Sparta	1.5	7.6	6.6	0.8	16.4	0.5	2.4	1.9	0.2	5.1
	Queen City	75.1	76.5	36.8	4.7	193.1	20.2	19.7	9.8	1.0	50.7
	Carrizo	108.6	2.7	0.0	0.0	111.3	73.5	1.8	0.0	0.0	75.3
Wilcox	Upper Wilcox	7.2	5.6	0.8	0.0	13.7	3.6	3.0	0.4	0.0	7.0
	Middle Wilcox	14.0	45.5	32.6	1.2	93.4	5.8	20.1	14.0	0.5	40.3
	Lower Wilcox	6.0	55.8	33.5	6.1	101.5	2.4	26.8	17.7	3.3	50.2
	Carrizo-Wilcox	135.8	109.6	66.9	7.3	319.9	85.3	51.7	32.1	3.8	172.8
	Total	212.4	193.7	110.4	12.8	529.3	106.0	73.9	43.8	4.9	228.6
	Gonzales										
	Sparta	4.8	24.5	62.8	139.6	231.8	0.5	2.7	7.2	17.7	28.1
	Queen City	62.3	19.0	23.8	30.9	136.1	9.4	2.7	3.1	3.7	18.9
	Carrizo	80.4	19.9	21.0	20.4	141.8	48.1	11.7	12.1	11.6	83.4
Wilcox	Upper Wilcox	2.4	0.2	1.6	1.6	5.8	1.1	0.1	0.7	0.8	2.6
	Middle Wilcox	10.4	31.3	74.6	126.5	242.8	3.1	10.6	29.8	46.7	90.2
	Lower Wilcox	1.4	13.1	55.4	150.8	220.7	0.2	3.8	19.0	61.7	84.8
	Carrizo-Wilcox	94.6	64.5	152.6	299.3	611.1	52.5	26.2	61.6	120.8	261
	Total	161.8	108.0	239.3	469.8	979.0	62.3	31.6	71.9	142.2	308.0
	Guadalupe										
	Queen City	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Aquifer Unit		Total Volume (AF)					Total Volume in Sand (AF)				
		Fresh	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**	**Fresh**	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**
	Carrizo	5.0	0.1	0.0	0.0	5.1	2.6	0.0	0.0	0.0	2.6
Wilcox	Upper Wilcox	0.5	0.1	0.0	0.0	0.5	0.1	0.0	0.0	0.0	0.1
Wilcox	Middle Wilcox	13.6	8.1	1.9	0.1	23.7	2.7	1.4	0.3	0.0	4.4
Wilcox	Lower Wilcox	19.0	5.1	8.0	0.4	32.5	3.3	0.8	1.2	0.0	5.3
	Carrizo-Wilcox	38.1	13.4	9.9	0.5	61.8	8.7	2.2	1.5	0	12.4
	Total	38.1	13.3	9.9	0.5	61.8	8.8	2.2	1.5	0.1	12.5
Karnes											
	Sparta	0.0	0.0	14.0	61.7	75.8	0.0	0.0	1.7	7.9	9.7
	Queen City	14.0	2.6	4.9	9.9	31.4	1.9	0.5	0.9	1.6	5.0
	Carrizo	4.6	10.6	12.4	0.7	28.3	2.9	6.9	7.9	0.5	18.2
Wilcox	Upper Wilcox	0.1	0.6	0.5	0.2	1.5	0.1	0.4	0.4	0.2	0.9
Wilcox	Middle Wilcox	0.1	4.7	9.1	8.6	22.4	0.0	2.2	3.8	3.6	9.6
Wilcox	Lower Wilcox	0.0	0.3	11.3	38.9	50.5	0.0	0.1	6.1	20.9	27.2
	Carrizo-Wilcox	4.8	16.2	33.3	48.4	102.7	3	9.6	18.2	25.2	55.9
	Total	18.8	18.7	52.3	120.2	209.9	4.9	10.2	20.8	34.7	70.5
La Salle											
	Sparta	49.1	77.5	121.2	64.1	311.8	17.3	26.3	40.9	21.0	105.6
	Queen City	33.9	158.6	203.4	54.8	450.6	12.4	64.8	86.4	21.5	185.2
	Carrizo	102.0	33.2	3.7	0.1	139.0	67.3	20.3	2.2	0.0	89.9
Wilcox	Upper Wilcox	23.6	71.0	55.0	3.0	152.7	9.1	25.9	19.1	0.9	55.0
Wilcox	Middle Wilcox	0.3	3.1	91.3	84.5	179.1	0.1	1.1	23.7	17.2	42.1
Wilcox	Lower Wilcox	0.0	2.2	20.0	220.0	242.2	0.0	1.1	9.5	53.5	64.1
	Carrizo-Wilcox	125.9	109.5	170	307.6	713	76.5	48.4	54.5	71.6	251.1
	Total	208.9	345.6	494.6	426.4	1475.4	106.2	139.6	181.9	114.2	541.9
Maverick											
	Carrizo	0.8	0.0	0.0	0.0	0.8	0.5	0.0	0.0	0.0	0.5
Wilcox	Upper Wilcox	0.3	0.0	0.0	0.0	0.3	0.2	0.0	0.0	0.0	0.2
Wilcox	Middle Wilcox	0.4	0.1	0.6	0.4	1.5	0.2	0.0	0.1	0.1	0.3
Wilcox	Lower Wilcox	0.0	0.5	0.6	3.3	4.4	0.0	0.0	0.1	0.6	0.7
	Carrizo-Wilcox	1.5	0.6	1.2	3.7	7	0.9	0	0.2	0.7	1.7
	Total	1.5	0.6	1.2	3.7	7.1	0.8	0.1	0.2	0.7	1.7

Aquifer Unit		Total Volume (AF)					Total Volume in Sand (AF)				
		Fresh	Slightly saline	Moderately saline	Very saline	Total	Fresh	Slightly saline	Moderately saline	Very saline	Total
McMullen											
Sparta		14.4	31.2	207.3	154.7	407.7	3.6	7.7	49.5	36.9	97.7
Queen City		5.9	100.7	107.5	29.4	243.5	2.8	49.6	52.6	13.1	118.1
Carrizo		41.8	37.2	8.5	0.6	88.2	26.2	21.9	5.0	0.3	53.4
Wilcox	Upper Wilcox	9.6	28.1	40.8	10.2	88.7	5.1	14.5	20.9	4.8	45.3
	Middle Wilcox	0.2	4.0	35.9	78.6	118.7	0.1	1.0	7.1	12.8	20.9
	Lower Wilcox	0.0	0.2	2.7	185.9	188.8	0.0	0.1	0.6	10.4	11.1
Carrizo-Wilcox		51.6	69.5	87.9	275.3	484.4	31.4	37.5	33.6	28.3	130.7
Total		71.9	201.4	402.8	459.4	1135.6	37.8	94.7	135.7	78.2	346.4
Medina											
Carrizo		3.0	0.0	0.0	0.0	3.1	1.2	0.0	0.0	0.0	1.2
Wilcox	Upper Wilcox	0.6	0.1	0.0	0.0	0.7	0.2	0.0	0.0	0.0	0.2
	Middle Wilcox	5.2	1.9	0.2	0.0	7.3	1.4	0.4	0.0	0.0	1.8
	Lower Wilcox	5.4	4.7	0.5	0.0	10.6	0.8	0.6	0.1	0.0	1.5
Carrizo-Wilcox		14.2	6.7	0.7	0	21.7	3.6	1	0.1	0	4.7
Total		14.2	6.7	0.7	0.0	21.6	3.7	1.0	0.1	0.0	4.8
Uvalde											
Carrizo		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wilcox	Upper Wilcox	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1
	Middle Wilcox	0.9	0.1	0.1	0.0	1.1	0.3	0.0	0.0	0.0	0.4
	Lower Wilcox	1.6	1.0	0.1	0.0	2.7	0.3	0.2	0.0	0.0	0.5
Carrizo-Wilcox		2.6	1.1	0.2	0	3.9	0.7	0.2	0	0	1
Total		2.7	1.1	0.2	0.0	4.0	0.8	0.2	0.0	0.0	1.1
Webb											
Sparta		56.2	91.9	88.9	8.4	245.3	15.9	27.9	28.9	2.8	75.5
Queen City		11.6	134.8	319.0	80.0	545.5	2.7	39.6	88.8	21.5	152.6
Carrizo		25.6	57.6	33.3	0.8	117.3	11.7	26.3	14.6	0.5	53.1
Wilcox	Upper Wilcox	31.9	81.8	119.0	44.7	277.4	9.9	24.5	33.8	12.2	80.3
	Middle Wilcox	0.0	0.3	31.4	217.9	249.6	0.0	0.1	6.1	34.5	40.7
	Lower Wilcox	0.0	0.0	0.2	319.0	319.2	0.0	0.0	0.1	61.6	61.7
Carrizo-Wilcox		57.5	139.7	183.9	582.4	963.5	21.6	50.9	54.6	108.8	235.8
Total		125.3	366.4	591.7	670.7	1754.2	40.2	118.3	172.3	133.1	463.9
Wilson											

Aquifer Unit		Total Volume (AF)					Total Volume in Sand (AF)				
		Fresh	Slightly saline	Moderately saline	Very saline	Total	Fresh	Slightly saline	Moderately saline	Very saline	Total
Sparta		0.0	0.0	19.4	29.8	49.2	0.0	0.0	2.8	3.6	6.4
Queen City		38.2	11.7	12.1	19.1	81.0	13.2	4.1	4.0	5.7	27.0
Carrizo		97.1	11.7	2.9	0.4	112.0	69.7	8.3	2.0	0.3	80.3
Wilcox	Upper Wilcox	4.5	1.7	0.5	0.0	6.8	2.1	0.9	0.2	0.0	3.2
	Middle Wilcox	17.5	37.7	41.7	2.9	99.9	4.8	12.5	14.3	1.0	32.5
	Lower Wilcox	2.3	42.3	120.7	11.4	176.7	0.3	15.9	51.3	5.6	73.0
Carrizo-Wilcox		121.4	93.4	165.8	14.7	395.4	76.9	37.6	67.8	6.9	189
Total		159.7	105.1	197.2	63.5	525.5	90.1	41.6	74.5	16.2	222.4
Zavala											
Sparta		0.0	0.0	0.3	0.2	0.5	0.0	0.0	0.0	0.0	0.0
Queen City		17.0	41.5	25.4	9.2	93.1	2.1	5.6	3.4	1.3	12.4
Carrizo		49.2	3.4	0.0	0.0	52.6	29.1	1.8	0.0	0.0	30.9
Wilcox	Upper Wilcox	20.7	7.1	0.8	0.0	28.6	9.2	3.1	0.3	0.0	12.6
	Middle Wilcox	17.8	21.6	6.9	0.0	46.3	6.1	7.5	2.2	0.0	15.9
	Lower Wilcox	7.3	30.4	31.1	0.7	69.6	1.8	9.1	8.6	0.2	19.8
Carrizo-Wilcox		95	62.5	38.8	0.7	197.1	46.2	21.5	11.1	0.2	79.2
Total		112.0	104.0	64.6	10.1	290.7	48.4	27.2	14.5	1.5	91.6
Grand Total											
Sparta		140.2	265.9	583.0	512.2	1501.3	40.6	71.0	139.2	93.0	343.7
Queen City		346.5	677.5	843.6	292.4	2160.0	96.4	231.1	280.6	84.2	692.3
Carrizo		737.3	206.9	84.4	23.0	1051.6	481.1	119.0	45.4	13.1	658.6
Wilcox	Upper Wilcox	151.1	234.1	238.8	59.8	683.8	58.6	86.8	82.8	18.9	247.2
	Middle Wilcox	128.7	216.9	422.6	583.1	1351.3	37.1	74.6	128.9	132.8	373.4
	Lower Wilcox	61.3	226.4	420.6	1126.3	1834.5	11.0	85.1	161.4	274.6	532.1
Carrizo-Wilcox		1078.4	884.3	1166.4	1792.2	4921.2	587.8	365.5	418.5	439.4	1811.3
Total		1565.1	1827.7	2592.9	2596.8	8582.6	724.7	667.6	838.4	616.6	2847.3

Table 5-5. The volume of fresh, slightly saline, moderately saline, very saline, and total groundwater in the Carrizo-Wilcox Aquifer within GMA 13 calculated using specific yield by GCD and by aquifer unit. The water levels were assumed from 1999 water level conditions.

Aquifer Unit		Total Volume (AF)					Total Volume in Sand (AF)				
		Fresh	Slightly saline	Moderately saline	Very saline	Total	Fresh	Slightly saline	Moderately saline	Very saline	Total
Area with No GCD											
Sparta		25.6	45.5	52.5	28.0	151.6	7.2	13.0	14.5	4.0	38.7
Queen City		11.0	63.2	145.8	37.9	257.8	2.0	18.8	41.2	10.1	72.0
Carrizo		15.8	30.0	20.3	6.7	72.8	7.6	14.0	9.5	3.9	34.9
Wilcox	Upper Wilcox	14.9	42.0	62.0	25.3	144.2	4.6	12.6	17.7	7.1	42.0
Wilcox	Middle Wilcox	3.3	1.4	13.2	98.9	116.8	0.6	0.3	2.9	18.8	22.6
Wilcox	Lower Wilcox	4.1	2.2	3.7	150.9	160.9	0.4	0.3	0.7	31.2	32.7
Carrizo-Wilcox		38.1	75.6	99.2	281.8	494.7	13.2	27.2	30.8	61	132.2
Total		74.7	184.4	297.4	347.7	904.1	22.4	58.9	86.4	75.1	242.8
Evergreen UWCD											
Sparta		6.4	17.2	44.9	64.6	133.0	1.3	2.7	5.5	6.5	16.0
Queen City		85.0	75.0	42.7	25.4	228.1	27.2	25.7	14.5	7.4	74.8
Carrizo		169.3	25.2	8.7	0.6	203.8	118.5	17.2	5.6	0.4	141.7
Wilcox	Upper Wilcox	9.0	8.7	3.1	0.2	21.0	4.6	4.8	1.7	0.1	11.2
Wilcox	Middle Wilcox	15.8	42.9	43.2	14.0	115.9	5.4	15.9	14.9	4.0	40.3
Wilcox	Lower Wilcox	2.6	53.9	91.8	55.5	203.8	0.8	23.0	39.5	20.3	83.7
Carrizo-Wilcox		196.7	130.7	146.8	70.3	544.5	129.3	60.9	61.7	24.8	276.9
Total		288.2	222.9	234.4	160.1	905.7	157.9	89.2	81.8	38.7	367.6
Gonzales County UWCD											
Sparta		1.3	6.5	16.5	39.7	64.0	0.1	0.7	2.0	5.3	8.2
Queen City		22.8	7.2	9.0	11.9	51.0	3.5	1.0	1.1	1.4	7.1
Carrizo		37.3	8.7	7.6	4.6	58.3	21.4	5.0	4.4	2.4	33.2
Wilcox	Upper Wilcox	1.2	0.1	0.6	0.3	2.3	0.5	0.0	0.2	0.1	0.9
Wilcox	Middle Wilcox	5.6	10.1	24.1	34.3	74.1	1.3	3.4	9.6	12.2	26.4
Wilcox	Lower Wilcox	1.3	4.4	20.2	48.6	74.5	0.1	1.3	6.8	18.9	27.1
Carrizo-Wilcox		45.4	23.3	52.5	87.8	209.2	23.3	9.7	21	33.6	87.6
Total		69.4	37.0	78.2	139.4	324.0	26.9	11.5	24.1	40.4	102.8
Guadalupe County GCD											

Aquifer Unit		Total Volume (AF)					Total Volume in Sand (AF)				
		Fresh	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**	**Fresh**	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**
	Queen City	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Carrizo	2.1	0.0	0.0	0.0	2.1	1.1	0.0	0.0	0.0	1.1
Wilcox	Upper Wilcox	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
Wilcox	Middle Wilcox	3.7	2.3	0.5	0.0	6.6	0.8	0.4	0.1	0.0	1.2
Wilcox	Lower Wilcox	5.3	1.5	2.3	0.1	9.2	0.9	0.2	0.3	0.0	1.5
	Carrizo-Wilcox	11.3	3.8	2.8	0.1	18.1	2.8	0.6	0.4	0	3.8
	Total	11.3	3.8	2.9	0.1	18.1	2.8	0.6	0.4	0.0	3.9
McMullen GCD											
	Sparta	6.8	14.6	96.9	73.3	191.6	1.7	3.6	23.1	17.4	45.9
	Queen City	2.9	50.5	54.7	15.1	123.1	1.4	24.8	26.7	6.7	59.5
	Carrizo	22.1	20.8	5.0	0.3	48.1	13.8	12.2	2.9	0.1	29.1
Wilcox	Upper Wilcox	5.4	16.2	24.7	6.5	52.8	2.9	8.3	12.6	3.0	26.9
Wilcox	Middle Wilcox	0.1	1.6	15.4	35.0	52.1	0.0	0.4	3.0	5.6	9.0
Wilcox	Lower Wilcox	0.0	0.1	1.2	91.9	93.1	0.0	0.0	0.3	4.7	4.9
	Carrizo-Wilcox	27.6	38.7	46.3	133.7	246.1	16.7	20.9	18.8	13.4	69.9
	Total	37.2	103.8	197.8	222.0	560.7	19.8	49.4	68.6	37.6	175.3
Medina County GCD											
	Carrizo	1.2	0.0	0.0	0.0	1.2	0.5	0.0	0.0	0.0	0.5
Wilcox	Upper Wilcox	0.2	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.1
Wilcox	Middle Wilcox	1.4	0.5	0.1	0.0	2.0	0.4	0.1	0.0	0.0	0.5
Wilcox	Lower Wilcox	1.5	1.3	0.1	0.0	2.9	0.2	0.2	0.0	0.0	0.4
	Carrizo-Wilcox	4.3	1.8	0.2	0	6.4	1.2	0.3	0	0	1.5
	Total	4.4	1.9	0.2	0.0	6.5	1.2	0.3	0.0	0.0	1.5
Uvalde County GCD											
	Carrizo	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wilcox	Upper Wilcox	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Wilcox	Middle Wilcox	0.3	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.1
Wilcox	Lower Wilcox	0.4	0.3	0.0	0.0	0.7	0.1	0.0	0.0	0.0	0.1
	Carrizo-Wilcox	0.8	0.3	0	0	1.1	0.2	0	0	0	0.2
	Total	0.8	0.3	0.0	0.0	1.1	0.2	0.1	0.0	0.0	0.3
Wintergarden GCD											
	Sparta	21.5	33.7	52.8	28.6	136.6	7.5	11.4	17.8	9.4	46.1
	Queen City	28.8	110.0	132.7	42.3	313.8	7.6	36.1	47.3	13.2	104.3

Aquifer Unit		Total Volume (AF)					Total Volume in Sand (AF)				
		Fresh	Slightly saline	Moderately saline	Very saline	Total	Fresh	Slightly saline	Moderately saline	Very saline	Total
Carrizo		93.3	20.9	2.4	0.0	116.7	60.2	12.6	1.4	0.0	74.3
Wilcox	Upper Wilcox	39.1	53.1	37.5	1.7	131.5	14.8	19.1	12.7	0.5	47.1
	Middle Wilcox	7.5	9.8	51.5	43.0	111.9	2.4	3.3	14.1	9.8	29.6
	Lower Wilcox	2.1	10.0	27.3	125.3	164.7	0.5	3.2	9.8	33.1	46.7
Carrizo-Wilcox		142	93.8	118.7	170	524.8	77.9	38.2	38	43.4	197.7
Total		192.3	237.6	304.3	241.0	975.2	93.1	85.8	103.1	66.0	348.1
Grand Total											
Sparta		61.6	117.6	263.5	234.1	676.7	17.9	31.5	62.9	42.6	154.8
Queen City		150.5	305.9	384.9	132.6	973.8	41.7	106.3	130.8	38.8	317.7
Carrizo		341.1	105.8	44.0	12.1	503.0	223.0	61.0	23.8	6.9	314.8
Wilcox	Upper Wilcox	70.2	120.1	127.9	34.1	352.2	27.5	44.9	45.0	10.9	128.2
	Middle Wilcox	37.6	68.8	148.1	225.2	479.7	11.0	23.8	44.5	50.3	129.7
	Lower Wilcox	17.4	73.6	146.7	472.2	709.9	3.2	28.3	57.5	108.2	197.2
Carrizo-Wilcox		466.3	368.3	466.7	743.6	2044.8	264.7	158	170.8	176.3	769.9
Total		678.3	791.7	1115.1	1110.3	3695.4	324.2	295.8	364.5	257.8	1242.4

Note: UWCD stands for underground water conservation district

Table 5-6. **The volume of fresh, slightly saline, moderately saline, very saline, and total groundwater in the Carrizo-Wilcox Aquifer within GMA 13 calculated using porosity by GCD and by aquifer unit. The water levels were assumed from 1999 water level conditions.**

		Total Volume (AF)					Total Volume in Sand (AF)				
Aquifer Unit		Fresh	Slightly saline	Moderately saline	Very saline	Total	Fresh	Slightly saline	Moderately saline	Very saline	Total
Area with No GCD											
Sparta		58.0	101.3	114.0	59.0	332.3	16.1	28.9	31.6	8.5	85.1
Queen City		23.3	137.7	322.7	84.8	568.4	4.3	40.0	89.2	22.1	155.7
Carrizo		33.4	59.9	39.1	12.2	144.6	15.9	27.6	18.0	7.2	68.7
Wilcox	Upper Wilcox	32.6	81.8	119.4	45.6	279.5	10.1	24.5	34.0	12.8	81.4
Wilcox	Middle Wilcox	12.1	5.0	38.2	256.1	311.4	2.3	1.0	8.3	48.8	60.5
Wilcox	Lower Wilcox	14.7	7.8	12.0	363.6	398.2	1.5	1.1	2.0	78.7	83.3
Carrizo-Wilcox											
Total		174.2	393.5	645.4	821.3	2034.4	50.2	123.1	183.2	178.1	534.6
Evergreen UWCD											
Sparta		15.3	40.5	102.5	145.3	303.6	3.1	6.4	12.7	14.5	36.8
Queen City		198.3	173.0	96.7	55.2	523.1	63.6	58.8	32.6	16.2	171.2
Carrizo		370.1	49.8	16.9	1.1	438.0	258.2	34.0	11.0	0.8	303.9
Wilcox	Upper Wilcox	19.4	16.9	5.7	0.4	42.3	9.8	9.2	3.2	0.2	22.4
Wilcox	Middle Wilcox	51.9	132.4	124.9	35.3	344.6	17.8	49.1	43.4	10.2	120.5
Wilcox	Lower Wilcox	8.9	161.6	254.6	129.4	554.4	2.8	68.2	109.1	48.4	228.5
Carrizo-Wilcox											
Total		664.0	574.2	601.3	366.6	2206.1	355.3	225.7	212.0	90.4	883.3
Gonzales County UWCD											
Sparta		3.0	15.2	37.6	89.0	144.8	0.3	1.7	4.5	12.0	18.5
Queen City		51.7	16.2	20.2	26.2	114.3	8.0	2.4	2.6	3.1	16.1
Carrizo		83.4	18.5	15.2	9.0	126.1	47.6	10.5	8.8	4.8	71.7
Wilcox	Upper Wilcox	2.8	0.2	1.3	0.6	4.8	1.0	0.1	0.5	0.2	1.8
Wilcox	Middle Wilcox	18.7	32.7	72.1	97.6	221.1	4.2	10.7	28.3	33.8	77.0
Wilcox	Lower Wilcox	4.2	13.1	57.7	124.2	199.2	0.5	3.8	18.7	46.6	69.6
Carrizo-Wilcox											
Total		163.8	95.7	204.1	346.6	810.3	61.6	29.2	63.3	100.5	254.6

Aquifer Unit		Total Volume (AF)					Total Volume in Sand (AF)				
		Fresh	Slightly saline	Moderately saline	Very saline	Total	Fresh	Slightly saline	Moderately saline	Very saline	Total
Guadalupe County GCD											
Queen City		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Carrizo		5.0	0.1	0.0	0.0	5.1	2.6	0.0	0.0	0.0	2.6
Wilcox	Upper Wilcox	0.5	0.1	0.0	0.0	0.5	0.1	0.0	0.0	0.0	0.1
	Middle Wilcox	13.6	8.1	1.9	0.1	23.7	2.7	1.4	0.3	0.0	4.4
	Lower Wilcox	19.0	5.1	8.0	0.4	32.5	3.3	0.8	1.2	0.0	5.3
Carrizo-Wilcox											
Total		38.1	13.3	9.9	0.5	61.8	8.8	2.2	1.5	0.1	12.5
McMullen GCD											
Sparta		14.4	31.2	207.3	154.7	407.7	3.6	7.7	49.5	36.9	97.7
Queen City		5.9	100.7	107.5	29.4	243.5	2.8	49.6	52.6	13.1	118.1
Carrizo		41.8	37.2	8.5	0.6	88.2	26.2	21.9	5.0	0.3	53.4
Wilcox	Upper Wilcox	9.6	28.1	40.8	10.2	88.7	5.1	14.5	20.9	4.8	45.3
	Middle Wilcox	0.2	4.0	35.9	78.6	118.7	0.1	1.0	7.1	12.8	20.9
	Lower Wilcox	0.0	0.2	2.7	185.9	188.8	0.0	0.1	0.6	10.4	11.1
Carrizo-Wilcox											
Total		71.9	201.4	402.8	459.4	1135.6	37.8	94.7	135.7	78.2	346.4
Medina County GCD											
Carrizo		3.0	0.0	0.0	0.0	3.1	1.2	0.0	0.0	0.0	1.2
Wilcox	Upper Wilcox	0.6	0.1	0.0	0.0	0.7	0.2	0.0	0.0	0.0	0.2
	Middle Wilcox	5.2	1.9	0.2	0.0	7.3	1.4	0.4	0.0	0.0	1.8
	Lower Wilcox	5.4	4.7	0.5	0.0	10.6	0.8	0.6	0.1	0.0	1.5
Carrizo-Wilcox											
Total		14.2	6.7	0.7	0.0	21.6	3.7	1.0	0.1	0.0	4.8
Uvalde County UWCD											
Carrizo		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wilcox	Upper Wilcox	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1
	Middle Wilcox	0.9	0.1	0.1	0.0	1.1	0.3	0.0	0.0	0.0	0.4
	Lower Wilcox	1.6	1.0	0.1	0.0	2.7	0.3	0.2	0.0	0.0	0.5
Carrizo-Wilcox											
Total		2.7	1.1	0.2	0.0	4.0	0.8	0.2	0.0	0.0	1.1
Wintergarden GCD											
Sparta		49.4	77.8	121.6	64.3	313.0	17.4	26.4	40.9	21.0	105.7
Queen City		67.4	250.0	296.4	96.9	710.7	17.7	80.3	103.6	29.7	231.3

Aquifer Unit		Total Volume (AF)					Total Volume in Sand (AF)				
		Fresh	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**	**Fresh**	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**
	Carrizo	200.4	41.5	4.6	0.1	246.6	129.3	25.0	2.7	0.0	156.9
Wilcox	Upper Wilcox	85.6	106.9	71.6	3.0	267.1	32.2	38.5	24.3	0.9	95.8
Wilcox	Middle Wilcox	25.9	32.7	149.4	115.3	323.3	8.3	11.0	41.4	27.1	87.9
Wilcox	Lower Wilcox	7.3	33.0	84.9	322.8	448.0	1.8	10.4	29.7	90.5	132.4
	Carrizo-Wilcox Total	436.1	541.8	728.5	602.3	2308.7	206.6	191.5	242.6	169.3	810.0
Grand Total											
	Sparta	140.2	265.9	583.0	512.2	1501.3	40.6	71.0	139.2	93.0	343.7
	Queen City	346.5	677.5	843.6	292.4	2160.0	96.4	231.1	280.6	84.2	692.3
	Carrizo	737.3	206.9	84.4	23.0	1051.6	481.1	119.0	45.4	13.1	658.6
Wilcox	Upper Wilcox	151.1	234.1	238.8	59.8	683.8	58.6	86.8	82.8	18.9	247.2
Wilcox	Middle Wilcox	128.7	216.9	422.6	583.1	1351.3	37.1	74.6	128.9	132.8	373.4
Wilcox	Lower Wilcox	61.3	226.4	420.6	1126.3	1834.5	11.0	85.1	161.4	274.6	532.1
	Carrizo-Wilcox Total	1565.1	1827.7	2592.9	2596.8	8582.6	724.7	667.6	838.4	616.6	2847.3

Note: UWCD stands for underground water conservation district

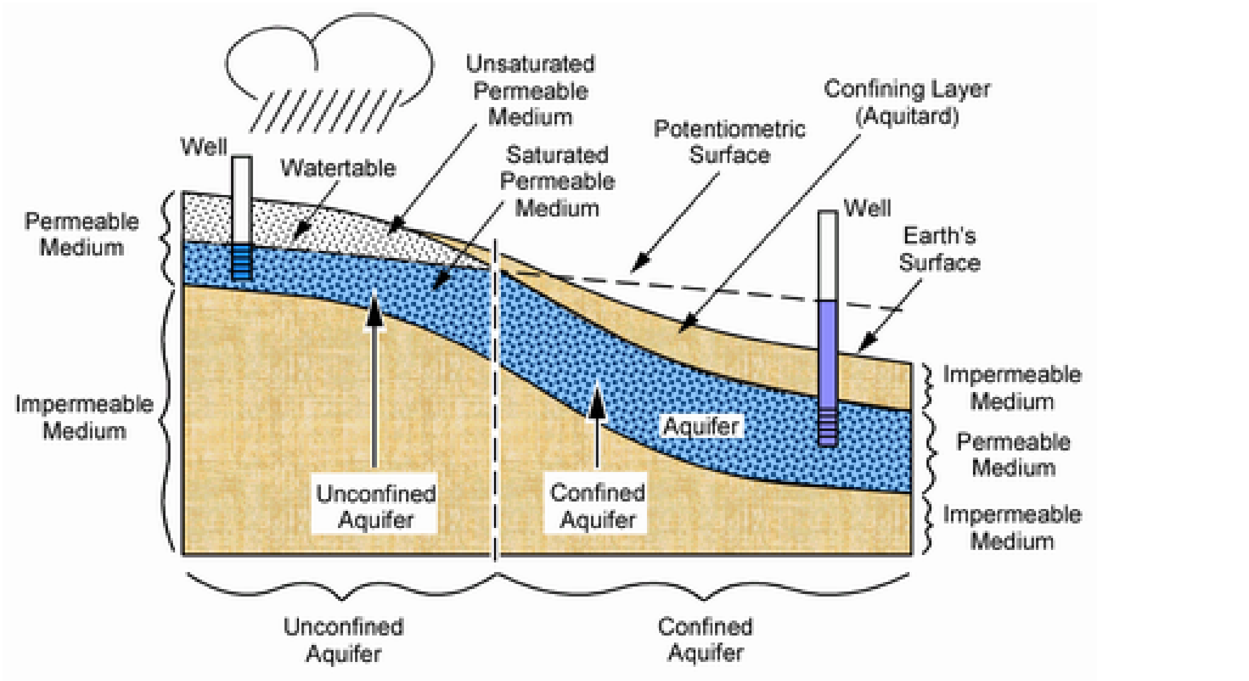


Figure 5-1. **Schematic showing the unconfined and confined portions of an aquifer. (from http://www.geo.brown.edu/research/Hydrology/ge58_IntrodHydrology/ge58_index.htm).**

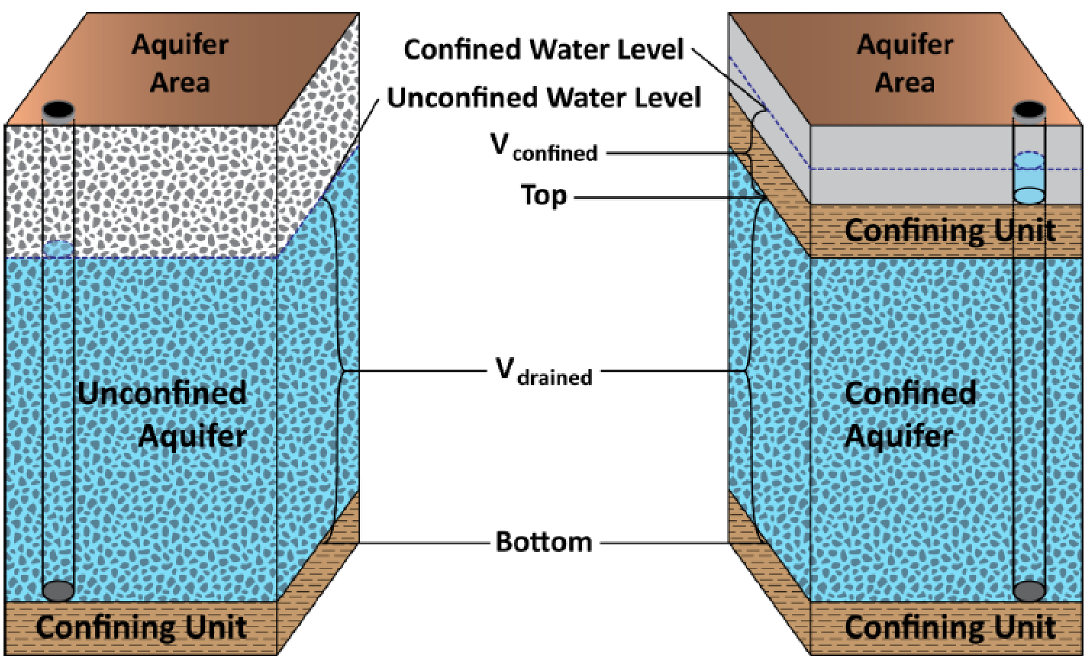


Figure 5-2. **Schematic showing the difference between unconfined and confined aquifers (from Wade and Bradley, 2013).**

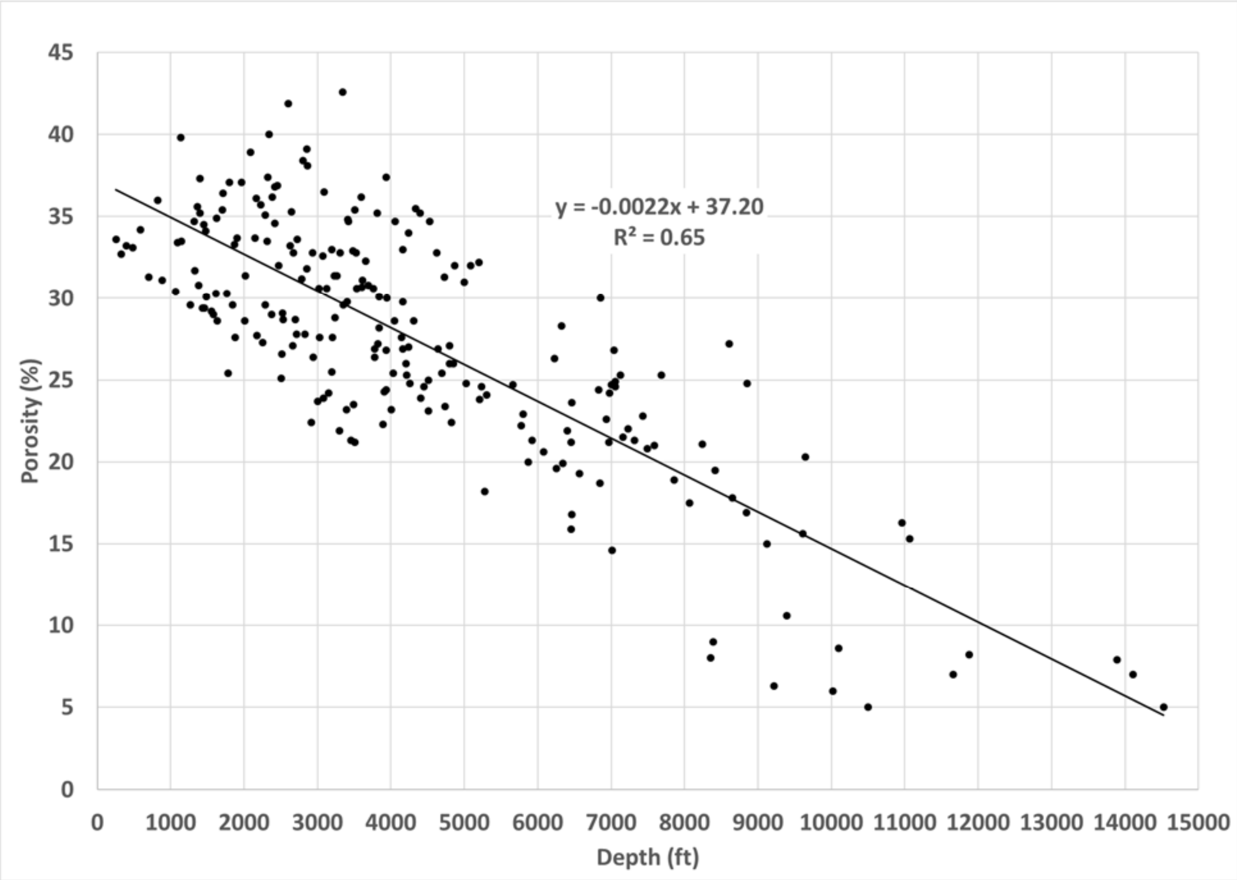


Figure 5-3. Porosity as a function of depth based on porosity data from this study and McBride and others (1991).

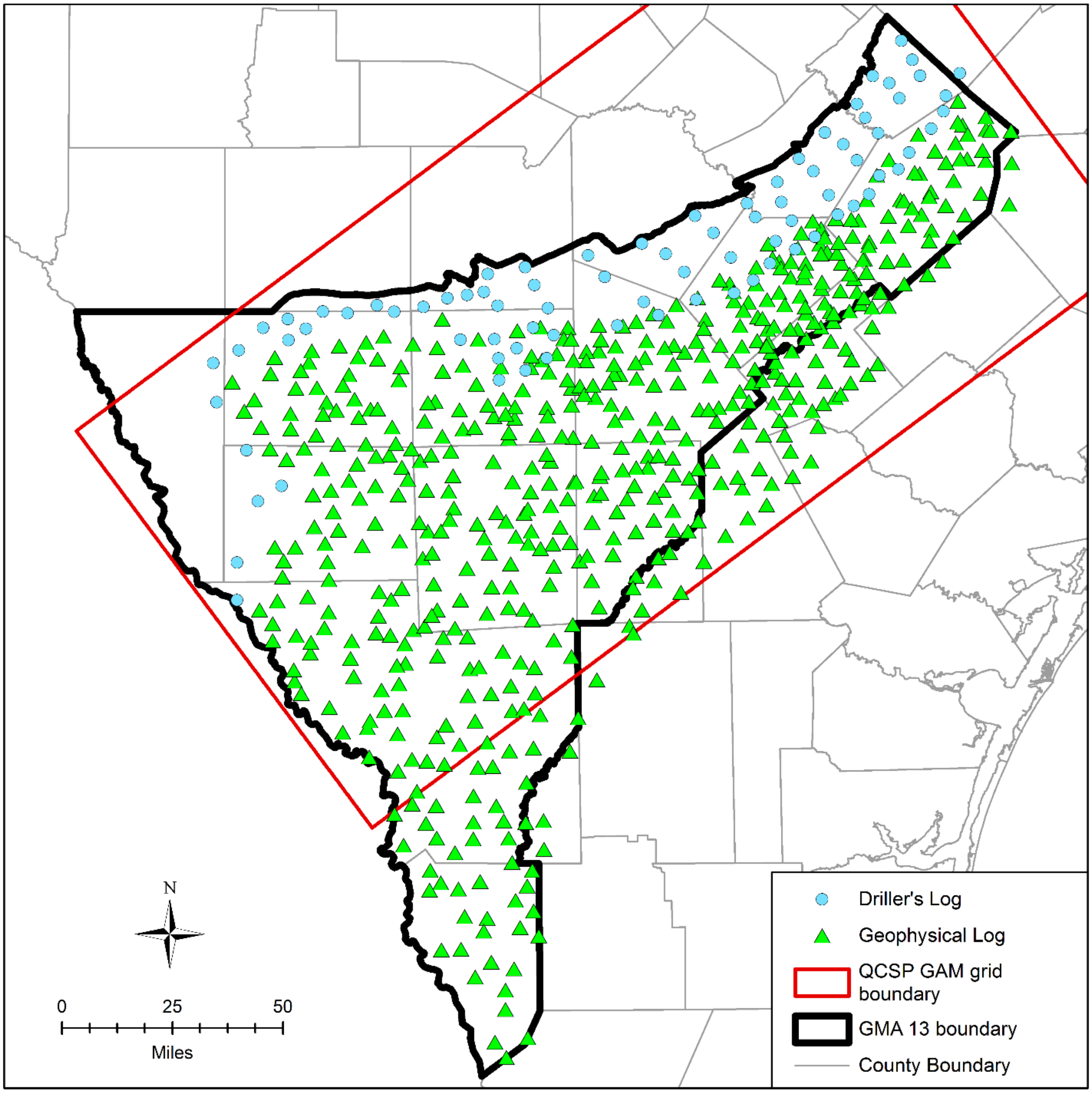


Figure 5-4. **Location of the 82 driller's logs and 530 geophysical logs with continuous profiles of sand and clay sequences. Logs located within the Southern QCSP boundary were used by the Volume Calculator Tool to construct volumes.**

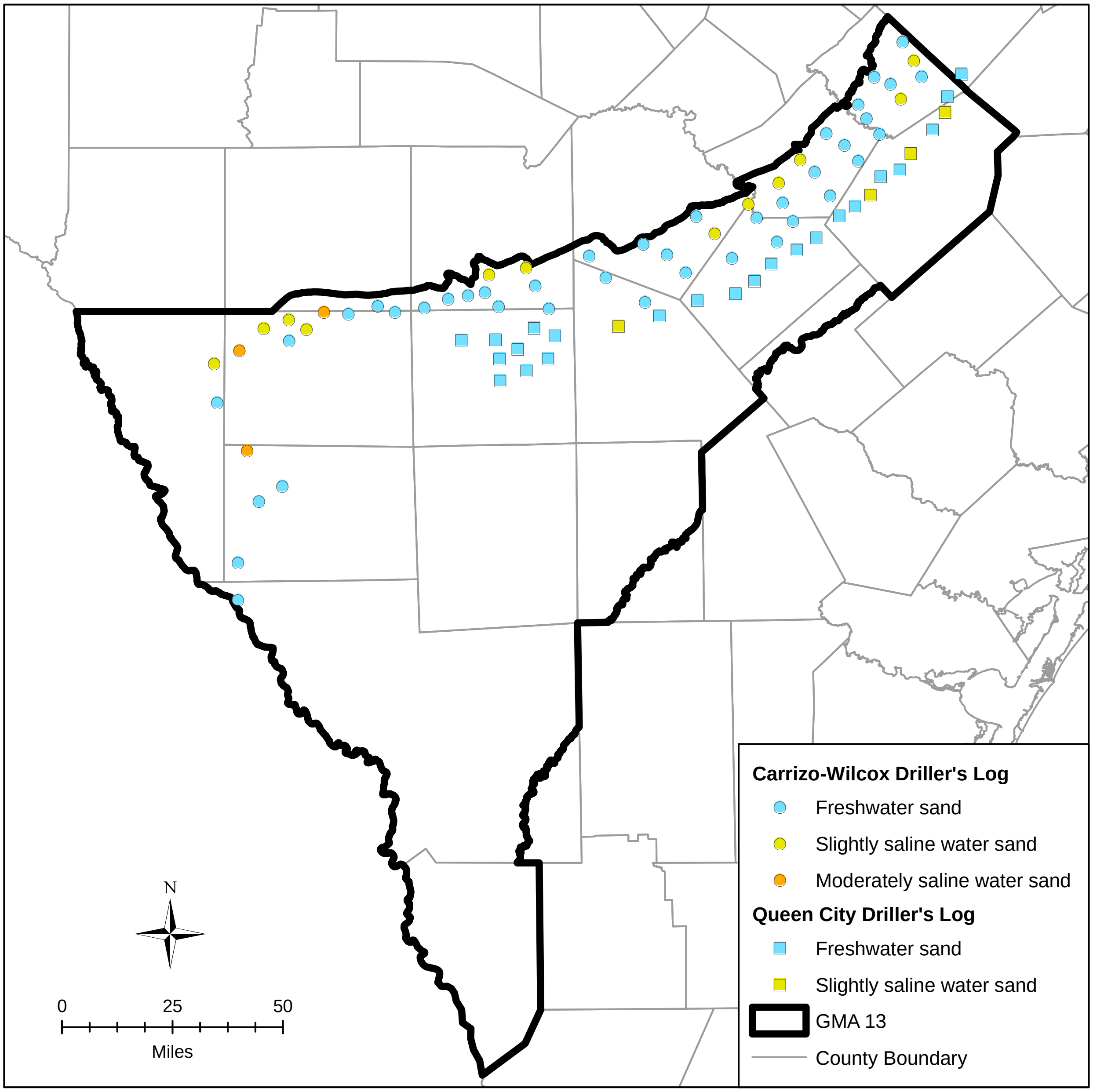


Figure 5-5. **Locations where groundwater was assigned to a water quality category based on a total dissolved solids concentration measured in a TWDB well.**

6 Construction and Application of Groundwater Models to Predict Drawdowns Associated with Pumping the Potential Production Areas

This section discusses the development and application of groundwater models to simulate changes in groundwater levels caused by pumping from Potential Production Areas (PPAs) identified in Section 4 for the Carrizo-Wilcox, Queen City and Sparta aquifers. Section 6.1 discusses modeling objectives and approach. Section 6.2 presents modeling results for pumping well fields in the Carrizo-Wilcox Aquifer in two PPAs. Section 6.3 presents modeling results for pumping two well fields in the Queen City and Sparta aquifers in one PPA.

6.1 Modeling Objectives and Approach

The primary modeling objective is to provide the TWDB with sufficient modeling results to adequately address House Bill 30 requirements and to determine the amount of brackish groundwater that a PPA can produce over a 30- and 50-year period without causing a significant impact to water availability.

The expedited schedule of the project, as well as the lack of measured water levels and aquifer tests in the areas of the PPAs, precluded the development of predictions with a high level of accuracy. The model simulations are considered preliminary because the groundwater models have not undergone the high level of model construction and calibration required by the TWDB Groundwater Availability Modeling Program. The model results have not yet been thoroughly evaluated. Model results that are based on inadequate hydrogeologic data will not likely provide representative or accurate simulations of the real aquifer system.

To help offset the inadequacy of data, the modeling approach includes four investigations listed in **Table 6-1.** The four investigations involve simulating the impacts of pumping from two hypothetical well fields in each PPA, pumping at three different rates at each well field, simulating pumping using two groundwater models with different criteria for developing aquifer properties, and performing sensitivity analyses to quantify predictive uncertainty.

The two groundwater models developed for each PPA have the same numerical grid, which means they have the same model layers and grid cells. The two groundwater models differ in the hydraulic properties assigned to the grid cells that represent the aquifers. One groundwater model has hydraulic properties for the Carrizo-Wilcox Aquifer based primarily on aquifer properties used in the Southern QCSP GAM. The other groundwater model has hydrological properties based on a geohydrostratigraphic model developed for the project. The sensitivity analysis involved performing a series of model runs to document how changes in the different aquifer hydraulic properties affect the amount of drawdown simulated by the groundwater model.

Table 6-1. Four investigations that comprise the Modeling Approach.

Major Feature of the Modeling Approach	Rationale for the Modeling Approach
Two Well Fields	Because the drawdown impacts are a function of time, distance, and pumping rate, the groundwater modeling at each PPA includes simulating drawdown from two hypothetical well fields located at different distances down dip from the outcrop in the PPA. One well field was located in the up-dip portion of the PPA, and the other well field was located in the down dip portion of the PPA.
Three Pumping Rates	Because the drawdown impacts are a function of time, distance, and pumping rate, the drawdown produced by pumping each well field was evaluated at three different withdrawal rates.
Two Groundwater Models	Because of uncertainties with assigning hydraulic properties to model layers representing aquifers and hydrogeologic barriers, two groundwater models were used to simulate drawdown impacts caused by pumping a well field. Both groundwater models are three-dimensional models that have the same model layers and grid cells. One groundwater model has aquifer hydraulic properties primarily based on aquifer properties used in the Southern QCSP GAM. The other groundwater model has aquifer hydraulic properties based a geohydrostratigraphic model developed for the project.
Sensitivity Analysis	Because of the uncertainties associated with defining the aquifer properties based on limited field data, a sensitivity analysis was performed for both groundwater models for a mid-level pumping rate. Each sensitivity model simulation involved adjusting between one to three hydraulic properties of the entire Carrizo-Wilcox Aquifer at a time.

Table 6-2 lists the sixteen model runs that comprise the sensitivity analysis. The primary focus of the sensitivity analysis was on specific storage (Ss), vertical hydraulic conductivity (Kz), and horizontal hydraulic conductivity (Kh). These three parameters were increased and decreased by a factor of 3. In the report discussion, the baseline simulation is referred as a Run 0. Sensitivity Model Runs 1 through 8 involved varying only one model parameter. Sensitivity Model Runs 9 through 16 involved varying three hydraulic properties at the same time. The only runs involving a change in the recharge rate are Model Runs 7 and 8.

Table 6-2. The sixteen model simulations that comprised the model sensitivity analysis.

Run #	Number of Variables	Variable #1	Multiplier	Variable #2	Multiplier	Variable #3	Multiplier
1	1	Ss	0.33	NA	NA	NA	NA
2	1	Ss	3	NA	NA	NA	NA
3	1	Kz	0.33	NA	NA	NA	NA
4	1	Kz	3	NA	NA	NA	NA
5	1	Kh	0.33	NA	NA	NA	NA
6	1	Kh	3	NA	NA	NA	NA
7	1	R	0.5	NA	NA	NA	NA
8	1	R	1.5	NA	NA	NA	NA
9	3	Ss	3	Kz	3	Kh	3
10	3	Ss	3	Kz	0.33	Kh	3
11	3	Ss	0.33	Kz	3	Kh	3
12	3	Ss	0.33	Kz	0.33	Kh	3
13	3	Ss	3	Kz	3	Kh	0.33
14	3	Ss	3	Kz	0.33	Kh	0.33
15	3	Ss	0.33	Kz	3	Kh	0.33
16	3	Ss	0.33	Kz	0.33	Kh	0.33

Note: Ss = Specific Storage; Kz=vertical hydraulic conductivity; Kh=horizontal hydraulic conductivity, R= Potential Recharge; NA = Not Applicable

The pumping that occurs in the groundwater model simulations is only from the wellfield in the PPA. Thus, all drawdown simulated by the groundwater model is attributed to the development of the PPA. The primary reason for excluding other sources of pumping is so that all simulated drawdowns can be directly attributed to pumping in the PPA.

6.2 Carrizo-Wilcox Aquifer

This section describes the construction and application of the groundwater models to simulate pumping from the Carrizo-Wilcox Aquifer. These models were constructed prior to the study's interpretation of geophysical log in the Queen City and Sparta aquifers that is presented in Section 4.2. As a result, there are some differences in the representation of the Queen City and Sparta aquifers in Section 6.3 and this section.

6.2.1 Model Layers

Figure 6-1 shows two transects that intersect the two PPAs identified in Section 4. **Table 6-3** summarizes several key characteristics of the PPAs. **Figures 6-2** and **6-3** show the vertical cross sections that were used to construct the groundwater models for the two PPAs. Each of vertical cross sections has nine layers. **Table 6-4** shows which aquifer or formation is represented by a model layer for the two vertical cross sections. For all of the groundwater models, the elevations for the top and bottom surfaces for the Sparta Aquifer, Weches formation, and Queen City aquifer were extracted from the Southern QCSP GAM; the top and bottom surfaces for the Carrizo-upper Wilcox, middle Wilcox, and lower Wilcox were generated as part of this project in Section 4. At the time these models were constructed, the surfaces this project developed for the Sparta and Queen City aquifers were not available. The Lower Wilcox was subdivided in order to represent more accurately the vertical location of pumping, hydraulic gradients, and simulated drawdown in the aquifer.

Table 6-3. Description of the two potential production areas (PPAs).

PPA Number	County	Formation	Depth (ft) Below Ground Surface	Salinity Classification of Groundwater
1	Wilson Atascosa	Lower Wilcox	1,500 to 5,500	slightly to moderately saline
2	Frio Zavala	Lower Wilcox	1,500 to 5,500	slightly to moderately saline

Table 6-4. Formation or aquifer assigned to the nine layers in the vertical cross sections and groundwater models for the two PPAs.

Model Layer	Formation or Aquifer
1	Sparta
2	Weches
3	Queen City
4	Reklaw
5	Carrizo-upper Wilcox
6	Middle Wilcox
7	Lower Wilcox (upper third)
8	Lower Wilcox (middle third)
9	Lower Wilcox (lower third)

6.2.2 Well Fields

Figure 6-1 shows the location of the well fields in each PPA. **Table 6-5** provides the distance down dip to the two well fields in each PPA. The distance is measured from the start of the transect to the centroid of the well field. To produce 5,000, 15,000, and 30,000 AFY, the well fields were comprised of 3, 9, and 15 wells, respectively. **Figures 6-4 and 6-5** provide a map of the location of the two well fields for in PPAs #1, and #2, respectively. Each of the well fields consist of the 15 wells used to extraction 30,000 AFY. For each well field, all wells have the same pumping rate. As shown in **Table 6-6**, these pumping rates varied between 1,032 to 1,239 gallons per minute (gpm). For PPAs #1 and #2, the production wells pump model layer 8, which is the middle third of the lower Wilcox formation.

Table 6-5. Average distance to the center of the well fields from the up-dip extent of the Carrizo-Wilcox outcrop.

Potential Brackish Production Zone	Distance from Up-Dip Extent of Carrizo-Wilcox Outcrop to Well Field	
	Up-Dip Well Field	Down-Dip Well Field
#1	32 miles	41 miles
#2	31 miles	39 miles

Table 6-6. Number of wells and average pumping rates for the modeled well fields.

Total Pumping (AFY)	Number of Wells	Pumping Rate (gpm) Per Well
5,000	3	1,032
15,000	9	1,032
30,000	15	1,239

6.2.3 Development of Three-Dimensional Groundwater Models

The code selected for the groundwater modeling is MODFLOW-USG (Panday and others, 2013). MODFLOW-USG is a three-dimensional control volume finite difference groundwater flow code supported by a suite of MODFLOW packages that simulate recharge, evapotranspiration, streams, springs and reservoirs. MODFLOW-USG is an enhanced version of the MODFLOW family of codes developed and supported by the United States Geological Survey. The benefits of using MODFLOW-USG for the current effort include the following: (1) MODFLOW incorporates the necessary physics of groundwater flow, (2) MODFLOW is the most widely accepted groundwater flow code in use today, (3) MODFLOW was written and is supported by the United States Geological Survey and is public domain, (4) MODFLOW is well documented (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; Harbaugh and others, 2000; Harbaugh, 2005; Niswonger and others, 2011; Panday and others, 2013), and (5) MODFLOW has a large user group.

A primary difference between MODFLOW-USG and the previous version of MODFLOW is that the former uses an unstructured grid and the later uses a structure grid. MODFLOW-USG's unstructured grid option provides the capability to restrict grid refinement to the areas where is needed. An example of local grid refinement is shown in Figure 6-7. In Figure 6-7, the local grid refinement of the 1-mile by 1-mile grid cells to 1/8-mile by 1/8-mile grid cells occurs only in the vicinity of the well field. In versions of MODFLOW with a structured grid, the grid refinement cannot occur locally; so, to have a refined grid at the well field, refinement in the model grid would need to extend the entire length of the rows and columns passing through the well field area. In addition, an unstructured grid supports the grid cell pinching out which a structured grid does not.

Also MODFLOW-USG has the advantage of having superior matrix solvers than previous MODFLOW versions.

As previously stated, two groundwater models were constructed for each PPA. Both these models have the same numerical grid and differ only in the aquifer properties used to represent the Carrizo-Wilcox Aquifer. For each PPA, the three-dimensional model grid was constructed from a representative vertical cross section of the aquifers for that PPA. The construction of a three-dimensional groundwater flow model can be conceptualized through the following four-step process.

<u>Step 1: Construct a Vertical Cross sectional Grid</u>. Figures 6-2 and 6-3 show the representative vertical cross section developed for PPAs #1 and #2, respectively. For all cross sections, recharge occurs where the aquifers outcrop, which is illustrated by the blue-colored grid cells. The green-colored grid cells mark where the Sparta aquifer is overlain by the Yegua-Jackson Aquifer. At the locations of the green-colored grid cells, a general head boundary (GHB) condition is used to represent the exchange of groundwater between the Sparta and Yegua-Jackson aquifers. This assumption is the same assumption used in the Southern QCSP GAM. The lowest and deepest model layer is model layer 9, which represents the lower Wilcox Aquifer. The base of the lower Wilcox Aquifer is considered to be a no-flow boundary. This is the same assumption used in the Southern QCSP GAM. For the grid cells located at the most down-dip extent of each model layer, a no-flow boundary condition is imposed. This assumption is the same assumption used in the Southern QCSP GAM.

<u>Step 2: Assign Aquifer Properties</u>. The hydraulic properties assigned to the grid cells in the top four model layers were determined by intersecting the transects in Figure 6-1 with the Southern QCSP GAM. The top four model layers represent, from youngest to oldest formation, the Sparta Aquifer, the Weches formation, the Queen City Aquifer, and the Reklaw formation. Two different methods were used to assign hydraulic properties for the Carrizo-upper Wilcox, middle Wilcox, and lower Wilcox formations identified in Section 3. One method is called the groundwater availability model (GAM)-based method, and the other method is called the geohydrostratigraphic model (GHSM)-based method. The GAM-based method involves extracting aquifer information from the Southern QCSP GAM in a similar manner as done for the top four model layers. The GHSM-based method involves using a geohydrostratigraphic (GHS) model of the Carrizo-Wilcox Aquifer to determine hydraulic properties for the grid cells. Three key parameters used to calculate hydraulic properties for the grid cells are measured values of hydraulic conductivity in the outcrop of the model layer, the depth below ground surfaced associated with the grid cell, and the average sand fraction in the aquifer at the grid cell location.

<u>Step 3. Develop a Three-Dimensional Model.</u> **Figure 6-6** shows the process used to construct the three-dimensional model grids by replicating the vertical cross section grids multiple times. With each replication, the width of vertical cross section is expanded by another grid cell until the total width of the three-dimensional groundwater model is 100 miles wide. This procedure maintains the structure, hydraulic properties, and hydraulic boundaries in the original vertical cross sectional model throughout the entire model domain. The lateral expansion of 50 miles on both sides of the original vertical cross section is performed so that the lateral model boundaries are sufficiently far

from the pumping at the well fields in the middle of the model that so that no-flow boundary conditions are justified.

The primary reason to expand the two-dimensional model to a three-dimensional model is to better represent pumping in the model and better simulate drawdown along the dip section that crosses through the well field. A major problem with a two-dimensional vertical cross sectional model is that it cannot simulate radial flow to the well field. A two-dimensional model can only simulate linear flow to the well from the up-dip and down-dip directions. In such a case, one would need to somehow develop a scaling factor to adjust the simulated drawdown from physical unrealistic two-dimensional plane to the three-dimensional aquifer system.

In expanding to three dimensions, the preferred approach would be not to replicate the same cross sectional properties laterally outward but rather to represent the three-dimensional structure of the aquifer. In our situation, the option for expanding laterally outward was constrained by limits of data, time and budget. A limitation associated with the data was that no surfaces for the tops and bottoms for the aquifer of interest were created from the stratigraphic picks in Section 4 for the entire aquifer area in time to be used to develop the groundwater models. A limitation associated with time was that four different three-dimensional models for four PPAs had to be constructed and applied within less than a month. A limitation associated with cost was that the budget allocated for each model construction and application was approximately $10,000.

Given the limitations of the data, time, and budget associated with our model results, we stress that our modeling results should be viewed as preliminary. The authors advocate that more detailed modeling should be performed before specific brackish water projects are considered in GMA 13. The detail modeling should involve a fully three-dimensional model that is supported by aquifer hydraulic properties derived from aquifer tests in the brackish aquifers of interest.

<u>Step 4. Refine Grid Spacing for Placement of Faults and Wells.</u> The three-dimensional model developed in Step 3 consists of grid cells that are 1-mile by 1-mile. In the vicinity of the faults and the well, grid cells were refined. **Figure 6-7** shows examples of grid refinement from a three-dimensional groundwater models developed for PPA #1. In the vicinity of the faults, the 1-mile by 1-mile grid spacing was replaced by a uniform grid spacing of 1/8-mile by 1/8-mile for approximately one mile up dip and approximately one mile down dip of the fault location along the entire width of the model. The grid refinement was performed after the hydraulic properties were assigned to the 1-mile by 1-mile grids in order to preserve as much as possible the granularity of the hydraulic properties extracted from the GAM.

6.2.4 Development of a Geohydrostratigraphic Model for the Carrizo-Wilcox Aquifer

The continuous profiles of sand and clay sequences calculated from in Section 4 provide an excellent basis for developing a geohydrostratigraphic model for the Carrizo-Wilcox Aquifer. For this study, the purpose of a GHSM is to provide transmissive and storage properties for the Carrizo-Wilcox Aquifer that are reasonable, defensible, and also independent and separate from the existing Southern QCSP GAM. The process of building a GHSM involves developing relationships among the different geologic data sets, such as sand fraction and porosity, which can be used to estimate aquifer properties such as hydraulic conductivity and specific storage. Once this has been accomplished, then the continuous lithology data can be transformed via the GHSM to a continuous set of hydraulic properties.

A simple GHSM that has been commonly used to guide the development of groundwater model is to use sand thickness as an indicator of transmissivity. This practice is often used in developing regional scale groundwater models. More advanced applications of GHSM consider other factors besides sand thickness, such as porosity, depositional environment, depth, and temperature. Examples of GHSM that have been used to guide the development of groundwater models in Texas include: a groundwater transport models for Former Kelly Air Force Base in Bexar County (Young and others, 2003), water availability models for the Catahoula formation in Montgomery County , (LGB Guyton and INTERA, 2012); the Lower Colorado River Basin model in the Central Texas Gulf Coast (Young and Kelley, 2006; Young and others, 2009); and groundwater availability models for the Yegua-Jackson Aquifer (Deeds and others, 2010); Central Queen City/Sparta GAM (Dutton and others, 2003), the Southern Queen City/Sparta (Deeds and others, 2003), and the Northern Trinity and Woodbine Aquifers (Kelley and others, 2014).

6.2.4.1 Spatial Patterns in the Sand Fraction

Figures 6-8 through **6-9** show the sand fraction for the grid cells that represent the Carrizo-upper Wilcox (model layer 5), the middle Wilcox (model layer 6), and the lower Wilcox (model layers 7, 8, and 9) for the groundwater models for PPA #1 through #2, respectively. In the up dip region of the aquifers, the average sand fractions are about 0.80, 0.35, and 0.55 for the Carrizo-upper Wilcox Aquifer, the middle Wilcox, and the lower Wilcox aquifers, respectively. Where in the down dip region of the aquifers, the average sand fractions are about 0.35, 0.05, and 0.05 for the Carrizo-upper Wilcox Aquifer, the middle Wilcox, and the lower Wilcox aquifers, respectively. All four figures show that the middle Wilcox has significantly less sand than the other two aquifers and has sufficient clay across most of its extent to act as a hydrogeological barrier.

6.2.4.2 Calculation of Equivalent Horizontal and Vertical Hydraulic Conductivity for a Model Layer

For this study, the GHSM will estimate the horizontal and vertical hydraulic conductivity for a model layer based on the assumption of one-dimension flow through uniform layered media. For this condition, the equivalent horizontal and vertical hydraulic conductivity values (Kx and Kz, respectively) can be obtained using basic averaging equations (Maliva, 2016; Freeze and Cherry, 1979; Domenico and Schwartz, 1990). The equivalent horizontal hydraulic conductivity is the weighted arithmetic mean of the horizontal hydraulic conductivity of the individual layers that is weighted by layer thicknesses. The equivalent vertical hydraulic conductivity is the weighted harmonic mean of the vertical hydraulic conductivity of the individual layers that is weighted by layer thicknesses. **Figure 6-10** is a schematic showing the calculation of a weighted arithmetic average and of a weighted harmonic average to calculate equivalent horizontal and vertical hydraulic conductivities based on one-dimensional vertical flow through layered media. For an aquifer consisting of a sand and clay layers, **Equation 6-1** calculates the arithmetic average weighted by sand and clay layer thicknesses and **Equation 6-2** calculates the harmonic average weighted by sand and clay layer thicknesses.

$$K_{Heffective} = [(K_{Hs} * D_s) + (K_{Hc} * D_c)]/(D_s + D_c) \quad \text{(Equation 6-1)}$$

$$K_{Zeffective} = (D_s + D_c) / [(D_s/Kz_s) + (D_c/Kz_c)] \quad \text{(Equation 6-2)}$$

where:

$K_{Heffective}$	=	equivalent horizontal hydraulic conductivity for the media
$Kz_{effective}$	=	equivalent vertical hydraulic conductivity for the media
D_s	=	total thickness of sand
D_c	=	total thickness of clay
K_{Hc}	=	hydraulic conductivity of clay
K_{Hs}	=	hydraulic conductivity of sand
Kz_c	=	vertical hydraulic conductivity of clay
Kz_s	=	vertical hydraulic conductivity of sand

6.2.4.3 Calculation of Horizontal Hydraulic Conductivity for Individual for Layers

The application of Equation 6-1 to calculate an equivalent horizontal hydraulic conductivity value is, for all practical purposes, determined by the hydraulic conductivity of the sandy layers. As long as the clay layers are at least 100 times less permeable than the sands, then the actual permeability of the horizontal clay layers will have only a negligible impact on the calculation of equivalent horizontal hydraulic conductivity. The GHSM for the Carrizo-Wilcox Aquifer presumes that the hydraulic conductivity of the clay can be ignored in the application of Equation 6-1. The GHSM uses **Equation 6-3** to assign a horizontal hydraulic conductivity value to a sand bed. In using Equation 6-3, the GHSM is assuming that in the shallow regions of the Carrizo-Wilcox outcrop, the sands have similar hydraulic conductivity values, and these values change as a function of depth because of changes in porosity and temperature.

$$K_{Hlayer} = K_{baseline} * A_{porosity} * A_{temperature} * \quad \text{(Equation 6-3)}$$

where

K_{Hlayer}	=	horizontal hydraulic conductivity of the layer
$K_{baseline}$	=	baseline value of horizontal hydraulic conductivity based on field data
$A_{porosity}$	=	adjustments to account for the relationship between permeability and porosity based on Dutton and Loucks (2014)
$A_{temperature}$	=	adjustments to account for the change in the viscosity and density of water with depth

Table 6-7 lists the hydraulic conductivity baseline value used by Equation 6-3 for Model Layers 5 through 9. The baseline values represent the median value of the hydraulic conductivity values assembled by Deeds and others (2003) from well tests primarily performed in the outcrop of the Carrizo-Wilcox Aquifer. Table 6-7 lists a hydraulic conductivity value of about 30 feet per day

(ft/day) for the Carrizo-upper Wilcox aquifer and values between 4 and 8 ft/day for the middle and lower Wilcox aquifers.

Figure 6-11 shows the relationship used by the GHSM to adjust hydraulic conductivity with depth to account for a reduction in porosity with depth. The relationship shown in Figure 6-11 was developed by combining the information in **Figures 5-3** and **6-12**. Figure 5-3 shows the data developed in Section 4 to express porosity as a function of depth. Figure 6-12 shows a relationship between relative hydraulic conductivity and porosity that was developed from porosity and permeability data assembled by Dutton and Loucks (2014) in the Wilcox aquifer in south Texas. The relationship in Figure 6-12 is used by the GHSM.

Table 6-7. Baseline hydraulic conductivity values used for the Carrizo-upper Wilcox, middle Wilcox, and lower Wilcox aquifers by the Geohydrostratigraphic model.

Aquifer	Model Layer (s)	Number of Hydraulic Conductivity Measurements *	Median Value Used to Represent the Baseline Hydraulic Conductivity of Sand
Carrizo-upper Wilcox	5	626	30.5 ft/day
Middle Wilcox	6	217	8 ft/day
Lower Wilcox	7,8,9	17	4.5 ft/day

*Measurements are from Deeds and others (2003)

Equation 6-3 includes a temperature adjustment because hydraulic conductivity is a function of the density and viscosity of water, which are temperature dependent. **Equation 6-4** (Freeze and Cherry, 1979) shows how hydraulic conductivity is dependent on the density and viscosity of water. **Figure 6-13** shows how hydraulic conductivity will increase with increases in temperature from 32 degrees Fahrenheit (°F) to 180°F. This increase occurs primarily because the dynamic viscosity of water decreases with increases in temperature. The GHSM assumed that at shallow groundwater at GMA 13 is at 77°F (Gass, 1982; PRISM Climate Group, 2013) and a geothermal gradient of about 20°F per 1,000 ft (Blackwell and others, 2011). These conditions lead to an increase in the hydraulic conductivity of approximately 140% per 5,000 feet of depth, or approximately 0.03% per one foot of depth.

$$K = k * \rho * g/\mu \qquad \text{(Equation 6-4)}$$

where

- K = hydraulic conductivity of media (L/T)
- k = intrinsic permeability of media (L^2)
- ρ = density of fluid (M/L^3)
- g = gravitational constant (980.6 cm/s^2)
- μ = dynamic viscosity of fluid (M/[L*T])

6.2.4.4 Calculation of Vertical Hydraulic Conductivity for Individual for Layers

The GHSM determines the vertical hydraulic conductivity of a sand layer by dividing the horizontal hydraulic conductivity of the sand layer by 10. The value of 10 is the upper range for ratio of horizontal to vertical hydraulic conductivity provided by Freeze and Cherry (1979) for a single deposit. The high value of 10 is used because in a modeled aquifer layer several different sand deposits will be combined and thereby increase the heterogeneity of the deposit, which will increase the vertical anisotropy.

For the clay deposits, the GHSM uses hydraulic conductivity of 0.028 ft/day (0.00001 centimeter per second [cm/s]). The value of clay is based on the large amount of measured (Gabrysch and Bonnet, 1974) and modeled (Fugro, 2013; Williamson and others, 1990) values for marine clays in the Texas Gulf Coast Aquifer System. For clay deposits with average high percentage of clay, the measured or assigned hydraulic conductivity values are less than 0.0028 ft/day (0.0000001 cm/s). We have assumed that the majority the clay deposits identified on the geophysical logs are not predominately clay and are better characterized as fine grain sediment with moderate amounts of clay. To represent the vertical hydraulic conductivity of these fine-grained deposits, we have selected a vertical hydraulic conductivity that is consistent with values provided by Williamson and others (1990) for fine-grained deposits and by Freeze and Cherry (1979) for silts. The hydraulic conductivity values from Williamson and others (1990) are those used for the more permeable fine-grained deposits modeled in the USGS Regional Aquifer-System Analysis Groundwater model of South Central United States. In the USGS, the vertical hydraulic conductivity values ranged from 0.05 ft/day to 0.0001 ft/day.

6.2.4.5 Calculation of Specific Storage for a Model Layer

The GHSM uses the model of Shestakov (2002) to estimate specific storage values. Shestakov (2002) postulated a relationship based on geomechanical considerations as follows:

$$Ss = A / [D + Zo] \qquad \text{(Equation 6-5)}$$

where

- Ss = Specific storage (L^{-1})
- D = Depth (L)
- Zo = calibrated parameter
- A = Calibrated parameter, which is a function of [1/(1+e)]
- e = void space, which is defined as e= [θ /(1-θ)], where θ = porosity

Shestakov (2002) showed that “A” in Equation 6-5 varied in the narrow range between 0.00020 to 0.00098 per foot for sandy rocks and between 0.0033 to 0.033 per foot for clayey rocks. Shestakov (2002) also shows that the variable “A” is also a function of the void space such that as the porosity becomes smaller, the specific storage value decreases with all other factors remaining equal. This relationship is consistent with the Jacob Equation (Jacob, 1940) for calculating the specific storage from porosity and the compressibility of water and the rock matrix. The Shestakov model assumes a power-law relationship between porosity and depth, where the decrease is more pronounced at shallower depth than is allowed by a linear relationship between porosity and depth. The power-law relationship is consistent with the Magara (1978) observation that the rate of porosity decrease is fast at shallow depths and slows down with greater burial depth.

Previous application of the Shestakov model for estimating specific storage values include the Northern Trinity and Woodbine GAM (Kelly and others, 2014), the Yegua-Jackson GAM (Deeds and others, 2010), and the Lower-Colorado River Basin Model (Young and others, 2009; Young and Kelley, 2006). These applications have involved a modified version of Equation 6-5 that allows accounting for mixed sands and clay layers and forces a minimal value of specific storage.

The GHSM for the Carrizo-Wilcox Aquifer uses Equation 6-6 to calculate specific storage. In applying Equation 6-6, all the variables are fixed, except for SF, D, and e. The three unfixed variables are dependent on the grid cell location and vary across the model. The values for the fixed variables are based on primarily previous application of the Shestakov model.

$$Ss = Ss_{min} + \{\frac{\mathrm{A1} * [\mathrm{e}/(1+\mathrm{e})] * [\mathrm{SF} + \mathrm{CM} * (1-\mathrm{SF})]}{A2+D}\} \qquad \text{(Equation 6-6)}$$

where

Ss = Specific storage (L^{-1})
Ss_{min} = set to 5.0 E-7 ft^{-1}
A1= calibrated parameter that is set to 0.0025
e = void space that is calculated based on the porosity, θ, which is depth specific
SF = sand fraction that is determined by interpolation of measured sand fractions calculated from geophysical logs
CM = clay multiplier, which is set to 20
A2 = a calibrated parameter that is set to 5
D = depth which is determined by the location of the grid cell (L)

6.2.4.6 Representation of Faults

Our review of the stratigraphy and water quality near the three faults shown in the vertical cross sections in Figures 6-2 and 6-3 indicate the fault offsets are not large enough to notably hinder horizontal flow. The primary impact of the fault on groundwater is for the offsets to cause discontinuities and/or breeches in confining layers. Most of the faults offsets were less than 200 ft. The greatest offset was about 400 ft. To account for this effect, the vertical hydraulic conductivity of the model layers within one-quarter of a mile of fault location was increased.

The basis for adjusting the vertical hydraulic conductivity near the faults is the substantial number of studies that document the importance of fault zones as conduits of vertical fluid migration into ancient sediments (Losh and others, 1999; Mozley and Goodwin, 1995; Anderson and others, 1994; Billeaud and others, 1994; Echols and others, 1994; Zimmerman, 1994; McManus and Hanor, 1993; Esch and Hanor, 1995; Galloway and others, 1986). Evidence indicates that subsurface fluids can migrate vertically into modern sediments via growth faults (Kuecher and Roberts, 2000; Kuecher, 1995a, 1995b; Mitchell-Tapping, 1995; Verberne, 1992; Morgan, 1961). Galloway and others (1986) states that growth-fault zones function as major conduits for large-scale circulation of both ground waters and hydrocarbon fluids within the sedimentary prism.

Based on our interpretation of the reference above, we constructed a relationship between the estimated vertical offset at fault and an increase in vertical conductance between two adjacent grid cells. The relationships presumes a liner-log relationship for offsets between 0 and 1,000 feet with a vertical offset of 1,000 ft increase the vertical conductance by a factor of 100. Application of our relationship to a vertical offset of 200 ft produces an increase in the vertical conductance of 2.5.

6.2.5 Simulated drawdowns from Well Fields Located in Potential Production Area #1

This section describes the construction and application of two groundwater models to simulate the drawdowns that would be created by pumping Potential Production Area #1 at two hypothetical well fields.

6.2.5.1 Construction of Groundwater Models based on GAM and GHSM properties

The two groundwater models constructed to simulate pumping from PPA #1 are three-dimensional models with the same model layers and vertical grid discretization as shown in Figure 6-2. The width of the two models is along the geologic strike for the Carrizo-Wilcox Aquifer and is 100 miles. The length of the two models along dip is 71 miles. The recharge rate applied to the outcrop was a uniform 1.5 inches per year. Across the outcrop drains cells were set with drain elevations about 50 feet below ground surface. The net effect of the combination of recharge cells and the drain cells was to create a water table that was near the ground surface. Over 70% of the recharge exited the model through drain cells so that net recharge that occurred in the outcrop was several tenths of inch.

Table 6-8 provides the average values for horizontal hydraulic conductivity (Kx), vertical hydraulic conductivity (Kz), and specific storage (Ss) for 15-mile reaches for both models. The model properties extracted from the Southern QCSP GAM and assigned to model layers 1 to 9. The values for vertical hydraulic conductivity (Kz) were determined by imposing ratio of Kx/Kz of 1,000 for all model layers except for the model layers that represent the Reklaw formation and the middle Wilcox Aquifer. The ratio of Kx/Kz for these two model layers was 10,000. In addition, adjustments to the Kx/Kz ratios for the middle Wilcox were made based on the degree of confinement provided by the clay layers contained within the middle Wilcox and present on geophysical logs. These adjustments allow the Kx/Kz ratio to vary between 1,000 and 100,000. Table 6-8 also provides the values for Kx, Kz, and Ss that were produced by the GHSM for model Layers 5 to 9.

Figures 6-14 and **6-15** shows the Kx values along a vertical cross section for the GAM-based and the GHSM-based models. The average value for Kx of these model layers were used to create Table 6-8. The Kx for model layers 1 through 4 are the same for both models and these values are only shown in Figure 6-14. The two models have comparable Kx values for the Carrizo-upper Wilcox, but the GHSM-model has much lower Kx values for the lower Wilcox at large depths. Among the most notable difference between the two sets of hydraulic properties for the Carrizo-Wilcox Aquifer is that the vertical hydraulic conductivity values and the specific storage values are significantly lower for the GAM-based properties than the GHSM-based properties.

6.2.5.2 Simulated Drawdown Produced by Pumping from Potential Production Area #1

Groundwater pumping at the rate of 5,000, 15,000 and 30,000 AFY was simulated at two well fields in PPA #1 shown in Figure 6-1. Both well fields pump model layer 8, which represents the middle third of the lower Wilcox Aquifer. The up dip well field #1 is located 32 miles down dip from the outcrop, and the down dip well field #2 is located 41 miles down dip from the outcrop. **Figures 6-16** and **6-17** show the simulated drawdown at 50 years for the three pumping rates at Well Field #1 and Well Field #2, respectively, by the groundwater model with the GAM-based hydraulic properties for the Carrizo-Wilcox aquifer. **Figures 6-18** and **6-19** show the simulated drawdown at 50 years for the three pumping rates at Well Field #1 and Well Field #2, respectively, by the groundwater model with the GHSM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

Among the notable results that can be observed in the plotted drawdown in Figures 6-16 to 6-19 are the following:

- The Reklaw provides as an effective hydraulic barrier that prevents appreciable drawdowns from migrating from the Carrizo-Wilcox Aquifer into the Queen City Aquifer
- The drawdown predicted in the Carrizo-Wilcox Aquifer outcrop is significantly higher from pumping Well Field #1 than from pumping Well Field #2
- There is less predicted drawdown in down-dip of the well field in the Carrizo-Wilcox Aquifer from the GHSM-based model than in the GAM-based model
- The GHSM-based model shows more widespread drawdown in the Carrizo Formation than does the GAM-based model

To help to quantify the drawdown in areas of interest and at time of interest, drawdown values were recorded for all four model simulations at several monitoring locations at 30 and 50 years. The monitoring locations are located at down dip distances of 2.5, 5.5, 10.5, 15.5, and 30.5 miles. Table 6-9 provides the elevations and depths associated with these five monitoring locations.

Table 6-8. **Average values for Kx (ft per day), Kz (feet per day), and Ss (1/ foot) by model layer for 15-mile reaches along dip for the groundwater models for PPA # 1.**

Common to Both GAM and GHSM based Groundwater Models for Cross section 2

Reach (miles)	Property	Layer 1	Layer 2	Layer 3	Layer 4
0-15	Kx	n/a	n/a	n/a	n/a
	Kz	n/a	n/a	n/a	n/a
	Ss	n/a	n/a	n/a	n/a
15-30	Kx	5.53	1	4.27	1
	Kz	5.5E-03	1.0E-03	4.3E-03	1.0E-04
	Ss	2.1E-05	1.6E-05	3.6E-05	8.6E-06
30-45	Kx	2.7	1.2	1.2	1.0
	Kz	2.7E-03	1.2E-03	1.2E-03	1.0E-04
	Ss	4.2E-06	6.2E-06	4.1E-06	4.8E-06
45-60	Kx	0.2	1.0	0.3	1.0
	Kz	1.8E-04	1.0E-03	2.8E-04	1.0E-04
	Ss	4.1E-06	4.2E-06	2.6E-06	2.9E-06
60-714	Kx	0.0	1.0	0.0	1.0
	Kz	4.6E-06	1.1E-03	2.8E-05	1.1E-04
	Ss	2.8E-06	2.5E-06	2.0E-06	1.8E-06

Carrizo-Wilcox Aquifer Properties Extracted from the Southern QCSP GAM

Reach (miles)	Property	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
0-15	Kx	2.3	3.1	7.7	7.7	7.7
	Kz	2.3E-03	7.0E-04	1.9E-02	1.9E-02	1.9E-02
	Ss	3.2E-04	5.2E-05	6.4E-06	3.0E-06	3.0E-06
15-30	Kx	31.84	1.06	3	3	3
	Kz	3.2E-02	1.1E-04	3.0E-03	3.0E-03	3.0E-03
	Ss	5.3E-06	3.0E-06	3.0E-06	3.0E-06	3.0E-06
30-45	Kx	12.9	0.5	2.8	2.8	2.8
	Kz	1.3E-02	2.1E-05	2.8E-03	2.8E-03	2.8E-03
	Ss	2.6E-06	3.0E-06	3.0E-06	3.0E-06	3.0E-06
45-60	Kx	10.2	0.3	1.0	1.0	1.0
	Kz	1.0E-02	9.4E-06	1.0E-03	1.0E-03	1.0E-03
	Ss	1.5E-06	3.0E-06	3.0E-06	3.0E-06	3.0E-06
60-71	Kx	2.0	0.4	1.0	1.0	1.0
	Kz	2.1E-03	5.8E-06	1.1E-03	1.1E-03	1.1E-03
	Ss	2.0E-06	3.0E-06	3.0E-06	3.0E-06	3.0E-06

Carrizo-Wilcox Aquifer Properties Developed from the Geohydrostratigraphic Model (GHSM)

Reach (miles)	Property	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
0-15	Kx	30.1	4.0	3.8	3.8	3.7
	Kz	5.0E-03	1.5E-03	5.7E-03	5.5E-03	5.5E-03
	Ss	3.7E-01	3.7E-01	3.6E-01	3.6E-01	3.6E-01
15-30	Kx	26.0	2.7	2.7	2.5	2.3
	Kz	4.7E-03	1.1E-03	1.4E-03	1.3E-03	1.3E-03
	Ss	3.5E-01	3.3E-01	3.3E-01	3.2E-01	3.1E-01
30-45	Kx	16.7	1.1	1.4	1.2	1.1
	Kz	2.2E-03	5.9E-04	7.5E-04	6.6E-04	5.7E-04
	Ss	3.2E-01	3.0E-01	2.9E-01	2.8E-01	2.7E-01
45-60	Kx	7.7	0.4	0.2	0.1	0.1
	Kz	9.2E-04	2.4E-04	1.8E-04	1.5E-04	1.2E-04
	Ss	2.7E-01	2.5E-01	2.4E-01	2.3E-01	2.2E-01
60-71	Kx	2.3	0.0	0.0	0.0	0.0
	Kz	2.6E-04	8.0E-05	4.9E-05	3.6E-05	2.6E-05
	Ss	2.3E-01	2.1E-01	1.9E-01	1.8E-01	1.7E-01

Table 6-9. Locations where drawdowns were monitored for the simulated pumping at Well Field #1 and Well Field #2 in Potential Production Area #1.

Monitoring Location (miles)	Ground Surface (ft, msl)	Vertical Boundary	Carrizo-upper Wilcox	Middle Wilcox	Lower Wilcox		
			Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
2.5	740.8	Top			740.8	570.6	550.3
		Bottom			570.6	550.3	529.3
5.5	675.4	Top		675.4	469.3	267.3	222.5
		Bottom		469.3	267.3	222.5	176.5
10.5	743.9	Top	743.9	649.6	-30.7	-225.4	-309.8
		Bottom	649.6	-30.7	-225.4	-309.8	-396.7
15.5	621.6	Top	621.6	11.4	-532.5	-719.9	-844.1
		Bottom	11.4	-532.5	-719.9	-844.1	-972
30.5	459.9	Top	-910.8	-1783.8	-2348.6	-2702.8	-3056.9
		Bottom	-1783.8	-2348.6	-2702.8	-3056.9	-3421.8

6.2.5.1.1 Simulated Drawdown from the Groundwater Model with GAM-based Properties for the Carrizo-Wilcox Aquifer

Tables 6-10 and **6-11** provide drawdown at 30 and 50 years at the monitoring locations listed in Table 6-9 for pumping at 5,000, 15,000, and 30,000 acre-feet as determined by the groundwater model that uses GAM-based properties for the Carrizo-Wilcox Aquifer. **Figures 6-20** to **6-21** show the simulated drawdown along the center dip line of the groundwater model at elapsed times of 5, 10, 30, and 50 years for pumping Well Field #1 at 15,000 AFY. **Figures 6-22** to **6-23** shows the simulated drawdown along the center dip line of the groundwater model at elapsed times of 5, 10, 30, and 50 years for pumping Well Field #2 at 15,000 AFY.

Among the notable results that can be gleaned from a review of Tables 6-20 and 6-21 and Figures 6-20 through 6-23 are the following:

- Except for a small area near the model up-dip boundary at the outcrop, the model exhibits a linear response between increase pumping and increase aquifer drawdown at the monitoring locations after 30 years of pumping.
- After 30 years pumping 15,000 AFY from Well Field #1, the groundwater model predicts about 13 feet of drawdown in the lower Wilcox at the 2.5 mile monitoring point location and about 15 feet in the lower Wilcox at the 5.5 mile monitoring point location
- After 30 years pumping 15,000 AFY from Well Field #2, the groundwater model predicts about 10 feet of drawdown in the lower Wilcox at the 2.5 mile monitoring point location and about 12 feet in the lower Wilcox at the 5.5 mile monitoring point location
- After 30 years of pumping 15,000 AFY, the groundwater model predicts about 400 ft of drawdown at the Well Field #1

- After 30 years of pumping 15,000 AFY, the groundwater model predicts about 400 ft of drawdown at the Well Field #2
- After 30 years of pumping 15,000 AFY the drawdown, the groundwater model predicts less than 1 foot of across the entire Carrizo Aquifer for pumping the lower Wilcox at either Well Field #1 or Well Field #2

6.2.5.1.2 Simulated Drawdown from the Groundwater Model with GHSM-based Properties for the Carrizo-Wilcox Aquifer

Tables 6-12 and **6-13** provide drawdown at 30 and 50 years at the monitoring locations listed in Table 6-9 for pumping at 5,000, 15,000, and 30,000 years as determined by the groundwater model that uses GHSM-based properties for the Carrizo-Wilcox Aquifer. **Figures 6-24** to **6-25** shows the simulated drawdown along the center dip line of the groundwater model elapsed times of 5, 10, 30, and 50 years for pumping Well Field #1 at 15,000 AFY. **Figures 6-26** to **6-27** shows the simulated drawdown along the center dip line of the groundwater model at elapsed times of 5, 10, 30, and 50 years for pumping Well Field #2 at 15,000 AFY.

Among the notable results that can be gleaned from a review of Tables 6-12 and 6-13 and Figures 6-24 through 6-27 are the following:

- Except for a small area near the model up-dip boundary at the outcrop, the model exhibits a linear response between increase pumping and increase aquifer drawdown at the monitoring locations after 30 years of pumping.
- After 30 years pumping 15,000 AFY from Well Field #1 the groundwater model predicts about 5 of drawdown in the lower Wilcox at the 2.5 mile monitoring point location and about 8 feet in the lower Wilcox at the 5.5 mile monitoring point location
- After 30 years pumping 15,000 AFY from Well Field #2 the groundwater model predicts about 2 feet of drawdown in the lower Wilcox at the 2.5 mile monitoring point location and about 4 to 5 feet in the lower Wilcox at the 5.5 -mile monitoring point location
- After 30 years of pumping 15,000 AFY, the groundwater model predicts about 500 ft of drawdown at the Well Field #1
- After 30 years of pumping 15,000 AFY, the groundwater model predicts about 800 ft of drawdown at the Well Field #2
- After 30 years of pumping 15,000 AFY the drawdown, the groundwater model predicts a maximum of about 3 ft of drawdown in the Carrizo-upper Wilcox Aquifer above the location of the pumping wells in the lower Wilcox for both Well Field #1 and #2.

Table 6-10. Simulated drawdown at monitoring locations after pumping Well Field #1 in PPA #1 for 30 years and 50 years, as determined by the groundwater model using GAM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

Monitoring Location (miles)	Pumping Rate (AFY)	Carrizo-upper Wilcox	Middle Wilcox	Lower Wilcox		
		Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
30 Years						
2.5	5,000	Not Present	Not Present	4.5	4.6	4.6
	15,000	Not Present	Not Present	13.6	13.7	13.7
	30,000	Not Present	Not Present	27.1	27.5	27.5
5.5	5,000	Not Present	0.3	5.2	5.1	5.2
	15,000	Not Present	0.8	15.7	15.2	15.6
	30,000	Not Present	1.6	31.4	30.5	31.2
10.5	5,000	0.0	0.2	7.4	7.1	6.7
	15,000	0.0	0.5	22.1	21.1	20.0
	30,000	0.0	1.1	44.2	42.3	40.0
15.5	5,000	0.0	0.6	10.6	12.0	11.0
	15,000	0.0	1.8	31.7	35.8	32.9
	30,000	0.1	3.6	63.3	71.8	65.7
30.5	5,000	0.1	1.2	45.3	84.8	36.5
	15,000	0.2	3.6	136.1	249.3	108.7
	30,000	0.4	7.1	265.2	448.8	212.3
50 Years						
2.5	5,000	Not Present	Not Present	7.3	7.4	7.4
	15,000	Not Present	Not Present	22.0	22.2	22.2
	30,000	Not Present	Not Present	44.0	44.4	44.4
5.5	5,000	Not Present	0.5	7.9	7.9	8.0
	15,000	Not Present	1.6	23.7	23.7	24.0
	30,000	Not Present	3.2	47.4	47.3	48.0
10.5	5,000	0.0	0.3	10.1	9.9	9.5
	15,000	0.0	1.0	30.2	29.6	28.5
	30,000	0.0	2.0	60.5	59.3	57.1
15.5	5,000	0.0	0.9	13.4	15.0	14.0
	15,000	0.0	2.6	40.3	44.8	42.0
	30,000	0.1	5.2	80.5	89.8	83.9
30.5	5,000	0.1	1.5	49.2	88.7	40.6
	15,000	0.3	4.5	147.8	261.0	120.8
	30,000	0.6	9.0	288.6	472.3	236.5

Table 6-11. **Simulated drawdown at monitoring locations after pumping Well Field #2 in PPA #1 for 30 years and 50 years, as determined by the groundwater model using GAM-based hydraulic properties for the Carrizo-Wilcox Aquifer.**

Monitoring Location (miles)	Pumping Rate (AFY)	Carrizo-upper Wilcox	Middle Wilcox	Lower Wilcox		
		Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
30 Years						
2.5	5,000	Not Present	Not Present	3.4	3.4	3.4
	15,000	Not Present	Not Present	10.1	10.1	10.1
	30,000	Not Present	Not Present	20.1	20.1	20.1
5.5	5,000	Not Present	0.2	4.1	3.9	3.9
	15,000	Not Present	0.5	12.2	11.8	11.7
	30,000	Not Present	1.0	24.2	23.6	23.2
10.5	5,000	0.0	0.2	5.7	5.0	5.0
	15,000	0.0	0.5	17.0	15.1	14.8
	30,000	0.0	1.0	33.9	30.0	29.6
15.5	5,000	0.0	0.5	9.0	8.6	8.2
	15,000	0.0	1.4	26.9	25.6	24.7
	30,000	0.0	2.9	53.7	51.1	49.2
30.5	5,000	0.1	0.9	34.9	31.3	23.2
	15,000	0.2	2.8	104.8	93.7	69.3
	30,000	0.3	5.6	208.2	186.6	137.8
50 Years						
2.5	5,000	Not Present	Not Present	5.9	5.9	5.9
	15,000	Not Present	Not Present	17.7	17.7	17.7
	30,000	Not Present	Not Present	35.4	35.4	35.4
5.5	5,000	Not Present	0.4	6.5	6.5	6.5
	15,000	Not Present	1.2	19.5	19.6	19.4
	30,000	Not Present	2.4	39.0	39.0	38.7
10.5	5,000	0.0	0.3	8.2	7.7	7.6
	15,000	0.0	0.9	24.7	23.0	22.8
	30,000	0.0	1.9	49.3	45.9	45.5
15.5	5,000	0.0	0.7	11.8	11.5	11.2
	15,000	0.0	2.2	35.5	34.5	33.7
	30,000	0.0	4.4	70.8	68.7	67.2
30.5	5,000	0.1	1.3	39.2	35.6	27.7
	15,000	0.3	3.8	117.7	106.7	82.7
	30,000	0.5	7.5	234.1	212.4	164.6

Table 6-12. Simulated drawdown at monitoring locations after pumping Well Field #1 in PPA #1 for 30 years and 50 years, as determined by the groundwater model using GHSM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

Monitoring Location (miles)	Pumping Rate (AFY)	Carrizo-upper Wilcox	Middle Wilcox	Lower Wilcox		
		Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
30 Years						
2.5	5,000	Not Present	Not Present	1.35	1.57	1.57
	15,000	Not Present	Not Present	4.64	5.22	5.22
	30,000	Not Present	Not Present	11.10	11.97	11.98
5.5	5,000	Not Present	0.07	2.71	2.55	2.83
	15,000	Not Present	0.20	8.46	8.08	8.87
	30,000	Not Present	0.41	17.89	17.47	19.00
10.5	5,000	0.01	0.21	6.75	7.54	5.92
	15,000	0.04	0.64	20.39	22.77	17.87
	30,000	0.09	1.27	41.04	46.50	36.57
15.5	5,000	0.06	0.75	10.13	13.64	10.20
	15,000	0.17	2.26	30.53	40.83	30.45
	30,000	0.34	4.47	61.02	82.53	61.35
30.5	5,000	0.69	2.28	46.65	129.65	34.45
	15,000	2.11	6.92	140.87	378.76	101.97
	30,000	4.12	13.51	273.64	678.23	198.34
50 Years						
2.5	5,000	Not Present	Not Present	2.30	2.66	2.66
	15,000	Not Present	Not Present	10.25	10.87	10.87
	30,000	Not Present	Not Present	24.22	25.18	25.19
5.5	5,000	Not Present	0.16	4.11	3.84	4.19
	15,000	Not Present	0.52	14.41	14.00	14.92
	30,000	Not Present	1.09	31.45	31.17	32.91
10.5	5,000	0.05	0.39	8.91	9.62	7.95
	15,000	0.14	1.18	27.83	30.32	25.31
	30,000	0.28	2.37	57.15	63.09	53.02
15.5	5,000	0.1	1.2	12.8	16.4	13.1
	15,000	0.3	3.8	40.7	58.4	49.1
	30,000	0.6	7.4	79.3	102.2	81.5
30.5	5,000	0.11	1.23	12.77	16.41	13.06
	15,000	0.32	3.72	39.17	50.06	39.90
	30,000	0.63	7.43	79.31	102.19	81.48

Table 6-13. Simulated drawdown at monitoring locations after pumping Well Field #2 in PPA #1 for 30 years and 50 years, as determined by the groundwater model using GHSM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

Monitoring Location (miles)	Pumping Rate (AFY)	Carrizo-upper Wilcox	Middle Wilcox	Lower Wilcox		
		Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
30 Years						
2.5	5,000	Not Present	Not Present	0.72	0.74	0.74
	15,000	Not Present	Not Present	2.14	2.22	2.22
	30,000	Not Present	Not Present	4.67	4.75	4.75
5.5	5,000	Not Present	0.03	1.72	1.48	1.37
	15,000	Not Present	0.10	5.15	4.45	4.11
	30,000	Not Present	0.20	10.35	9.07	8.40
10.5	5,000	0.01	0.19	4.35	3.23	2.70
	15,000	0.03	0.58	12.96	9.67	8.09
	30,000	0.07	1.14	25.72	19.37	16.19
15.5	5,000	0.03	0.53	7.51	6.36	4.62
	15,000	0.10	1.56	22.40	19.04	13.79
	30,000	0.19	3.08	44.37	37.96	27.45
30.5	5,000	0.03	0.53	7.51	6.36	4.62
	15,000	0.10	1.56	22.40	19.04	13.79
	30,000	0.19	3.08	44.37	37.96	27.45
50 Years						
2.5	5,000	Not Present	Not Present	0.03	0.53	7.51
	15,000	Not Present	Not Present	0.10	1.56	22.40
	30,000	Not Present	Not Present	0.19	3.08	44.37
5.5	5,000	Not Present	0.10	2.99	2.64	2.50
	15,000	Not Present	0.31	9.37	8.49	8.06
	30,000	Not Present	0.63	20.15	18.72	17.87
10.5	5,000	0.04	0.40	6.50	5.07	4.56
	15,000	0.13	1.21	19.65	15.56	13.99
	30,000	0.25	2.40	39.92	32.34	29.12
15.5	5,000	0.07	1.00	10.49	9.24	7.42
	15,000	0.22	2.98	31.47	27.88	22.36
	30,000	0.43	5.91	63.11	56.45	45.32
30.5	5,000	1.16	2.90	43.87	38.16	19.59
	15,000	3.44	8.64	131.06	114.62	58.41
	30,000	6.76	17.03	259.50	228.53	116.11

6.2.5.3 Sensitivity Analysis on the Simulated Drawdown for Potential Production Area #1

Table 6-2 describes the changes in the model input parameter associated with set of sixteen sensitivity runs performed for the groundwater model's simulations involving GAM-based and the GHSM-based aquifer properties. In this section, Model Run 0 refers to the baseline run of 15,000 AF for which simulated drawdowns are shown in Figures 6-20 to 6-24. **Tables 6-14** and **6-15** provide the sensitivity results for drawdowns at five monitoring locations at 30 and 50 years for the well fields #1 and #2 determined by the GAM-based groundwater model. **Tables 6-16** and **6-17** provide the sensitivity results for drawdowns at five monitoring locations at 30 and 50 years for the well fields #1 and #2 determined by the GHSM-based groundwater model.

Among the notable results that can be gleaned from a review of **Tables 6-14** through **6-17** are:

- After 30 years of pumping the Well Field #1 for 15,000 AFY, the model with GAM-based properties predicts that at the 2.5 mile monitoring location in the lower Wilcox, the drawdown is between 2 and 19 ft.
- After 30 years of pumping the Well Field #1 for 15,000 AFY, the model with GAM-based properties predicts that at the 5.5 mile monitoring location in the lower Wilcox, the drawdown is between 4 and 21 ft.
- After 30 years of pumping the Well Field #2 for 15,000 AFY, the model with GAM-based properties predicts that at the 2.5 mile monitoring location in the lower Wilcox, the drawdown is between 0.6 and 16 ft.
- After 30 years of pumping the Well Field #2 for 15,000 AFY, the model with GAM-based properties predicts that at the 5.5 mile monitoring location in the lower Wilcox, the drawdown is between 2 and 18 ft.
- After 30 years of pumping the Well Field #1 for 15,000 AFY, the model with GHSM-based properties predicts that at the 2.5 mile monitoring location in the lower Wilcox, the drawdown is between less than 0.1 and 12 ft.
- After 30 years of pumping the Well Field #1 for 15,000 AFY, the model with GHSM-based properties predicts that at the 5.5 mile monitoring location in the lower Wilcox, the drawdown is between 0.1 and 18 ft.
- After 30 years of pumping the Well Field #2 for 15,000 AFY, the model with GHSM-based properties predicts that at the 2.5 mile monitoring location in the lower Wilcox, the drawdown is between less than 0.1 and 11.0 ft.
- After 30 years of pumping the Well Field #2 for 15,000 AFY, the model with GHSM-based properties predicts that at the 5.5 mile monitoring location in the lower Wilcox, the drawdown between less than 0.1 and 12 ft.

Table 6-14. **Results from a sensitivity analysis of simulated drawdowns caused by pumping 15,000 AFY from Well Field #1 located in PPA #1 at five monitoring locations, as determined by the groundwater model using GAM-based hydraulic properties for the Carrizo-Wilcox Aquifer.**

		30 years					50 years				
		5	6	7	8	9	5	6	7	8	9
Monitoring Location at 2.5 miles	Run 0			13.6	13.7	13.7			22.0	22.2	22.2
	Run 1			18.6	18.8	18.8			28.3	28.6	28.6
	Run 2			7.6	7.7	7.7			13.8	14.0	14.0
	Run 3			8.2	9.0	9.0			10.7	11.8	11.8
	Run 4			10.8	11.0	11.0			16.6	16.8	16.8
	Run 5			4.6	5.5	5.5			9.3	10.3	10.3
	Run 6			14.3	14.4	14.4			21.6	21.7	21.7
	Run 7			13.6	13.7	13.7			22.0	22.2	22.2
	Run 8			7.4	7.9	7.9			10.0	10.7	10.7
	Run 9			8.0	8.1	8.1			11.9	12.0	12.0
	Run 10			6.6	7.0	7.0			8.6	9.2	9.2
	Run 11			14.4	14.5	14.5			19.7	19.8	19.8
	Run 12			10.5	11.2	11.2			13.3	13.9	13.9
	Run 13			2.5	2.7	2.7			6.1	6.4	6.4
	Run 14			2.0	2.4	2.4			4.0	4.9	4.9
	Run 15			11.5	12.0	12.0			18.7	19.3	19.3
	Run 16			8.1	9.8	9.8			10.7	12.9	13.0
Monitoring Location at 5.5 miles	Run 0		0.8	15.7	15.2	15.6		1.6	23.7	23.7	24.0
	Run 1		1.1	21.1	20.6	21.1		2.1	30.2	30.3	30.7
	Run 2		0.4	9.1	8.7	8.9		1.0	15.2	15.1	15.3
	Run 3		0.2	12.0	11.0	11.4		0.4	14.8	13.9	14.4
	Run 4		1.6	11.9	12.4	12.6		3.1	17.2	18.2	18.4
	Run 5		0.5	10.7	9.8	10.3		1.2	15.8	15.2	15.7
	Run 6		0.7	15.0	14.9	15.0		1.3	22.1	22.2	22.3
	Run 7		0.8	15.7	15.2	15.6		1.6	23.7	23.7	24.0
	Run 8		0.6	10.6	9.8	10.2		1.0	13.4	12.6	13.0
	Run 9		1.0	8.4	8.5	8.6		1.8	12.1	12.4	12.5
	Run 10		0.1	7.4	7.7	7.5		0.2	9.6	9.9	9.7
	Run 11		2.0	14.8	15.0	15.2		3.1	19.8	20.3	20.5
	Run 12		0.2	11.8	12.1	12.0		0.3	14.5	14.8	14.7
	Run 13		0.4	3.9	4.3	4.4		1.2	7.5	8.5	8.6
	Run 14		0.1	5.8	4.5	5.0		0.2	9.8	8.0	8.6
	Run 15		2.1	14.6	16.5	16.7		4.0	20.6	23.5	23.8
	Run 16		0.4	19.7	16.0	17.4		0.8	23.3	19.7	21.1
Monitoring Location at 10.5 miles	Run 0	0.0	0.5	22.1	21.1	20.0	0.0	1.0	30.2	29.6	28.5
	Run 1	0.0	0.8	28.6	27.5	26.3	0.0	1.3	37.7	37.1	35.9
	Run 2	0.0	0.3	13.7	13.0	12.0	0.0	0.6	20.4	19.8	18.7
	Run 3	0.0	0.2	19.3	18.9	15.5	0.0	0.3	22.8	22.2	18.8
	Run 4	0.0	1.2	18.1	18.0	17.2	0.0	1.9	23.7	23.9	23.1
	Run 5	0.0	0.7	25.7	24.2	22.1	0.0	1.1	33.4	31.8	29.5
	Run 6	0.0	0.5	17.2	17.3	16.2	0.0	1.0	24.2	24.6	23.4
	Run 7	0.0	0.5	22.1	21.1	20.0	0.0	1.0	30.2	29.6	28.5
	Run 8	0.0	0.5	17.8	16.3	15.2	0.0	0.7	21.0	19.6	18.4
	Run 9	0.0	0.8	10.2	10.1	9.8	0.0	1.4	14.1	14.1	13.8
	Run 10	0.0	0.1	9.0	11.1	7.9	0.0	0.1	11.5	13.5	10.3
	Run 11	0.0	1.5	17.3	17.3	16.9	0.0	2.4	22.4	22.6	22.2
	Run 12	0.0	0.2	14.2	16.0	12.9	0.0	0.3	16.9	18.8	15.7
	Run 13	0.0	0.4	10.6	10.8	9.9	0.0	0.9	17.1	17.4	16.2
	Run 14	0.0	0.1	14.1	12.7	10.4	0.0	0.1	22.1	19.6	16.9
	Run 15	0.0	2.7	32.9	33.4	31.2	0.0	3.4	40.0	40.8	38.6
	Run 16	0.0	0.6	43.0	37.5	33.9	0.0	0.8	48.5	42.8	39.0

		30 years					50 years				
		5	6	7	8	9	5	6	7	8	9
Monitoring Location at 15.5 miles	Run 0	0.0	1.8	31.7	35.8	32.9	0.0	2.6	40.3	44.8	42.0
	Run 1	0.1	2.8	39.6	44.1	41.3	0.1	3.6	48.9	53.9	51.1
	Run 2	0.0	0.7	21.0	24.4	21.2	0.0	1.3	28.6	32.4	29.3
	Run 3	0.0	0.6	28.8	39.1	25.7	0.0	0.9	33.1	43.5	30.2
	Run 4	0.1	4.0	27.7	31.2	30.8	0.2	5.4	33.9	37.8	37.4
	Run 5	0.1	4.8	48.9	56.6	55.2	0.2	7.6	60.4	69.5	68.1
	Run 6	0.0	0.7	20.3	23.9	19.4	0.0	1.2	27.4	31.2	26.8
	Run 7	0.0	1.8	31.7	35.8	32.9	0.1	2.6	40.3	44.8	42.0
	Run 8	0.0	1.7	27.8	31.8	28.9	0.0	2.2	31.8	36.0	33.2
	Run 9	0.0	1.0	13.2	14.7	13.7	0.1	1.6	17.2	18.8	17.9
	Run 10	0.0	0.1	11.4	20.1	9.2	0.0	0.2	14.1	22.9	11.8
	Run 11	0.1	2.2	21.1	23.0	22.1	0.2	3.1	26.3	28.3	27.5
	Run 12	0.0	0.3	17.3	26.2	15.4	0.0	0.4	20.0	29.0	18.3
	Run 13	0.1	2.4	23.2	27.8	27.4	0.2	5.5	34.2	40.4	39.9
	Run 14	0.0	0.3	27.5	35.3	26.1	0.0	0.8	40.5	49.3	39.9
	Run 15	0.8	19.1	62.3	72.5	72.0	1.3	22.3	71.1	82.1	81.6
	Run 16	0.0	4.5	74.5	86.1	77.3	0.1	5.6	82.2	94.5	85.9
Monitoring Location at 30.5 miles	Run 0	0.2	3.6	136.1	249.3	108.7	0.3	4.5	147.8	261.0	120.8
	Run 1	0.4	5.1	152.7	265.9	126.4	0.5	6.0	163.6	276.9	137.8
	Run 2	0.1	2.0	110.4	223.7	82.5	0.1	2.7	124.5	237.7	96.5
	Run 3	0.0	1.4	119.1	313.3	73.1	0.0	1.8	128.0	322.0	82.1
	Run 4	1.1	6.6	142.0	202.7	130.8	1.4	7.7	151.9	212.6	141.0
	Run 5	1.6	12.7	354.8	537.0	318.9	2.2	15.9	390.9	573.4	356.3
	Run 6	0.0	1.0	50.9	115.3	35.3	0.0	1.4	58.4	122.9	43.0
	Run 7	0.2	3.6	136.1	249.3	108.7	0.3	4.5	147.8	261.0	120.8
	Run 8	0.2	3.5	134.4	247.6	107.2	0.3	4.3	142.9	256.1	116.3
	Run 9	0.1	1.3	46.8	84.5	37.6	0.1	1.8	51.9	89.6	42.7
	Run 10	0.0	0.2	32.8	130.1	14.8	0.0	0.2	37.2	134.5	18.2
	Run 11	0.3	2.7	60.0	97.8	51.6	0.4	3.3	65.8	103.6	57.6
	Run 12	0.0	0.4	43.8	141.3	25.9	0.0	0.6	46.9	144.5	29.5
	Run 13	3.1	13.5	281.1	369.9	272.5	4.6	17.1	318.4	407.6	310.9
	Run 14	0.1	2.7	242.0	586.0	165.3	0.1	3.9	284.9	628.6	203.0
	Run 15	10.5	29.7	422.5	512.2	416.9	12.0	32.5	442.9	532.8	437.6
	Run 16	0.6	10.5	402.2	745.1	320.1	0.7	12.6	424.3	767.2	343.9

Note: NP = Not Present; 0.0 represents a drawdown that is less than 0.1 foot

Table 6-15. Results from a sensitivity analysis of simulated drawdowns caused by pumping 15,000 AFY from Well Field #2 located in PPA #1 at five monitoring locations, as determined by the groundwater model using GAM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

		30 years					50 years				
		5	6	7	8	9	5	6	7	8	9
Monitoring Location at 2.5 miles	Run 0			10.1	10.1	10.1			17.7	17.7	17.7
	Run 1			15.8	15.8	15.8			25.0	25.0	25.0
	Run 2			4.1	4.1	4.1			9.1	9.1	9.1
	Run 3			6.4	6.6	6.6			8.9	9.4	9.4
	Run 4			8.2	8.2	8.2			13.6	13.6	13.6
	Run 5			2.9	2.9	2.9			5.6	5.7	5.7
	Run 6			12.2	12.2	12.2			19.3	19.3	19.3
	Run 7			10.1	10.1	10.1			17.7	17.7	17.7
	Run 8			5.9	6.0	6.0			8.2	8.3	8.3
	Run 9			6.1	6.1	6.1			9.9	9.9	9.9
	Run 10			4.9	5.0	5.0			7.1	7.3	7.3
	Run 11			13.3	13.3	13.3			18.6	18.7	18.7
	Run 12			9.5	9.9	9.9			12.0	12.3	12.4
	Run 13			0.7	0.7	0.7			2.5	2.5	2.5
	Run 14			0.6	0.6	0.6			1.9	2.0	2.0
	Run 15			8.8	8.8	8.8			15.2	15.2	15.2
	Run 16			6.9	7.3	7.3			9.7	10.3	10.3
Monitoring Location at 5.5 miles	Run 0		0.5	12.2	11.8	11.7		1.2	19.5	19.6	19.4
	Run 1		0.9	18.2	18.0	17.8		1.7	27.0	27.3	27.1
	Run 2		0.2	5.4	5.1	5.0		0.6	10.5	10.3	10.2
	Run 3		0.2	10.2	8.6	8.3		0.3	13.2	11.6	11.3
	Run 4		1.1	9.3	9.8	9.7		2.3	14.3	15.3	15.2
	Run 5		0.3	6.8	6.6	6.4		0.7	10.8	10.9	10.6
	Run 6		0.6	13.2	12.8	12.7		1.1	20.1	19.8	19.7
	Run 7		0.5	12.2	11.8	11.7		1.2	19.5	19.6	19.4
	Run 8		0.4	8.6	8.0	7.9		0.7	11.2	10.7	10.5
	Run 9		0.7	6.5	6.6	6.5		1.4	10.2	10.4	10.3
	Run 10		0.1	6.1	5.7	5.3		0.2	8.4	8.0	7.6
	Run 11		1.7	13.7	14.0	14.0		2.8	18.9	19.4	19.4
	Run 12		0.2	11.2	10.8	10.5		0.3	13.7	13.3	13.0
	Run 13		0.1	1.2	1.4	1.4		0.4	3.4	4.0	3.9
	Run 14		0.0	2.1	1.5	1.4		0.1	5.1	4.0	3.8
	Run 15		1.5	11.7	13.7	13.5		3.2	17.3	20.2	20.1
	Run 16		0.3	16.7	14.3	13.6		0.6	20.7	18.3	17.6
Monitoring Location at 10.5 miles	Run 0	0.0	0.5	17.0	15.1	14.8	0.0	0.9	24.7	23.0	22.8
	Run 1	0.0	0.9	24.3	22.1	22.0	0.0	1.4	33.2	31.4	31.3
	Run 2	0.0	0.2	8.3	6.9	6.6	0.0	0.4	14.1	12.6	12.3
	Run 3	0.0	0.2	16.6	12.1	10.8	0.0	0.3	20.4	15.7	14.3
	Run 4	0.0	1.1	13.6	13.1	13.1	0.0	1.9	19.0	18.8	18.9
	Run 5	0.0	0.6	15.1	13.4	13.3	0.0	1.2	22.3	20.1	20.0
	Run 6	0.0	0.5	15.2	13.9	13.4	0.0	0.9	22.2	21.0	20.5
	Run 7	0.0	0.5	17.0	15.1	14.8	0.0	0.9	24.7	23.0	22.8
	Run 8	0.0	0.5	13.9	11.6	11.4	0.0	0.7	17.2	14.8	14.7
	Run 9	0.0	0.6	7.9	7.5	7.4	0.0	1.1	11.7	11.3	11.3
	Run 10	0.0	0.1	8.0	6.9	5.5	0.0	0.1	10.7	9.4	7.9
	Run 11	0.0	1.4	15.8	15.4	15.4	0.0	2.3	21.0	20.8	20.8
	Run 12	0.0	0.2	14.1	12.6	11.2	0.0	0.3	16.6	15.2	13.8
	Run 13	0.0	0.2	3.2	3.1	3.1	0.0	0.6	7.5	7.4	7.3
	Run 14	0.0	0.0	5.1	3.2	2.7	0.0	0.1	11.1	7.7	6.9
	Run 15	0.0	3.6	24.4	24.1	23.9	0.0	4.7	31.3	31.4	31.2
	Run 16	0.0	0.8	33.8	26.1	25.5	0.0	1.1	39.9	31.6	31.1

		30 years					50 years				
		5	6	7	8	9	5	6	7	8	9
Monitoring Location at 15.5 miles	Run 0	0.0	1.4	26.9	25.6	24.7	0.0	2.2	35.5	34.5	33.7
	Run 1	0.0	2.4	36.4	35.3	34.8	0.0	3.2	45.7	45.0	44.6
	Run 2	0.0	0.4	14.7	13.2	11.8	0.0	0.9	22.1	20.8	19.5
	Run 3	0.0	0.6	28.4	24.2	17.6	0.0	0.8	33.4	29.1	22.6
	Run 4	0.1	3.0	22.8	23.5	24.3	0.1	4.3	29.2	30.2	31.1
	Run 5	0.0	2.5	33.1	33.8	34.7	0.0	4.9	46.1	47.4	49.1
	Run 6	0.0	0.7	19.4	18.1	15.8	0.0	1.1	26.4	25.3	23.1
	Run 7	0.0	1.4	26.9	25.6	24.7	0.0	2.2	35.5	34.5	33.7
	Run 8	0.0	1.4	24.3	22.8	22.0	0.0	1.9	28.8	27.4	26.7
	Run 9	0.0	0.7	11.0	10.7	10.3	0.0	1.3	15.0	14.8	14.5
	Run 10	0.0	0.1	11.6	11.5	6.1	0.0	0.2	14.7	14.6	8.8
	Run 11	0.1	2.0	20.2	20.1	20.0	0.1	3.0	25.5	25.6	25.6
	Run 12	0.0	0.3	19.0	18.9	13.4	0.0	0.4	21.6	21.5	16.2
	Run 13	0.0	0.6	8.4	8.9	9.2	0.0	2.0	17.6	18.7	19.5
	Run 14	0.0	0.1	12.3	9.4	6.4	0.0	0.4	24.0	20.0	15.9
	Run 15	0.2	14.2	52.4	55.4	57.7	0.2	17.6	62.3	65.9	68.4
	Run 16	0.0	3.6	66.2	61.5	58.9	0.0	4.8	76.0	71.4	69.5
Monitoring Location at 30.5 miles	Run 0	0.2	2.8	104.8	93.7	69.3	0.3	3.8	117.7	106.7	82.7
	Run 1	0.3	4.5	124.7	113.6	90.8	0.4	5.4	136.5	125.4	103.2
	Run 2	0.1	1.2	74.2	63.7	39.6	0.1	1.9	90.4	79.5	54.7
	Run 3	0.0	1.3	114.1	101.7	43.7	0.0	1.8	125.2	112.5	53.7
	Run 4	0.8	4.5	92.9	88.5	83.8	1.1	5.7	104.2	99.8	95.5
	Run 5	0.9	6.6	193.6	180.3	162.8	1.5	9.7	236.1	223.0	207.3
	Run 6	0.0	1.0	49.6	45.4	25.5	0.0	1.4	57.3	53.1	33.4
	Run 7	0.2	2.8	104.8	93.7	69.3	0.3	3.8	117.7	106.7	82.7
	Run 8	0.2	2.8	103.6	92.5	68.3	0.2	3.6	113.9	102.8	79.2
	Run 9	0.1	1.0	36.0	32.3	24.1	0.1	1.4	41.4	37.7	29.6
	Run 10	0.0	0.2	37.0	42.4	8.8	0.0	0.3	42.3	47.6	12.1
	Run 11	0.3	2.5	51.3	47.6	40.5	0.4	3.2	57.3	53.7	46.7
	Run 12	0.0	0.5	50.9	56.4	21.2	0.0	0.6	54.2	59.8	25.1
	Run 13	0.9	3.8	90.3	86.8	85.7	1.9	6.4	128.8	125.5	125.8
	Run 14	0.0	1.1	120.4	94.4	42.2	0.1	2.0	167.8	138.2	73.5
	Run 15	7.4	19.0	252.1	249.4	253.3	9.2	22.3	277.0	274.4	278.8
	Run 16	0.5	8.3	310.1	276.6	203.6	0.7	10.6	337.9	304.2	233.3

Note: NP = Not Present; 0.0 represents a drawdown that is less than 0.1 foot

Table 6-16. Results from a sensitivity analysis of simulated drawdowns caused by pumping 15,000 AFY from Well Field #1 located in PPA #1 at five monitoring locations, as determined by the groundwater model using GHSM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

		30 years					50 years				
		5	6	7	8	9	5	6	7	8	9
Monitoring Location at 2.5 miles	Run 0			4.6	5.2	5.2			10.2	10.9	10.9
	Run 1			11.2	11.8	11.8			19.3	19.9	19.9
	Run 2			0.9	1.2	1.2			2.5	3.0	3.0
	Run 3			4.5	5.7	5.8			7.7	9.5	9.5
	Run 4			5.3	5.6	5.6			10.6	10.9	10.9
	Run 5			0.8	1.2	1.2			2.2	3.1	3.1
	Run 6			11.1	11.3	11.3			18.1	18.3	18.4
	Run 7			6.9	7.2	7.2			14.4	14.8	14.8
	Run 8			4.0	4.7	4.7			6.7	7.7	7.7
	Run 9			4.0	4.1	4.1			7.6	7.7	7.7
	Run 10			3.5	4.3	4.3			6.0	7.1	7.1
	Run 11			13.9	14.1	14.1			19.9	20.1	20.1
	Run 12			10.4	11.9	11.9			13.0	14.6	14.6
	Run 13			0.0	0.1	0.1			0.4	0.5	0.5
	Run 14			0.0	0.1	0.1			0.3	0.6	0.6
	Run 15			4.5	4.9	4.9			8.9	9.4	9.4
	Run 16			4.2	6.0	6.0			6.9	9.7	9.7
Monitoring Location at 5.5 miles	Run 0		0.2	8.5	8.1	8.9		0.5	14.4	14.0	14.9
	Run 1		0.5	16.7	15.6	16.8		1.0	24.2	23.6	24.8
	Run 2		0.0	1.7	2.4	2.7		0.1	4.6	5.0	5.5
	Run 3		0.1	8.3	9.6	9.8		0.2	13.4	13.9	14.4
	Run 4		0.5	7.2	7.7	8.1		1.2	12.1	13.1	13.5
	Run 5		0.0	3.8	4.4	5.0		0.2	8.4	8.4	9.4
	Run 6		0.3	12.1	12.5	12.5		0.6	18.9	19.5	19.5
	Run 7		0.2	9.9	9.8	10.6		0.6	17.5	17.6	18.4
	Run 8		0.2	8.1	7.6	8.4		0.4	12.1	11.2	12.2
	Run 9		0.3	4.5	4.8	4.9		0.7	8.1	8.5	8.7
	Run 10		0.0	3.6	6.1	4.9		0.1	6.5	9.1	7.8
	Run 11		1.3	14.8	15.1	15.5		2.1	20.3	21.1	21.4
	Run 12		0.1	12.3	14.4	13.3		0.2	14.9	17.1	16.1
	Run 13		0.0	0.1	0.3	0.3		0.0	0.7	1.3	1.4
	Run 14		0.0	0.1	0.6	0.6		0.0	0.8	2.2	2.4
	Run 15		0.4	8.2	9.7	10.1		0.8	12.2	14.6	15.0
	Run 16		0.1	18.9	15.5	18.3		0.2	26.1	21.2	24.7
Monitoring Location at 10.5 miles	Run 0	0.0	0.6	20.4	22.8	17.9	0.1	1.2	27.8	30.3	25.3
	Run 1	0.1	1.6	32.5	34.4	29.4	0.3	2.1	39.5	42.4	37.4
	Run 2	0.0	0.1	6.8	10.2	6.3	0.0	0.3	12.9	16.1	11.6
	Run 3	0.0	0.2	19.0	32.1	16.1	0.0	0.4	27.4	39.2	22.5
	Run 4	0.2	1.4	16.2	17.9	16.5	0.6	2.4	21.8	24.3	22.8
	Run 5	0.0	0.5	18.3	21.2	17.7	0.1	1.4	30.9	34.0	29.8
	Run 6	0.0	0.4	15.9	20.4	14.6	0.1	0.7	22.5	27.3	21.5
	Run 7	0.1	0.7	21.2	23.9	19.0	0.2	1.5	29.9	33.0	28.1
	Run 8	0.0	0.6	20.3	22.5	17.6	0.1	1.1	26.7	28.5	23.5
	Run 9	0.1	0.4	7.7	9.0	7.4	0.2	0.8	11.4	13.0	11.4
	Run 10	0.0	0.0	4.9	16.4	5.2	0.0	0.1	8.5	20.6	8.3
	Run 11	0.4	1.7	19.1	20.8	19.3	0.7	2.3	24.1	26.5	25.1
	Run 12	0.0	0.2	16.6	28.1	14.9	0.0	0.3	19.4	31.0	17.8
	Run 13	0.0	0.0	1.8	2.5	1.9	0.0	0.2	5.4	7.0	6.0
	Run 14	0.0	0.0	1.8	5.7	1.6	0.0	0.0	6.9	14.8	6.4
	Run 15	0.3	4.5	27.8	32.4	29.6	0.9	6.1	33.8	39.3	36.3
	Run 16	0.0	1.4	58.2	63.2	48.3	0.1	2.3	73.8	77.0	61.7

		30 years					50 years				
		5	6	7	8	9	5	6	7	8	9
Monitoring Location at 15.5 miles	Run 0	0.2	2.3	30.5	40.8	30.4	0.3	3.7	39.2	50.1	39.9
	Run 1	0.4	5.0	45.1	56.2	46.4	0.6	6.1	52.3	64.3	54.9
	Run 2	0.0	0.4	12.6	21.9	12.2	0.1	1.0	20.9	31.0	20.6
	Run 3	0.0	0.7	27.6	59.6	23.9	0.1	1.3	37.9	69.4	32.4
	Run 4	0.7	4.9	25.1	30.5	29.5	1.1	7.3	31.6	37.9	37.2
	Run 5	0.3	3.2	35.3	45.0	40.0	0.6	7.3	53.4	66.0	62.0
	Run 6	0.1	0.9	19.3	30.2	17.6	0.1	1.3	25.8	37.1	24.4
	Run 7	0.2	2.3	31.1	41.6	31.2	0.4	4.0	40.9	52.2	42.0
	Run 8	0.2	2.3	30.4	40.7	30.3	0.3	3.7	38.3	48.9	38.8
	Run 9	0.1	0.8	10.9	14.6	11.1	0.2	1.5	14.8	18.9	15.5
	Run 10	0.0	0.0	6.3	28.7	5.8	0.0	0.1	10.3	34.1	9.0
	Run 11	0.5	3.2	23.1	27.8	24.9	0.8	4.1	28.0	33.3	30.6
	Run 12	0.0	0.4	19.7	43.6	16.9	0.0	0.6	22.6	46.6	20.0
	Run 13	0.2	0.5	6.0	8.1	7.3	0.5	1.9	13.5	17.9	17.2
	Run 14	0.0	0.0	5.9	18.6	5.0	0.0	0.2	16.4	38.0	15.1
	Run 15	2.4	20.2	49.2	60.3	60.8	3.6	25.8	57.4	69.6	70.3
	Run 16	0.2	6.5	89.8	119.8	88.5	0.4	10.3	110.4	140.9	110.4
Monitoring Location at 30.5 miles	Run 0	2.1	6.9	140.9	378.8	102.0	3.0	8.9	156.2	394.7	118.4
	Run 1	4.0	10.8	168.5	407.4	132.9	5.0	12.3	178.0	417.5	144.6
	Run 2	0.8	3.4	101.1	337.4	66.5	1.3	4.9	120.7	358.1	82.8
	Run 3	0.3	2.6	108.5	489.8	59.0	0.5	3.7	127.5	509.4	72.7
	Run 4	7.8	13.8	147.2	283.8	135.7	10.0	16.6	158.4	295.8	149.2
	Run 5	11.6	24.7	353.9	759.2	304.8	16.6	32.2	399.5	808.0	356.8
	Run 6	0.3	1.8	50.1	177.2	31.0	0.5	2.4	57.1	184.5	38.0
	Run 7	2.1	6.9	141.0	378.9	102.1	3.0	8.9	157.0	395.5	119.1
	Run 8	2.1	6.9	140.9	378.7	102.0	3.0	8.8	156.0	394.4	118.1
	Run 9	0.7	2.3	47.2	126.5	34.2	1.1	3.0	52.9	132.4	40.3
	Run 10	0.0	0.2	21.1	196.7	9.4	0.0	0.3	27.5	206.5	12.9
	Run 11	2.3	5.1	64.8	145.0	54.6	2.9	6.0	69.7	150.2	60.3
	Run 12	0.1	1.0	42.4	223.5	24.0	0.1	1.2	45.9	227.4	27.9
	Run 13	16.4	27.2	263.5	477.7	261.5	24.1	36.6	299.6	517.4	304.9
	Run 14	0.6	4.1	185.3	872.7	114.3	1.2	6.5	238.9	945.4	151.3
	Run 15	57.6	74.2	398.4	624.0	421.5	66.9	84.0	417.2	643.7	442.7
	Run 16	6.2	20.8	426.1	1146.8	308.2	8.7	26.4	470.2	1192.2	355.4

Note: NP = Not Present; 0.0 represents a drawdown that is less than 0.1 foot

Table 6-17. Results from a sensitivity analysis of simulated drawdowns caused by pumping 15,000 AFY from Well Field #2 located in PPA #1 at five monitoring locations, as determined by the groundwater model using GHSM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

		30 years					50 years				
		5	6	7	8	9	5	6	7	8	9
Monitoring Location at 2.5 miles	Run 0			2.1	2.2	2.2			5.3	5.4	5.4
	Run 1			7.2	7.2	7.2			13.4	13.4	13.4
	Run 2			0.2	0.2	0.2			0.9	0.9	0.9
	Run 3			2.3	2.4	2.4			5.0	5.4	5.4
	Run 4			2.6	2.6	2.6			6.2	6.2	6.2
	Run 5			0.2	0.3	0.3			1.0	1.0	1.0
	Run 6			7.5	7.4	7.4			13.6	13.6	13.6
	Run 7			3.3	3.3	3.3			8.4	8.4	8.4
	Run 8			2.1	2.2	2.2			4.5	4.6	4.6
	Run 9			1.9	1.9	1.9			4.5	4.5	4.5
	Run 10			1.5	1.7	1.7			3.4	3.8	3.8
	Run 11			11.2	11.2	11.2			16.8	16.8	16.8
	Run 12			8.8	9.5	9.5			11.2	12.2	12.2
	Run 13			0.0	0.0	0.0			0.0	0.0	0.0
	Run 14			0.0	0.0	0.0			0.0	0.0	0.0
	Run 15			2.2	2.2	2.2			5.0	5.0	5.0
	Run 16			2.7	2.9	2.9			5.3	5.8	5.8
Monitoring Location at 5.5 miles	Run 0		0.1	5.1	4.4	4.1		0.3	9.4	8.5	8.1
	Run 1		0.4	12.6	11.4	10.9		0.7	18.7	17.8	17.3
	Run 2		0.0	0.5	0.6	0.5		0.0	2.1	1.9	1.7
	Run 3		0.0	5.9	4.9	3.9		0.1	10.8	9.0	7.7
	Run 4		0.2	3.9	4.4	4.2		0.7	7.6	8.5	8.3
	Run 5		0.0	1.1	1.4	1.3		0.1	3.7	4.2	3.9
	Run 6		0.2	9.2	8.6	8.1		0.5	15.2	14.8	14.2
	Run 7		0.1	5.8	5.3	4.9		0.4	11.6	11.1	10.7
	Run 8		0.1	5.1	4.4	4.1		0.3	8.9	7.9	7.5
	Run 9		0.1	2.4	2.4	2.3		0.4	5.2	5.2	5.1
	Run 10		0.0	2.0	2.9	1.9		0.0	4.5	5.5	4.1
	Run 11		1.0	12.3	12.4	12.3		1.8	17.5	18.0	17.9
	Run 12		0.1	11.7	12.3	10.5		0.2	14.4	15.1	13.2
	Run 13		0.0	0.0	0.0	0.0		0.0	0.1	0.2	0.2
	Run 14		0.0	0.0	0.0	0.0		0.0	0.1	0.2	0.1
	Run 15		0.2	4.4	5.8	5.7		0.5	7.5	9.6	9.4
	Run 16		0.1	13.1	10.2	9.2		0.2	20.9	16.6	15.3
Monitoring Location at 10.5 miles	Run 0	0.0	0.6	13.0	9.7	8.1	0.1	1.2	19.7	15.6	14.0
	Run 1	0.1	1.8	25.3	20.4	19.1	0.3	2.5	31.9	27.4	26.2
	Run 2	0.0	0.0	2.4	1.7	1.0	0.0	0.2	6.4	4.7	3.4
	Run 3	0.0	0.2	14.9	11.2	6.0	0.0	0.5	23.8	17.8	11.3
	Run 4	0.1	1.1	8.7	8.6	8.6	0.4	2.1	13.5	13.8	14.0
	Run 5	0.0	0.2	5.2	4.7	4.1	0.0	0.9	12.6	11.8	11.4
	Run 6	0.0	0.5	13.7	11.6	9.1	0.1	0.8	19.8	17.9	15.2
	Run 7	0.0	0.6	13.3	10.2	8.6	0.2	1.4	21.1	17.6	15.9
	Run 8	0.0	0.6	13.0	9.7	8.1	0.1	1.2	19.4	15.2	13.6
	Run 9	0.1	0.3	4.7	3.9	3.3	0.2	0.6	7.9	7.1	6.5
	Run 10	0.0	0.0	3.9	5.7	1.9	0.0	0.1	7.4	9.4	4.2
	Run 11	0.4	1.7	16.1	15.4	15.0	0.8	2.4	20.9	20.8	20.5
	Run 12	0.0	0.3	17.5	18.4	11.5	0.0	0.4	20.5	21.4	14.5
	Run 13	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.6	0.7	0.7
	Run 14	0.0	0.0	0.2	0.1	0.0	0.0	0.0	1.3	0.8	0.3
	Run 15	0.1	3.5	13.4	15.0	15.5	0.5	5.6	18.9	21.1	21.9
	Run 16	0.0	1.4	37.9	26.9	22.3	0.0	2.8	54.8	40.2	35.8

		30 years					50 years				
		5	6	7	8	9	5	6	7	8	9
Monitoring Location at 15.5 miles	Run 0	0.1	1.6	22.4	19.0	13.8	0.2	3.0	31.5	27.9	22.4
	Run 1	0.3	4.5	39.3	35.7	30.4	0.5	5.7	46.7	43.6	38.6
	Run 2	0.0	0.1	5.8	4.3	2.0	0.0	0.5	12.6	10.1	6.0
	Run 3	0.0	0.6	25.0	22.9	8.9	0.0	1.3	37.2	33.4	16.0
	Run 4	0.3	2.8	15.5	16.1	15.8	0.6	5.0	21.9	23.2	23.4
	Run 5	0.0	0.9	12.9	11.9	9.8	0.2	3.1	26.5	26.2	24.3
	Run 6	0.1	0.9	18.6	17.3	10.7	0.1	1.4	24.9	23.8	16.9
	Run 7	0.1	1.6	22.6	19.4	14.1	0.3	3.1	32.5	29.3	23.7
	Run 8	0.1	1.6	22.4	19.0	13.8	0.2	3.0	31.3	27.7	22.2
	Run 9	0.1	0.6	7.7	6.8	5.0	0.2	1.2	11.5	10.6	8.7
	Run 10	0.0	0.0	6.2	11.1	2.1	0.0	0.1	10.6	16.5	4.4
	Run 11	0.5	3.0	20.9	20.6	19.1	0.8	3.9	25.6	25.9	24.5
	Run 12	0.0	0.5	22.9	29.0	12.9	0.0	0.7	26.2	32.5	16.2
	Run 13	0.0	0.0	0.5	0.5	0.4	0.0	0.2	2.3	2.5	2.4
	Run 14	0.0	0.0	0.9	0.4	0.1	0.0	0.0	4.5	2.9	0.8
	Run 15	0.6	10.6	27.7	31.3	33.1	1.2	16.1	36.9	41.4	43.7
	Run 16	0.1	4.6	66.9	56.2	40.4	0.2	8.4	91.8	79.7	63.2
Monitoring Location at 30.5 miles	Run 0	2.3	6.2	110.7	94.7	41.6	3.4	8.6	131.1	114.6	58.4
	Run 1	4.9	11.3	148.5	132.0	75.7	6.2	13.4	160.7	144.5	89.1
	Run 2	0.6	2.1	60.9	47.9	13.6	1.2	3.7	84.8	69.9	24.7
	Run 3	0.4	2.8	109.9	117.5	22.0	0.7	4.4	136.1	143.5	33.6
	Run 4	6.8	10.2	87.4	79.1	61.2	9.5	13.6	101.6	93.8	77.6
	Run 5	7.1	12.0	155.8	130.0	77.8	##	19.8	208.0	181.6	125.6
	Run 6	0.4	2.2	54.6	56.9	17.2	0.6	2.9	62.5	65.0	23.8
	Run 7	2.3	6.2	110.8	94.7	41.6	3.5	8.7	131.5	115.1	58.8
	Run 8	2.2	6.2	110.7	94.7	41.6	3.4	8.6	131.0	114.6	58.4
	Run 9	0.8	2.1	37.0	31.6	13.9	1.2	2.9	44.1	38.7	19.9
	Run 10	0.0	0.3	25.3	54.6	3.7	0.0	0.5	33.9	67.1	6.2
	Run 11	2.9	5.6	59.4	54.3	36.3	3.6	6.6	64.5	59.7	42.2
	Run 12	0.1	1.4	55.0	92.3	17.4	0.2	1.6	59.5	97.4	21.5
	Run 13	3.6	4.8	44.1	37.4	27.2	8.3	10.4	72.4	65.4	54.9
	Run 14	0.2	1.1	59.7	38.3	6.3	0.6	2.7	109.7	79.1	16.9
	Run 15	##	47.4	178.9	176.7	178.8	##	60.1	203.9	202.8	207.9
	Run 16	6.7	18.6	335.2	286.5	125.7	##	25.9	395.7	345.7	175.6

Note: NP = Not Present; 0.0 represents a drawdown that is less than 0.1 foot

6.2.6 Simulated drawdowns from Well Fields Located in Potential Production Area #2

This section describes the construction and application of two groundwater models to simulate the drawdowns that would be created by pumping Potential Production Area #2 at two proposed well fields.

6.2.6.1 Construction of Groundwater Models based on GAM and GHSM properties

The two three-dimensional groundwater models constructed to simulate pumping from PPA #2 have the same model layers and vertical grid discretization as shown in Figure 6-8. The width of the two models is along the geologic strike for the Carrizo-Wilcox Aquifer and is 100 miles. The length of the two models along dip is 83 miles. The recharge rate applied to the outcrop was a uniform 1.5 inches per year. Across the outcrop drains cells were set with drain elevations about 50 feet below ground surface. The net effect of the combination of recharge cells and the drain cells was to create a water table that was near the ground surface. Over 70% of the recharge exited the model through drain cells so that net recharge that occurred in the outcrop was several tenths of inch.

Table 6-18 provides the average values for horizontal hydraulic conductivity (Kx), vertical hydraulic conductivity (Kz), and specific storage (Ss) for 15-mile reaches for both models. The model properties extracted from the Southern QCSP GAM and assigned to model layers 1 to 9. The values for vertical hydraulic conductivity (Kz) were determined by imposing ratio of Kx/Kz of 1,000 for all model layers except for the model layers that represent the Reklaw formation and the middle Wilcox Aquifer. The ratio of Kx/Kz for these two model layers was 10,000. In addition, adjustments to the Kx/Kz ratios for the middle Wilcox were made based on the degree of confinement provided by the clay layers contained within the middle Wilcox and present on geophysical logs. These adjustments allow the Kx/Kz ratio to vary between 1,000 and 100,000. Table 6-18 also provides the values for Kx, Kz, and Ss that were produced by the GHSM for model Layers 5 to 9.

Figures 6-28 and **6-29** shows the Kx values along a vertical cross section for the GAM-based and the GHSM-based models. The average value for Kx of these model layers were used to create Table 6-18. The Kx for model layers 1 through 4 are the same for both models and these values are only shown in Figure 6-28. Among the most notable difference between the two sets of hydraulic properties for the Carrizo-Wilcox Aquifer is that the vertical hydraulic conductivity values and the specific storage values are significantly lower for the GAM-based properties than for the GHSM-based properties.

6.2.6.2 Simulated Drawdown Produced by Pumping from Potential Production Area #2

Groundwater pumping at the rate of 5,000, 15,000 and 30,000 AFY was simulated at two well fields in PPA #2 shown in Figure 6-1. Both well fields pump model layer 8, which represents the middle third of the lower Wilcox Aquifer. The up dip well field #1 is located 31 miles down dip from the outcrop, and the down dip well field #2 is located 39 miles down dip from the outcrop. **Figures 6-30** and **6-31** show the simulated drawdown at 50 years for the three pumping rates at Well Field #1 and Well Field #2, respectively, by the groundwater model with the GAM-based hydraulic properties for the Carrizo-Wilcox aquifer. **Figures 6-32** and **6-33** show the simulated drawdown at 50 years for the three pumping rates at Well Field #1 and Well Field #2, respectively, by the groundwater model with the GHSM-based hydraulic properties for the Carrizo-Wilcox aquifer.

Among the notable results that can be observed in the plotted drawdown in Figures 6-30 to 6-33 are the following:

- The Reklaw provides as an effective hydraulic barrier that prevents appreciable drawdowns from migrating from the Carrizo-Wilcox Aquifer into the Queen City Aquifer
- The drawdown predicted in the Carrizo-Wilcox Aquifer outcrop is significantly higher from pumping Well Field #1 than from pumping Well Field #2
- There is less predicted drawdown in down-dip of the well field in the Carrizo-Wilcox Aquifer in the GHSM-based model than in the GAM-based model

To help to quantify the drawdown in areas of interest and at time of interest, drawdown values were recorded for all four model simulations at several monitoring locations at 30 and 50 years. The monitoring locations are located at down dip distances of 2.5, 5.5, 10.5, 15.5, and 30.5 miles. Table 6-19 provides the elevations and depths associated with these five monitoring locations.

Table 6-18 Average values for Kx (feet per day), Kz (feet per day), and Ss(1/feet) by model layer for 15-mile reaches along dip for the groundwater models for PPA # 2

Common to Both GAM and GHSM based Groundwater Models for Cross section 3

Distance (miles)	Property	Layer 1	Layer 2	Layer 3	Layer 4
0-15	Kx	n/a	n/a	2.5	1.0
	Kz	n/a	n/a	2.5E-03	1.0E-04
	Ss	n/a	n/a	5.5E-04	2.8E-05
15-30	Kx	1.77524962	1.23896884	1.44454073	1.0001
	Kz	1.8E-03	1.2E-03	1.5E-03	1.0E-04
	Ss	2.2E-03	1.7E-04	7.4E-05	4.8E-06
30-45	Kx	3.9	1.0	1.1	1.0
	Kz	3.9E-03	1.0E-03	1.1E-03	1.0E-04
	Ss	4.5E-06	7.2E-06	4.7E-06	3.3E-06
45-60	Kx	1.5	1.0	0.8	1.0
	Kz	1.5E-03	9.7E-04	8.3E-04	1.0E-04
	Ss	4.5E-06	5.7E-06	3.0E-06	2.2E-06
60-84	Kx	0.2	0.9	0.1	1.0
	Kz	1.8E-04	9.8E-04	1.5E-04	1.1E-04
	Ss	3.5E-06	3.6E-06	2.2E-06	1.4E-06

Carrizo-Wilcox Aquifer Properties Extracted from the Southern QCSP GAM

Distance (miles)	Property	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
0-15	Kx	19.7	5.0	4.1	6.4	6.4
	Kz	2.0E-02	2.3E-03	6.6E-03	1.0E-02	1.0E-02
	Ss	1.4E-05	1.9E-05	4.5E-06	3.0E-06	3.0E-06
15-30	Kx	41.11840131	1.95169999	2.57816925	2.99999999	2.99999999
	Kz	4.2E-02	3.6E-04	2.7E-03	3.1E-03	3.1E-03
	Ss	3.6E-06	3.2E-06	3.0E-06	3.0E-06	3.0E-06
30-45	Kx	31.2	1.6	3.0	3.0	3.0
	Kz	3.1E-02	9.0E-05	3.0E-03	3.0E-03	3.0E-03
	Ss	3.0E-06	3.0E-06	3.0E-06	3.0E-06	3.0E-06
45-60	Kx	14.1	1.4	1.4	1.4	1.4
	Kz	1.4E-02	4.7E-05	1.4E-03	1.4E-03	1.4E-03
	Ss	3.0E-06	3.0E-06	3.0E-06	3.0E-06	3.0E-06
60-84	Kx	4.0	0.4	1.0	1.0	1.0
	Kz	4.5E-03	6.7E-06	1.1E-03	1.1E-03	1.1E-03
	Ss	3.0E-06	3.0E-06	3.0E-06	3.0E-06	3.0E-06

Carrizo-Wilcox Aquifer Properties Developed from the geohydrostratigraphic Model (GHSM)

Distance (miles)	Property	Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
0-15	Kx	24.4	4.6	4.1	4.0	4.0
	Kz	2.9E-03	1.6E-03	3.7E-03	3.6E-03	3.6E-03
	Ss	3.7E-01	3.6E-01	3.6E-01	3.6E-01	3.6E-01
15-30	Kx	21.1	4.2	3.3	3.2	3.0
	Kz	2.9E-03	1.5E-03	2.1E-03	2.0E-03	1.9E-03
	Ss	3.4E-01	3.3E-01	3.2E-01	3.2E-01	3.2E-01
30-45	Kx	14.4	1.8	2.0	1.8	1.7
	Kz	1.7E-03	7.3E-04	1.1E-03	1.0E-03	9.3E-04
	Ss	3.1E-01	3.0E-01	3.0E-01	2.9E-01	2.9E-01
45-60	Kx	7.9	0.6	0.5	0.4	0.4
	Kz	8.4E-04	3.6E-04	3.6E-04	3.1E-04	2.7E-04
	Ss	2.8E-01	2.7E-01	2.6E-01	2.6E-01	2.5E-01
60-84	Kx	3.9	0.1	0.0	0.0	0.0
	Kz	4.5E-04	1.6E-04	1.2E-04	9.1E-05	6.9E-05
	Ss	2.5E-01	2.3E-01	2.2E-01	2.1E-01	2.0E-01

Table 6-19. Locations where drawdowns were monitored for the simulated pumping at Well Field #1 and Well Field #2 in Potential Production Area #2.

Monitoring Location (miles)	Ground Surface (ft, msl)	Vertical Boundary	Carrizo-upper Wilcox	Middle Wilcox	Lower Wilcox		
			Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
2.5	754.8	Top		754.8	712.8	623.7	596.7
		Bottom		712.8	623.7	596.7	569
5.5	650.8	Top		650.8	423.1	318.9	274.6
		Bottom		423.1	318.9	274.6	229
10.5	687.7	Top	487.6	159.6	-66.5	-196.2	-269.7
		Bottom	159.6	-66.5	-196.2	-269.7	-345.5
15.5	578.2	Top	73.2	-311.3	-548.8	-703.6	-805.9
		Bottom	-311.3	-548.8	-703.6	-805.9	-911.4
30.5	541.2	Top	-1258.1	-1824.5	-2098.3	-2333.7	-2528.6
		Bottom	-1824.5	-2098.3	-2333.7	-2528.6	-2729.5

6.2.6.2.1 Simulated Drawdown from the Groundwater Model with GAM-based Properties for the Carrizo-Wilcox Aquifer

Tables 6-20 and **6-21** provide drawdown at 30 and 50 years at the monitoring locations listed in Table 6-19 for pumping at 5,000, 15,000, and 30,000 years as determined by the groundwater model that uses GAM-based properties for the Carrizo-Wilcox Aquifer. **Figures 6-34** to **6-35** show the simulated drawdown along the center dip line of the groundwater model at elapsed times of 5, 10, 30, and 50 years for pumping Well Field #1 at 15,000 AFY. **Figures 6-36** to **6-37** show the simulated drawdown along the center dip line of the groundwater model at elapsed times of 5, 10, 30, and 50 years for pumping Well Field #2 at 15,000 AFY.

Among the notable results that can be gleaned from a review of Tables 6-20 and 6-21 and Figures 6-34 through 6-37 are the following:

- After 30 years pumping 15,000 AFY from Well Field #1 the groundwater model predicts about 9 to 11 ft of drawdown in the lower Wilcox at the 2.5 mile monitoring point location and 10 to 11 ft in the lower Wilcox at the 5.5 monitoring point location
- After 30 years pumping 15,000 AFY from Well Field #2 the groundwater model predicts about 5 ft of drawdown in the lower Wilcox at the 2.5 mile monitoring point location and between 5 to 7 ft in the lower Wilcox at the 5.5 monitoring point location
- After 30 years of pumping 15,000 AFY, the groundwater model predicts about 300 ft of drawdown at the Well Field #1
- After 30 years of pumping 15,000 AFY, the groundwater model predicts about 300 ft of drawdown at the Well Field #2

- After 30 years of pumping 15,000 AFY the drawdown, the groundwater model predicts a maximum drawdown of about 10 ft drawdown in the Carrizo-upper Wilcox Aquifer above the locations the pumping wells in the lower Wilcox for both Well Field #1 and #2.

6.2.6.2.2 Simulated Drawdown from the Groundwater Model with GHSM-based Properties for the Carrizo-Wilcox Aquifer

Tables 6-22 and **6-23** provide drawdown at 30 and 50 years at the monitoring locations listed in Table 6-9 for pumping at 5,000, 15,000, and 30,000 years as determined by the groundwater model that uses GHSM-based properties for the Carrizo-Wilcox Aquifer. **Figures 6-38** to **6-39** show the simulated drawdown along the center dip line of the groundwater model elapsed times of 5, 10, 30, and 50 years for pumping Well Field #1 at 15,000 AFY. **Figure 6-40** to **6-41** shows the simulated drawdown along the center dip line of the groundwater model at elapsed times of 5, 10, 30, and 50 years for pumping Well Field #2 at 15,000 AFY.

Among the notable results that can be gleaned from a review of Tables 6-32 and 6-33 and Figures 6-38 through 6-41 are the following:

- Except for a small area near the model up-dip boundary at the outcrop, the model exhibits a linear response between increase pumping and increase aquifer drawdown at the monitoring locations after 30 years of pumping
- After 30 years pumping 15,000 AFY from Well Field #1 the groundwater model predicts 5 to 7 ft of drawdown in the lower Wilcox at the 2.5 mile monitoring point location and between 6 to 9 ft in the lower Wilcox at the 5.5 monitoring point location
- After 30 years pumping 15,000 AFY from Well Field #2 the groundwater model predicts about 2 ft of drawdown in the lower Wilcox at the 2.5 mile monitoring point location and between 3 to 4 ft in the lower Wilcox at the 5.5 monitoring point location
- After 30 years of pumping 15,000 AFY, the groundwater model predicts about 500 ft of drawdown at the Well Field #1
- After 30 years of pumping 15,000 AFY, the groundwater model predicts about 800 ft of drawdown at the Well Field #2
- After 30 years of pumping 15,000 AFY the drawdown, the groundwater model predicts a maximum drawdown of about 10 ft drawdown in the Carrizo-upper Wilcox Aquifer above the locations the pumping wells in the lower Wilcox for both Well Field #1 and #2.

Table 6-20. Simulated drawdown at monitoring locations after pumping Well Field #1 in PPA #2 for 30 years and 50 years, as determined by the groundwater model using GAM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

Monitoring Location (miles)	Pumping Rate (AFY)	Carrizo-upper Wilcox	Middle Wilcox	Lower Wilcox		
		Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
30 Years						
2.5	5,000	Not Present	0.3	3.2	3.3	3.5
	15,000	Not Present	1.0	9.6	9.9	10.5
	30,000	Not Present	2.1	19.3	19.9	21.0
5.5	5,000	Not Present	0.2	3.4	3.8	3.9
	15,000	Not Present	0.6	10.1	11.4	11.6
	30,000	Not Present	1.3	20.2	22.8	23.3
10.5	5,000	0.9	2.8	4.9	6.9	6.2
	15,000	2.8	8.3	14.6	20.8	18.8
	30,000	5.7	16.5	29.3	41.7	37.6
15.5	5,000	1.5	2.9	12.5	12.9	14.0
	15,000	4.6	8.8	37.5	38.8	42.2
	30,000	9.2	17.6	74.8	77.7	84.4
30.5	5,000	2.3	8.5	70.1	98.6	36.3
	15,000	6.8	25.3	199.2	252.0	107.6
	30,000	13.6	49.8	373.1	443.2	210.3
50 Years						
2.5	5,000	Not Present	0.7	4.9	5.0	5.2
	15,000	Not Present	2.1	14.6	15.0	15.6
	30,000	Not Present	4.1	29.3	30.2	31.2
5.5	5,000	Not Present	0.3	5.0	5.5	5.6
	15,000	Not Present	0.9	14.9	16.5	16.7
	30,000	Not Present	1.9	30.0	33.0	33.5
10.5	5,000	1.3	3.4	6.4	8.6	8.0
	15,000	3.8	10.2	19.2	25.9	23.9
	30,000	8.9	20.9	38.6	52.0	48.0
15.5	5,000	2.0	3.6	14.0	14.7	15.9
	15,000	6.1	10.9	41.9	44.1	47.7
	30,000	13.1	22.1	83.8	88.4	95.4
30.5	5,000	3.0	9.6	72.1	100.6	38.5
	15,000	9.0	28.5	205.2	258.0	114.1
	30,000	18.5	56.5	385.2	455.3	223.4

Table 6-21. Simulated drawdown at monitoring locations after pumping Well Field #2 in PPA #2 for 30 years and 50 years, as determined by the groundwater model using GAM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

Monitoring Location (miles)	Pumping Rate (AFY)	Carrizo-upper Wilcox	Middle Wilcox	Lower Wilcox		
		Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
30 Years						
2.5	5,000	Not Present	0.2	1.8	1.9	1.9
	15,000	Not Present	0.6	5.4	5.8	5.8
	30,000	Not Present	1.1	10.9	11.7	11.5
5.5	5,000	Not Present	0.2	1.9	2.2	2.3
	15,000	Not Present	0.6	5.8	6.6	7.0
	30,000	Not Present	1.1	11.6	13.2	14.1
10.5	5,000	0.9	2.1	2.7	3.7	3.8
	15,000	2.6	6.4	8.1	11.1	11.4
	30,000	5.2	12.7	16.2	22.2	22.9
15.5	5,000	1.5	2.3	6.4	7.7	7.1
	15,000	4.4	6.9	19.2	23.1	21.4
	30,000	8.8	13.7	38.4	46.3	42.8
30.5	5,000	2.3	8.5	30.1	26.1	20.5
	15,000	7.0	25.5	90.8	78.9	61.2
	30,000	13.9	50.4	180.2	157.3	122.0
50 Years						
2.5	5,000	Not Present	0.4	3.1	3.2	3.2
	15,000	Not Present	1.3	9.2	9.7	9.6
	30,000	Not Present	2.5	18.5	19.5	19.4
5.5	5,000	Not Present	0.3	3.2	3.5	3.7
	15,000	Not Present	0.9	9.5	10.5	11.0
	30,000	Not Present	1.7	19.1	21.0	22.1
10.5	5,000	1.2	2.8	3.9	5.1	5.2
	15,000	3.6	8.4	11.8	15.3	15.7
	30,000	8.4	17.1	23.7	30.6	31.4
15.5	5,000	2.0	3.0	7.7	9.3	8.7
	15,000	6.0	9.0	23.3	27.9	26.2
	30,000	12.8	18.3	46.7	56.0	52.5
30.5	5,000	3.1	9.7	32.3	28.3	22.8
	15,000	9.4	29.1	97.4	85.4	68.2
	30,000	19.1	57.9	193.5	170.4	136.0

Table 6-22. Simulated drawdown at monitoring locations after pumping Well Field #1 in PPA #2 for 30 years and 50 years, as determined by the groundwater model using GHSM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

Monitoring Location (miles)	Pumping Rate (AFY)	Carrizo-upper Wilcox	Middle Wilcox	Lower Wilcox		
		Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
30 Years						
2.5	5,000	Not Present	0.2	1.8	1.9	2.2
	15,000	Not Present	0.6	5.4	5.7	6.8
	30,000	Not Present	1.2	10.9	11.6	13.8
5.5	5,000	Not Present	0.3	2.3	2.8	3.0
	15,000	Not Present	0.9	6.8	8.6	8.9
	30,000	Not Present	1.9	13.8	17.3	18.1
10.5	5,000	1.3	1.5	4.1	5.2	4.9
	15,000	4.0	4.5	12.2	15.7	14.9
	30,000	8.1	8.9	24.5	31.8	30.1
15.5	5,000	2.4	2.8	6.7	8.2	8.5
	15,000	7.0	8.2	20.0	24.9	25.9
	30,000	14.1	16.4	40.0	50.4	52.3
30.5	5,000	4.9	9.7	49.8	95.3	23.1
	15,000	14.5	28.7	140.9	236.0	68.6
	30,000	28.6	56.0	261.0	398.6	134.2
50 Years						
2.5	5,000	Not Present	0.4	3.1	3.2	3.5
	15,000	Not Present	1.2	9.3	9.7	10.7
	30,000	Not Present	2.6	18.8	19.6	21.7
5.5	5,000	Not Present	0.5	3.5	4.1	4.2
	15,000	Not Present	1.5	10.5	12.4	12.8
	30,000	Not Present	3.1	21.2	25.1	25.9
10.5	5,000	1.7	1.9	5.2	6.4	6.2
	15,000	4.9	5.7	15.5	19.4	18.7
	30,000	12.0	11.6	31.3	39.3	37.8
15.5	5,000	2.9	3.3	7.7	9.4	9.8
	15,000	8.5	10.0	23.2	28.6	29.7
	30,000	18.4	20.1	46.6	57.9	60.0
30.5	5,000	5.7	10.6	50.9	96.4	24.5
	15,000	16.9	31.4	144.2	239.4	73.0
	30,000	34.0	61.8	267.8	405.7	143.0

Table 6-23. Simulated drawdown at monitoring locations after pumping Well Field #2 in PPA #2 for 30 years and 50 years, as determined by the groundwater model using GHSM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

Monitoring Location (miles)	Pumping Rate (AFY)	Carrizo-upper Wilcox	Middle Wilcox	Lower Wilcox		
		Layer 5	Layer 6	Layer 7	Layer 8	Layer 9
30 Years						
2.5	5,000	Not Present	0.1	0.8	0.9	0.9
	15,000	Not Present	0.4	2.3	2.7	2.5
	30,000	Not Present	0.7	4.7	5.5	5.1
5.5	5,000	Not Present	0.2	1.1	1.3	1.5
	15,000	Not Present	0.7	3.2	3.8	4.4
	30,000	Not Present	1.5	6.5	7.7	8.9
10.5	5,000	1.1	1.1	1.9	2.3	2.4
	15,000	3.4	3.3	5.8	6.8	7.1
	30,000	6.8	6.5	11.7	13.7	14.2
15.5	5,000	2.1	2.3	3.1	3.8	3.6
	15,000	6.2	6.9	9.4	11.5	10.8
	30,000	12.3	13.7	18.9	23.3	21.7
30.5	5,000	4.6	8.0	17.2	16.2	11.1
	15,000	13.9	24.1	52.0	49.1	33.0
	30,000	27.5	47.6	103.5	98.5	65.9
50 Years						
2.5	5,000	Not Present	0.3	1.5	1.7	1.6
	15,000	Not Present	0.9	4.6	5.1	4.9
	30,000	Not Present	1.8	9.3	10.3	9.9
5.5	5,000	Not Present	0.4	1.9	2.1	2.3
	15,000	Not Present	1.2	5.5	6.3	7.0
	30,000	Not Present	2.5	11.2	12.6	14.0
10.5	5,000	1.5	1.5	2.8	3.2	3.3
	15,000	4.5	4.5	8.3	9.5	9.8
	30,000	10.4	9.0	16.8	19.1	19.9
15.5	5,000	2.6	2.9	4.1	4.9	4.6
	15,000	7.9	8.8	12.2	14.6	13.9
	30,000	16.6	17.7	24.5	29.4	28.0
30.5	5,000	5.6	9.1	18.5	17.5	12.7
	15,000	16.8	27.3	55.9	53.0	37.6
	30,000	33.5	54.2	111.4	106.4	75.3

6.2.6.3 Sensitivity Analysis on the Simulated Drawdown for Potential Production Area #2

Table 6-2 describes the changes in the model input parameter associated with set of sixteen sensitivity runs performed for the groundwater model's simulations involving GAM-based and the GHSM-based aquifer properties. In this section, Model Run 0 refers to the baseline run of 15,000 AF for which simulated drawdowns are shown in Figures 6-34 to 6-41. **Tables 6-20** and **6-27** provide the sensitivity results for drawdowns at five monitoring locations at 30 and 50 years for the well fields #1 and #2 determined by the GAM-based groundwater model. **Tables 6-26** and **6-27** provide the sensitivity results for drawdowns at five monitoring locations at 30 and 50 years for the well fields #1 and #2 determined by the GAM-based groundwater model. Among the notable results that can be gleaned from a review of **Tables 6-24** through **6-27** are:

- After 30 years of pumping the Well Field #1 for 15,000 AFY, the model with GAM-based properties predicts that at the 2.5 mile monitoring location in the lower Wilcox the drawdown is between 0.1 and 20 ft.
- After 30 years of pumping the Well Field #1 for 15,000 AFY, the model with GAM-based properties predicts that at the 5.5 mile monitoring location in the lower Wilcox the drawdown is between less than 0.1 and 21 ft.
- After 30 years of pumping the Well Field #2 for 15,000 AFY, the model with GAM-based properties predicts that at the 2.5 mile monitoring location in the lower Wilcox the drawdown is between 0.5 and 17 ft.
- After 30 years of pumping the Well Field #2 for 15,000 AFY, the model with GAM-based properties predicts that at the 5.5 mile monitoring location in the lower Wilcox the drawdown is between 0.1 and 18 ft.
- After 30 years of pumping the Well Field #1 for 15,000 AFY, the model with GHSM-based properties predicts that 2.5 mile monitoring location in the lower Wilcox the drawdown is between less than 0.1 and 19 ft.
- After 30 years of pumping the Well Field #1 for 15,000 AFY, the model with GHSM-based properties predicts that 5.5 mile monitoring location in the lower Wilcox the drawdown is between less than 0.1 and 22 ft.
- After 30 years of pumping the Well Field #2 for 15,000 AFY, the model with GHSM-based properties predicts that 2.5 mile monitoring location in the lower Wilcox the drawdown is between less than 0.1 and 15. ft.
- After 30 years of pumping the Well Field #2 for 15,000 AFY, the model with GHSM-based properties predicts that 5.5 mile monitoring location in the lower Wilcox the drawdown between less than 0.1 and 17 ft.

Table 6-24. Results from a sensitivity analysis of simulated drawdowns caused by pumping 15,000 AFY from Well Field #1 located in PPA #2 at five monitoring locations, as determined by the groundwater model using GAM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

		30 years					50 years				
		5	6	7	8	9	5	6	7	8	9
Monitoring Location at 2.5 miles	Run 0		1.0	9.6	9.9	10.5		2.1	14.6	15.0	15.6
	Run 1		1.4	12.3	12.7	13.3		2.6	17.8	18.3	18.9
	Run 2		0.6	6.0	6.2	6.6		1.3	10.2	10.5	10.9
	Run 3		0.5	11.7	11.9	12.6		1.0	19.0	19.4	20.0
	Run 4		1.6	5.7	6.0	6.3		2.8	8.1	8.5	8.8
	Run 5		0.8	6.1	6.6	7.4		1.9	10.3	11.0	11.8
	Run 6		1.1	11.5	11.7	11.9		1.9	16.9	17.1	17.3
	Run 7		1.2	9.7	10.0	10.5		2.6	14.8	15.2	15.8
	Run 8		1.0	9.6	9.9	10.5		2.1	14.6	15.0	15.6
	Run 9		1.2	5.5	5.7	5.8		2.1	7.7	7.9	8.0
	Run 10		0.3	9.7	9.8	9.8		0.7	15.7	15.9	15.8
	Run 11		2.2	8.9	9.1	9.3		3.5	11.7	11.9	12.1
	Run 12		0.8	19.7	20.0	20.1		1.5	31.0	31.3	31.5
	Run 13		0.4	1.6	1.8	2.0		1.2	3.3	3.6	3.8
	Run 14		0.1	1.8	2.2	3.1		0.2	3.5	3.9	5.2
	Run 15		1.6	4.7	5.1	5.5		3.1	7.0	7.6	8.0
	Run 16		0.4	6.7	7.3	9.5		0.8	9.9	10.5	12.7
Monitoring Location at 5.5 miles	Run 0		0.6	10.1	11.4	11.6		0.9	15.0	16.5	16.7
	Run 1		0.9	12.8	14.3	14.6		1.2	18.2	19.9	20.1
	Run 2		0.4	6.3	7.4	7.5		0.6	10.5	11.7	11.9
	Run 3		0.5	12.5	13.8	13.9		0.7	19.8	21.2	21.4
	Run 4		0.8	6.1	7.0	7.0		1.1	8.5	9.4	9.5
	Run 5		0.4	7.5	9.3	9.5		0.6	11.6	13.8	14.0
	Run 6		0.9	11.7	12.3	12.3		1.4	17.1	17.7	17.8
	Run 7		0.8	10.1	11.4	11.6		1.4	15.2	16.7	16.9
	Run 8		0.6	10.1	11.4	11.6		0.9	15.0	16.5	16.7
	Run 9		0.8	5.6	6.1	6.1		1.3	7.7	8.3	8.4
	Run 10		0.3	9.9	10.5	10.0		0.5	15.9	16.5	16.0
	Run 11		1.6	9.0	9.6	9.7		2.4	11.7	12.4	12.5
	Run 12		0.8	20.1	20.9	20.6		1.3	31.4	32.3	31.9
	Run 13		0.2	2.4	2.8	2.8		0.4	4.2	4.7	4.8
	Run 14		0.1	2.7	4.7	5.0		0.2	4.9	7.5	7.9
	Run 15		0.6	6.2	6.9	6.9		0.8	8.5	9.3	9.4
	Run 16		0.6	9.3	12.9	13.7		0.7	12.4	16.2	17.0
Monitoring Location at 10.5 miles	Run 0	2.8	8.3	14.6	20.8	18.8	3.8	10.2	19.2	25.9	23.9
	Run 1	4.5	11.2	17.9	24.6	22.5	5.4	13.0	22.8	30.0	28.0
	Run 2	1.3	4.8	10.0	15.2	13.4	2.0	6.6	14.2	20.1	18.2
	Run 3	1.1	6.6	20.5	26.6	21.3	1.7	8.5	27.7	34.3	29.0
	Run 4	4.9	9.1	9.0	13.3	12.2	6.2	11.0	11.3	15.8	14.8
	Run 5	6.3	15.9	15.3	27.0	23.9	8.3	19.9	19.8	32.3	29.2
	Run 6	1.4	4.2	14.1	16.6	14.8	2.0	5.5	19.2	21.9	20.3
	Run 7	4.9	8.9	14.8	20.9	18.8	8.5	12.1	19.7	26.2	24.2
	Run 8	2.8	8.3	14.6	20.8	18.8	3.8	10.2	19.2	25.9	23.9
	Run 9	1.5	3.3	6.8	8.9	8.3	2.3	4.4	8.8	11.2	10.6
	Run 10	0.2	1.6	12.7	15.9	11.3	0.3	2.4	18.6	22.0	17.3
	Run 11	4.4	6.6	10.5	13.0	12.3	6.3	8.3	13.0	15.7	15.1
	Run 12	0.8	4.3	23.9	27.6	22.9	1.2	5.7	34.8	38.9	34.3
	Run 13	5.0	8.9	6.5	10.0	8.7	7.3	12.8	9.5	13.3	11.8
	Run 14	0.9	4.9	8.8	20.4	16.2	1.7	8.8	15.2	28.8	23.7
	Run 15	13.3	22.4	15.3	18.5	16.4	15.1	25.0	17.8	21.2	19.0
	Run 16	5.7	21.7	26.8	44.3	37.9	7.1	24.9	30.5	48.8	42.2

		30 years					50 years				
		5	6	7	8	9	5	6	7	8	9
Monitoring Location at 15.5 miles	Run 0	4.6	8.8	37.5	38.8	42.2	6.1	10.9	41.9	44.1	47.7
	Run 1	7.2	11.9	42.6	44.1	48.0	8.6	13.8	46.8	49.3	53.3
	Run 2	2.1	5.2	29.4	30.6	33.1	3.3	7.1	34.7	36.4	39.3
	Run 3	1.8	7.0	57.5	51.0	44.5	2.7	8.9	65.2	59.3	53.1
	Run 4	7.8	9.8	20.8	25.9	30.2	9.7	11.8	23.2	28.6	33.0
	Run 5	11.9	17.6	47.6	61.8	73.9	15.4	21.9	53.8	68.8	81.5
	Run 6	1.9	4.4	26.1	24.8	22.8	2.6	5.7	30.7	30.1	28.2
	Run 7	6.1	9.5	37.8	38.9	42.3	9.7	12.7	42.8	44.5	48.1
	Run 8	4.6	8.8	37.5	38.8	42.2	6.1	10.9	41.9	44.1	47.7
	Run 9	2.1	3.5	13.7	14.5	15.6	3.0	4.6	15.7	16.9	18.0
	Run 10	0.2	1.7	25.6	26.4	15.9	0.4	2.5	31.5	32.5	21.9
	Run 11	5.4	6.9	18.4	19.4	20.8	7.3	8.6	20.7	22.1	23.5
	Run 12	1.1	4.5	40.6	40.3	30.3	1.5	6.0	50.9	51.5	41.7
	Run 13	9.9	10.6	17.4	25.7	31.8	13.7	14.8	22.8	31.5	38.2
	Run 14	1.9	5.6	45.7	52.9	55.8	3.3	9.7	67.4	70.6	76.3
	Run 15	24.2	25.5	34.1	41.6	49.3	27.1	28.3	37.1	44.7	52.6
	Run 16	10.8	23.3	103.9	103.2	114.4	13.4	26.7	110.3	109.8	121.8
Monitoring Location at 30.5 miles	Run 0	6.8	25.3	199.2	252.0	107.6	9.0	28.5	205.2	258.0	114.1
	Run 1	10.7	30.7	208.8	261.6	117.7	12.6	33.4	213.7	266.6	123.1
	Run 2	3.2	18.8	184.3	237.1	91.5	4.8	22.0	192.6	245.4	100.5
	Run 3	2.7	19.3	213.4	327.4	92.6	4.0	22.6	223.4	337.4	103.3
	Run 4	11.7	28.9	165.7	189.0	108.3	14.3	31.6	169.1	192.3	111.7
	Run 5	19.4	68.8	475.3	545.4	301.2	24.9	76.0	487.4	557.5	314.1
	Run 6	2.4	9.4	79.1	116.9	39.6	3.4	11.2	84.0	121.9	45.1
	Run 7	7.6	25.9	199.4	252.2	107.7	11.4	30.4	206.0	258.8	114.7
	Run 8	6.8	25.3	199.2	252.0	107.6	9.0	28.4	205.2	258.0	114.1
	Run 9	2.7	8.9	67.0	84.6	36.5	3.9	10.4	69.5	87.1	39.2
	Run 10	0.3	3.9	67.5	140.4	23.9	0.5	5.2	73.8	146.8	29.9
	Run 11	6.8	13.9	74.4	92.0	44.2	8.7	15.9	76.9	94.5	46.8
	Run 12	1.4	9.0	88.6	161.2	43.8	2.0	11.3	99.0	171.9	55.3
	Run 13	18.8	59.6	345.0	379.1	263.8	24.3	66.2	355.6	389.8	274.9
	Run 14	3.3	37.0	489.2	648.5	204.1	5.4	46.0	524.8	684.3	241.0
	Run 15	41.0	84.0	377.2	411.4	296.8	45.3	88.5	382.1	416.2	301.7
	Run 16	17.2	73.4	599.1	759.0	320.8	21.3	80.0	612.2	772.1	334.9

Note: NP = Not Present; 0.0 represents a drawdown that is less than 0.1 foot

Table 6-25. Results from a sensitivity analysis of simulated drawdowns caused by pumping 15,000 AFY from Well Field #2 located in PPA #2 at five monitoring locations, as determined by the groundwater model using GAM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

Monitoring Location at 2.5 miles	30 years					50 years				
	5	6	7	8	9	5	6	7	8	9
Run 0		0.6	5.4	5.8	5.8		1.3	9.2	9.7	9.7
Run 1		0.9	8.2	8.7	8.6		1.8	12.7	13.3	13.2
Run 2		0.2	2.5	2.7	2.6		0.6	5.1	5.4	5.4
Run 3		0.3	6.6	7.0	6.8		0.6	12.1	12.6	12.5
Run 4		0.8	3.1	3.4	3.4		1.6	5.0	5.3	5.3
Run 5		0.3	2.4	2.7	2.7		0.8	4.7	5.3	5.2
Run 6		0.8	8.5	8.7	8.7		1.6	13.4	13.7	13.6
Run 7		0.7	5.5	5.9	5.8		1.6	9.4	9.9	9.8
Run 8		0.6	5.4	5.8	5.8		1.3	9.2	9.7	9.7
Run 9		0.7	3.3	3.4	3.4		1.4	5.1	5.3	5.3
Run 10		0.2	6.1	6.3	6.1		0.5	11.1	11.3	11.1
Run 11		1.7	6.9	7.1	7.1		2.9	9.5	9.8	9.8
Run 12		0.7	16.7	17.0	16.8		1.3	27.5	27.9	27.8
Run 13		0.1	0.4	0.5	0.5		0.4	1.2	1.4	1.4
Run 14		0.0	0.4	0.7	0.6		0.1	1.2	1.6	1.5
Run 15		0.9	2.8	3.2	3.2		1.9	4.5	5.1	5.1
Run 16		0.2	3.7	4.6	4.3		0.4	4.6	5.7	5.4

Monitoring Location at 5.5 miles	30 years					50 years				
	5	6	7	8	9	5	6	7	8	9
Run 0		0.6	5.8	6.6	7.0		0.9	9.5	10.5	11.0
Run 1		0.9	8.6	9.6	10.2		1.2	13.1	14.2	14.8
Run 2		0.2	2.7	3.2	3.5		0.4	5.3	6.0	6.4
Run 3		0.5	7.2	8.0	8.5		0.7	12.7	13.7	14.3
Run 4		0.7	3.5	3.9	4.1		1.0	5.3	5.8	6.1
Run 5		0.4	3.1	3.8	4.3		0.6	5.6	6.5	7.2
Run 6		0.8	8.7	9.1	9.3		1.3	13.5	14.0	14.2
Run 7		0.7	5.8	6.6	7.1		1.2	9.8	10.7	11.2
Run 8		0.6	5.8	6.6	7.0		0.9	9.5	10.5	11.0
Run 9		0.6	3.4	3.6	3.8		1.0	5.2	5.6	5.7
Run 10		0.3	6.3	6.6	6.4		0.5	11.3	11.6	11.4
Run 11		1.4	7.0	7.4	7.7		2.2	9.6	10.1	10.3
Run 12		0.9	17.0	17.6	17.6		1.3	27.9	28.5	28.6
Run 13		0.1	0.7	0.8	0.9		0.3	1.7	1.8	2.0
Run 14		0.0	0.6	1.2	1.5		0.1	1.7	2.7	3.3
Run 15		0.7	4.0	4.2	4.6		0.9	5.8	6.1	6.5
Run 16		0.6	5.3	7.3	9.0		0.8	6.5	8.7	10.6

Monitoring Location at 10.5 miles	30 years					50 years				
	5	6	7	8	9	5	6	7	8	9
Run 0	2.6	6.4	8.1	11.1	11.4	3.6	8.4	11.8	15.3	15.7
Run 1	4.4	9.7	11.5	15.0	15.5	5.4	11.6	15.7	19.7	20.2
Run 2	1.0	2.9	4.0	6.2	6.3	1.7	4.5	7.0	9.6	9.9
Run 3	1.1	5.5	11.6	14.4	13.5	1.6	7.5	17.3	20.6	19.8
Run 4	4.3	7.1	5.2	6.7	6.9	5.6	9.1	7.2	8.8	9.1
Run 5	4.8	10.0	6.5	10.1	10.6	6.8	14.0	9.9	14.0	14.6
Run 6	1.4	3.8	10.1	11.4	11.2	2.0	5.1	14.8	16.4	16.2
Run 7	4.6	7.0	8.2	11.1	11.5	8.3	10.2	12.2	15.5	15.9
Run 8	2.6	6.4	8.1	11.1	11.4	3.6	8.4	11.8	15.3	15.7
Run 9	1.4	2.6	3.9	5.0	5.1	2.2	3.6	5.8	7.0	7.1
Run 10	0.1	1.4	8.1	9.2	7.4	0.3	2.2	13.1	14.4	12.4
Run 11	4.6	6.2	7.9	9.3	9.5	6.6	8.0	10.4	12.0	12.2
Run 12	0.9	4.4	19.9	21.5	19.8	1.2	5.9	30.5	32.4	30.8
Run 13	3.1	4.8	2.4	2.5	2.6	4.9	8.0	4.5	4.5	4.6
Run 14	0.6	1.6	1.7	4.6	4.5	1.2	4.0	4.5	9.1	9.3
Run 15	11.0	18.3	10.3	9.7	9.9	12.8	21.2	12.6	12.0	12.2
Run 16	5.2	16.8	14.1	22.5	23.7	6.8	20.5	16.4	25.5	27.0

Monitoring Location at 15.5 miles	30 years					50 years				
	5	6	7	8	9	5	6	7	8	9
Run 0	4.4	6.9	19.2	23.1	21.4	6.0	9.0	23.3	27.9	26.2
Run 1	7.3	10.4	24.7	29.3	27.4	8.8	12.4	28.7	34.1	32.3
Run 2	1.8	3.1	11.4	14.5	13.0	2.9	4.9	15.9	19.6	18.0
Run 3	1.8	5.9	32.2	31.4	24.5	2.7	7.9	39.3	39.0	32.0
Run 4	7.2	7.8	11.0	14.2	13.5	9.1	9.8	13.3	16.8	16.0
Run 5	9.8	11.2	18.8	27.3	25.6	13.5	15.6	24.7	34.1	32.2
Run 6	1.9	4.0	17.1	17.6	15.4	2.7	5.3	21.5	22.6	20.5
Run 7	5.8	7.5	19.4	23.2	21.4	9.6	10.8	24.1	28.4	26.6
Run 8	4.4	6.9	19.2	23.1	21.4	6.0	9.0	23.3	27.9	26.2
Run 9	2.0	2.7	7.2	8.7	8.2	2.9	3.8	9.0	10.9	10.3
Run 10	0.2	1.5	16.6	16.3	9.5	0.4	2.3	22.1	21.8	14.8
Run 11	5.7	6.5	12.3	14.3	13.7	7.8	8.3	14.7	16.9	16.3
Run 12	1.2	4.6	32.7	31.8	24.4	1.6	6.1	42.9	42.7	35.5
Run 13	6.5	5.9	5.8	7.5	6.9	9.9	9.5	9.8	12.0	11.1
Run 14	1.3	2.0	9.2	15.2	12.4	2.6	4.6	19.7	27.2	23.4
Run 15	21.2	21.2	21.5	23.5	21.8	24.3	24.4	24.8	26.8	25.0
Run 16	10.5	18.2	52.0	61.9	56.3	13.4	22.1	58.3	68.8	62.9

Monitoring Location at 30.5 miles	30 years					50 years				
	5	6	7	8	9	5	6	7	8	9
Run 0	7.0	25.5	90.8	78.9	61.2	9.4	29.1	97.4	85.4	68.2
Run 1	11.4	32.0	102.3	90.1	73.1	13.5	35.0	107.8	95.5	78.9
Run 2	3.1	17.7	73.7	62.3	43.6	4.7	21.5	82.7	71.1	52.9
Run 3	2.7	20.6	120.2	110.7	58.6	4.1	24.5	131.2	121.4	69.5
Run 4	11.9	24.6	60.1	51.6	48.9	14.6	27.7	63.9	55.3	52.7
Run 5	18.6	53.5	151.7	127.0	117.6	24.6	61.9	165.9	140.7	132.3
Run 6	2.6	10.2	48.4	45.2	28.3	3.6	12.1	53.4	50.2	33.8
Run 7	7.7	26.1	91.0	79.1	61.3	11.7	30.9	98.2	86.2	68.8
Run 8	7.0	25.5	90.8	78.9	61.2	9.4	29.1	97.4	85.4	68.2
Run 9	2.7	8.8	30.7	26.7	20.8	3.9	10.4	33.3	29.3	23.6
Run 10	0.3	4.0	45.2	50.5	15.5	0.5	5.4	51.8	57.0	21.0
Run 11	7.3	14.6	39.2	35.1	29.6	9.4	16.8	41.9	37.8	32.4
Run 12	1.5	9.9	69.5	73.8	37.0	2.1	12.3	80.0	84.6	48.5
Run 13	16.4	31.1	72.5	58.5	59.8	21.8	38.0	83.0	68.7	70.5
Run 14	2.8	29.8	156.9	124.5	69.3	5.0	40.8	188.9	155.3	98.3
Run 15	40.4	58.6	108.1	93.0	95.5	45.4	63.7	113.7	98.5	101.1
Run 16	18.0	74.5	272.4	236.2	182.3	22.8	82.8	288.5	251.7	199.0

Note: NP = Not Present; 0.0 represents a drawdown that is less than 0.1 foot

Table 6-26. Results from a sensitivity analysis of simulated drawdowns caused by pumping 15,000 AFY from Well Field #1 located in PPA #2 at five monitoring locations, as determined by the groundwater model using GHSM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

		30 years					50 years				
		5	6	7	8	9	5	6	7	8	9
Monitoring Location at 2.5 miles	Run 0		0.6	5.4	5.7	6.8		1.2	9.3	9.7	10.7
	Run 1		1.1	8.9	9.2	10.4		1.9	13.5	14.0	15.1
	Run 2		0.1	1.5	2.0	2.7		0.5	3.9	4.4	5.2
	Run 3		0.5	8.6	9.3	10.4		1.0	15.3	16.0	17.1
	Run 4		0.7	3.1	3.4	3.9		1.3	5.3	5.7	6.2
	Run 5		0.1	1.8	2.3	3.6		0.3	4.2	4.8	6.3
	Run 6		1.2	8.7	8.9	9.3		2.0	12.7	13.0	13.3
	Run 7		0.7	5.4	5.8	6.8		1.5	9.4	9.8	10.8
	Run 8		0.5	5.4	5.7	6.8		0.9	9.3	9.7	10.7
	Run 9		0.7	2.8	3.0	3.2		1.4	4.6	4.8	5.1
	Run 10		0.3	5.9	6.8	6.4		0.7	10.5	11.3	10.9
	Run 11		2.1	7.2	7.4	7.7		3.2	9.8	10.1	10.4
	Run 12		1.3	18.2	18.9	18.7		2.1	26.3	27.0	26.8
	Run 13		0.0	0.1	0.2	0.3		0.1	0.4	0.7	1.0
	Run 14		0.0	0.1	0.4	0.8		0.0	0.6	1.4	2.5
	Run 15		0.4	3.1	3.6	4.6		0.9	5.1	5.8	6.9
	Run 16		0.2	5.3	5.5	9.9		0.5	6.8	7.0	11.7
Monitoring Location at 5.5 miles	Run 0		0.9	6.8	8.6	8.9		1.5	10.5	12.4	12.8
	Run 1		1.5	10.7	12.4	12.9		2.1	14.8	16.8	17.3
	Run 2		0.3	2.2	4.0	4.1		0.7	4.7	6.7	7.0
	Run 3		0.8	11.2	14.2	13.2		1.3	17.7	20.8	19.8
	Run 4		1.0	4.0	5.1	5.2		1.6	6.0	7.3	7.5
	Run 5		0.4	3.6	6.1	6.4		0.8	6.7	9.4	9.9
	Run 6		1.3	9.3	10.4	10.1		2.0	13.0	14.3	14.0
	Run 7		1.0	6.9	8.6	9.0		1.8	10.7	12.6	13.0
	Run 8		0.8	6.8	8.6	8.9		1.2	10.4	12.4	12.8
	Run 9		0.8	3.1	3.8	3.8		1.4	4.8	5.5	5.6
	Run 10		0.4	6.3	9.4	6.7		0.7	10.9	13.9	11.1
	Run 11		2.3	7.5	8.3	8.4		3.2	9.9	10.9	11.0
	Run 12		1.4	19.0	21.8	19.3		2.1	26.6	29.8	27.3
	Run 13		0.0	0.2	0.7	0.7		0.2	1.0	1.9	2.0
	Run 14		0.0	0.4	2.1	1.8		0.1	1.7	5.3	5.3
	Run 15		1.1	5.7	7.3	7.4		1.4	7.6	9.7	9.8
	Run 16		1.0	12.8	16.3	17.9		1.3	15.1	18.5	20.3
Monitoring Location at 10.5 miles	Run 0	4.0	4.5	12.2	15.7	14.9	4.9	5.7	15.5	19.4	18.7
	Run 1	5.6	6.4	16.5	20.1	19.4	6.5	7.5	19.9	24.1	23.5
	Run 2	2.0	1.8	6.1	9.6	8.5	3.0	3.2	9.3	13.1	12.1
	Run 3	2.2	3.7	19.9	27.5	19.9	3.1	4.9	25.9	34.0	26.5
	Run 4	5.0	4.8	7.6	9.1	9.1	6.4	6.1	9.6	11.4	11.4
	Run 5	6.6	6.2	11.1	15.7	15.6	8.6	9.5	16.1	20.7	20.5
	Run 6	2.3	2.7	11.6	14.6	12.2	3.0	3.6	14.9	18.3	15.9
	Run 7	6.9	4.7	12.3	15.8	14.9	10.9	6.4	16.0	19.7	18.9
	Run 8	4.0	4.4	12.2	15.7	14.9	4.9	5.5	15.5	19.4	18.7
	Run 9	2.1	1.9	4.6	5.9	5.6	2.7	2.7	6.2	7.6	7.4
	Run 10	0.4	0.9	9.1	16.8	7.8	0.6	1.5	13.4	21.3	12.1
	Run 11	5.0	4.3	9.1	10.6	10.4	6.6	5.5	11.2	13.0	12.9
	Run 12	1.7	2.9	21.9	29.8	21.0	2.3	3.8	28.6	37.4	28.8
	Run 13	3.1	1.3	1.9	3.1	2.9	5.3	3.4	4.6	6.1	5.8
	Run 14	1.2	0.6	3.6	9.5	6.1	2.6	2.0	9.2	17.9	14.0
	Run 15	11.3	12.3	15.0	16.3	15.6	13.6	14.2	17.5	19.1	18.5
	Run 16	8.0	11.6	31.9	40.5	38.3	9.5	13.6	35.6	44.0	42.0

		30 years					50 years				
		5	6	7	8	9	5	6	7	8	9
Monitoring Location at 15.5 miles	Run 0	7.0	8.2	20.0	24.9	25.9	8.5	10.0	23.2	28.6	29.7
	Run 1	9.7	11.2	24.7	29.8	31.2	11.0	12.6	27.7	33.5	34.9
	Run 2	3.9	4.2	13.0	17.6	17.7	5.5	6.2	16.7	21.7	22.3
	Run 3	4.0	6.9	32.1	44.7	32.0	5.3	8.7	37.8	51.1	38.8
	Run 4	8.9	8.9	12.7	14.3	16.7	10.6	10.5	14.8	16.7	19.0
	Run 5	15.5	14.3	23.6	29.0	35.1	19.2	19.5	30.0	35.3	41.9
	Run 6	3.1	4.1	15.3	20.1	16.2	4.0	5.2	18.2	23.6	19.7
	Run 7	9.0	8.6	20.2	25.0	26.0	12.9	11.0	23.9	29.0	30.1
	Run 8	7.0	8.2	20.0	24.9	25.9	8.5	9.9	23.2	28.6	29.7
	Run 9	2.9	3.1	7.1	8.8	9.1	3.8	4.0	8.6	10.5	10.8
	Run 10	0.5	1.6	13.3	26.2	10.3	0.9	2.3	17.4	30.7	14.5
	Run 11	6.3	6.2	11.7	13.7	14.2	8.0	7.6	13.7	16.0	16.4
	Run 12	2.3	4.3	26.0	39.8	24.3	3.0	5.4	32.1	47.1	31.9
	Run 13	9.1	5.1	7.1	8.0	10.4	13.3	9.6	12.3	12.9	15.9
	Run 14	3.7	2.9	14.8	24.3	20.7	6.7	6.5	25.8	38.1	35.7
	Run 15	24.4	23.9	27.6	27.2	30.9	27.5	26.9	30.9	30.6	34.5
	Run 16	17.6	22.7	56.7	70.1	73.7	20.4	26.0	61.5	74.8	79.1
Monitoring Location at 30.5 miles	Run 0	14.5	28.7	140.9	236.0	68.6	16.9	31.4	144.2	239.4	73.0
	Run 1	19.1	33.7	146.8	242.0	76.0	21.1	35.8	149.3	244.6	79.4
	Run 2	9.3	22.7	132.6	227.2	56.9	11.8	25.7	137.0	231.9	63.2
	Run 3	7.9	22.6	157.2	348.5	65.0	10.1	25.7	162.7	354.6	72.9
	Run 4	19.7	31.7	109.4	153.6	65.1	22.2	34.2	112.0	156.3	67.9
	Run 5	42.2	77.9	311.2	444.3	175.5	48.7	84.9	319.1	452.4	185.3
	Run 6	4.9	10.3	56.6	120.4	27.6	6.1	11.7	58.9	122.9	30.9
	Run 7	15.1	29.3	141.3	236.3	68.8	18.9	33.1	145.5	240.6	73.7
	Run 8	14.4	28.7	140.9	236.0	68.6	16.9	31.4	144.2	239.4	72.9
	Run 9	5.2	9.9	47.3	78.9	23.1	6.3	11.1	48.7	80.4	24.9
	Run 10	0.9	4.6	47.8	161.2	16.5	1.4	5.9	51.7	165.9	20.7
	Run 11	9.6	14.5	52.3	84.0	29.0	11.2	16.1	54.1	85.9	31.0
	Run 12	3.5	9.4	60.7	176.4	32.3	4.4	11.0	65.2	182.0	39.6
	Run 13	39.5	64.3	198.2	262.9	143.5	46.4	71.4	206.0	270.8	152.5
	Run 14	13.6	47.9	362.7	646.5	120.3	19.5	57.4	383.3	668.8	146.2
	Run 15	65.8	91.2	226.6	291.5	174.6	70.9	96.3	231.8	296.7	179.9
	Run 16	39.9	83.5	424.2	712.2	205.6	45.3	89.5	431.5	719.8	215.3

Note: NP = Not Present; 0.0 represents a drawdown that is less than 0.1 foot

Table 6-27. Results from a sensitivity analysis of simulated drawdowns caused by pumping 15,000 AFY from Well Field #2 located in PPA #2 at five monitoring locations, as determined by the groundwater model using GHSM-based hydraulic properties for the Carrizo-Wilcox Aquifer.

Monitoring Location at 2.5 miles	30 years					50 years				
	5	6	7	8	9	5	6	7	8	9
Run 0		0.4	2.3	2.7	2.5		0.9	4.6	5.1	4.9
Run 1		0.8	5.0	5.4	5.2		1.5	8.2	8.7	8.5
Run 2		0.0	0.3	0.6	0.5		0.2	1.2	1.6	1.5
Run 3		0.3	4.0	4.8	4.3		0.8	8.2	9.0	8.5
Run 4		0.4	1.6	1.9	1.8		0.9	3.2	3.5	3.4
Run 5		0.0	0.5	0.9	0.8		0.1	1.7	2.3	2.1
Run 6		1.0	5.2	5.5	5.4		1.7	8.3	8.6	8.5
Run 7		0.4	2.3	2.7	2.6		1.0	4.7	5.2	5.0
Run 8		0.3	2.3	2.7	2.5		0.6	4.6	5.1	4.9
Run 9		0.5	1.2	1.4	1.3		1.0	2.4	2.6	2.5
Run 10		0.2	3.0	3.8	3.2		0.6	6.3	7.1	6.5
Run 11		1.8	4.9	5.1	5.1		2.8	7.1	7.4	7.3
Run 12		1.3	13.9	14.7	14.0		2.1	20.9	21.8	21.2
Run 13		0.0	0.0	0.1	0.0		0.0	0.1	0.3	0.3
Run 14		0.0	0.0	0.1	0.0		0.0	0.1	0.3	0.2
Run 15		0.3	2.1	2.8	2.6		0.7	3.7	4.7	4.5
Run 16		0.1	2.8	3.6	3.1		0.3	4.0	4.8	4.2

Monitoring Location at 5.5 miles	30 years					50 years				
	5	6	7	8	9	5	6	7	8	9
Run 0		0.7	3.2	3.8	4.4		1.2	5.5	6.3	7.0
Run 1		1.4	6.3	6.9	7.8		1.9	9.3	10.1	11.0
Run 2		0.1	0.6	1.1	1.3		0.4	1.7	2.4	2.8
Run 3		0.6	5.6	6.8	6.9		1.1	9.9	11.2	11.4
Run 4		0.8	2.3	2.7	3.1		1.2	3.9	4.4	4.8
Run 5		0.3	1.3	2.0	2.5		0.6	3.2	4.1	4.9
Run 6		1.2	5.7	6.2	6.3		1.9	8.7	9.3	9.4
Run 7		0.8	3.3	3.8	4.4		1.4	5.7	6.4	7.1
Run 8		0.7	3.2	3.8	4.4		1.0	5.5	6.3	7.0
Run 9		0.6	1.4	1.7	1.8		1.1	2.6	2.9	3.1
Run 10		0.3	3.5	5.1	3.6		0.6	6.8	8.4	6.8
Run 11		2.0	5.2	5.6	5.9		2.9	7.3	7.8	8.1
Run 12		1.5	14.9	16.4	15.0		2.2	21.6	23.4	22.1
Run 13		0.0	0.1	0.2	0.2		0.1	0.4	0.7	0.9
Run 14		0.0	0.0	0.2	0.2		0.0	0.3	0.9	1.0
Run 15		1.1	4.2	5.1	6.0		1.4	5.9	7.2	8.2
Run 16		0.9	6.6	7.6	9.8		1.3	8.7	9.5	12.2

Monitoring Location at 10.5 miles	30 years					50 years				
	5	6	7	8	9	5	6	7	8	9
Run 0	3.4	3.3	5.8	6.8	7.1	4.5	4.5	8.3	9.5	9.8
Run 1	5.3	5.3	9.7	10.7	11.2	6.2	6.4	12.4	13.8	14.3
Run 2	1.4	0.9	1.8	2.6	2.6	2.4	2.0	3.6	4.6	4.7
Run 3	2.0	2.9	10.2	12.7	10.3	2.9	4.2	14.8	17.5	15.2
Run 4	4.0	3.5	4.4	4.7	4.9	5.1	4.6	6.2	6.7	6.9
Run 5	4.3	3.3	4.2	5.2	5.5	6.2	6.0	7.8	8.8	9.2
Run 6	2.3	2.4	7.3	8.3	7.6	3.0	3.3	10.0	11.3	10.6
Run 7	5.9	3.4	5.9	6.8	7.1	10.0	5.1	8.7	9.7	10.1
Run 8	3.4	3.2	5.8	6.8	7.1	4.5	4.4	8.3	9.5	9.8
Run 9	1.8	1.3	2.2	2.6	2.6	2.5	2.1	3.4	3.8	3.9
Run 10	0.3	0.7	5.3	8.7	4.3	0.6	1.3	8.7	12.4	7.5
Run 11	4.9	3.8	6.3	6.8	7.0	6.5	4.9	8.2	9.0	9.2
Run 12	1.8	2.9	17.4	21.1	16.4	2.4	3.8	23.5	28.0	23.3
Run 13	1.2	0.4	0.5	0.7	0.7	2.7	1.5	1.8	2.2	2.3
Run 14	0.5	0.1	0.3	0.8	0.6	1.4	0.7	1.6	3.0	2.6
Run 15	8.1	9.0	10.5	10.9	11.1	9.7	10.9	13.0	13.7	14.0
Run 16	6.7	8.5	15.4	17.4	18.5	8.4	10.8	19.2	21.0	22.5

Monitoring Location at 15.5 miles	30 years					50 years				
	5	6	7	8	9	5	6	7	8	9
Run 0	6.2	6.9	9.4	11.5	10.8	7.9	8.8	12.2	14.6	13.9
Run 1	9.3	10.4	14.1	16.4	15.8	10.6	12.0	16.6	19.4	18.9
Run 2	2.9	2.8	4.0	5.6	4.7	4.5	4.7	6.5	8.5	7.7
Run 3	3.7	6.2	16.5	22.3	15.0	5.2	8.3	21.4	27.8	20.5
Run 4	7.2	7.2	7.3	7.9	7.6	8.8	9.0	9.3	10.1	9.8
Run 5	10.6	9.5	9.2	11.0	10.3	14.4	14.5	14.5	16.5	15.7
Run 6	3.1	4.1	9.4	11.8	9.4	4.1	5.2	11.9	14.6	12.4
Run 7	7.9	7.2	9.6	11.6	10.8	12.0	9.8	12.8	15.0	14.2
Run 8	6.2	6.9	9.4	11.5	10.8	7.9	8.8	12.2	14.5	13.9
Run 9	2.6	2.5	3.4	4.1	3.8	3.5	3.5	4.6	5.4	5.2
Run 10	0.5	1.5	8.0	14.8	5.4	0.8	2.3	11.6	18.9	8.7
Run 11	6.2	6.0	7.8	8.7	8.6	7.9	7.3	9.6	10.8	10.6
Run 12	2.5	4.8	20.7	28.7	18.3	3.1	5.9	26.2	35.2	25.1
Run 13	4.1	2.4	2.0	2.5	2.2	7.3	5.5	4.9	5.6	5.1
Run 14	1.7	1.1	1.6	3.2	1.9	4.0	3.3	5.1	8.3	6.0
Run 15	18.4	19.6	18.7	19.5	18.3	21.4	23.1	22.3	23.2	22.0
Run 16	15.5	19.0	26.5	32.5	30.3	18.8	23.3	31.7	37.9	35.9

Monitoring Location at 30.5 miles	30 years					50 years				
	5	6	7	8	9	5	6	7	8	9
Run 0	13.9	24.1	52.0	49.1	33.0	16.8	27.3	55.9	53.0	37.6
Run 1	19.5	30.2	59.2	56.2	41.4	21.7	32.5	61.9	59.0	44.8
Run 2	8.0	16.9	42.2	39.1	21.3	10.7	20.4	47.2	44.3	27.2
Run 3	7.7	22.4	80.3	97.5	35.2	10.3	26.2	87.3	104.9	42.8
Run 4	17.4	21.5	31.5	27.4	27.3	20.2	24.2	34.5	30.3	30.5
Run 5	33.9	45.3	73.7	61.5	58.3	41.3	53.2	82.9	70.7	69.4
Run 6	5.1	10.6	31.6	37.5	17.3	6.4	12.2	33.9	40.0	20.3
Run 7	14.5	24.6	52.4	49.4	33.1	18.5	28.9	57.0	54.0	38.2
Run 8	13.9	24.1	52.0	49.1	33.0	16.8	27.3	55.9	53.0	37.6
Run 9	4.9	8.3	17.5	16.6	11.1	6.2	9.6	19.1	18.1	12.9
Run 10	0.8	4.6	30.5	57.5	9.6	1.4	6.1	35.3	63.2	13.3
Run 11	9.8	13.4	23.2	22.2	17.4	11.5	15.1	24.9	24.0	19.4
Run 12	3.8	10.3	46.2	75.8	24.9	4.7	12.0	50.5	81.3	31.6
Run 13	23.6	25.1	33.0	26.5	28.3	30.5	32.4	41.2	34.6	37.8
Run 14	9.3	27.5	85.7	77.0	26.6	15.2	38.3	107.0	97.9	43.3
Run 15	52.3	54.6	65.0	58.0	63.3	58.1	60.5	71.1	63.9	69.5
Run 16	38.7	70.2	155.5	146.7	98.5	45.5	77.9	165.1	156.3	110.2

Note: NP = Not Present; 0.0 represents a drawdown that is less than 0.1 foot

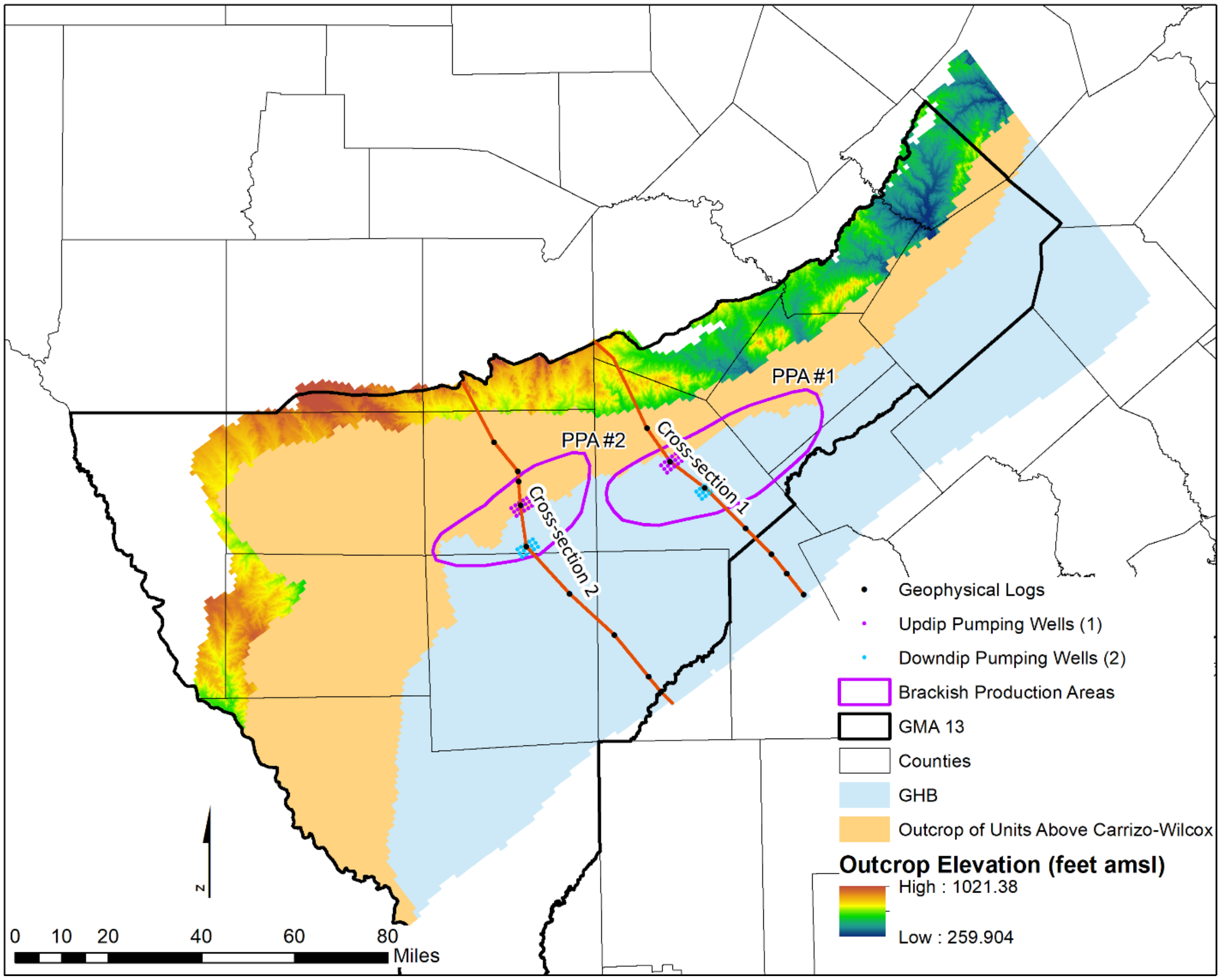


Figure 6-1. **Location of transects through the four potential brackish production zones that were used for developing groundwater models for each potential production area. PPA #1 is associated with cross section 1 and PPA #2 is associated with cross section #2. Geoscientific evaluation of the PPAs indicated that neither of the two met all required criteria of a PPA per House Bill 30. Presence of fresh groundwater in parts of both PPAs, in addition to the presence of a potentially leaky updip fault and the absence of effective hydrogeologic barriers in PPA #2 may lead to significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers.**

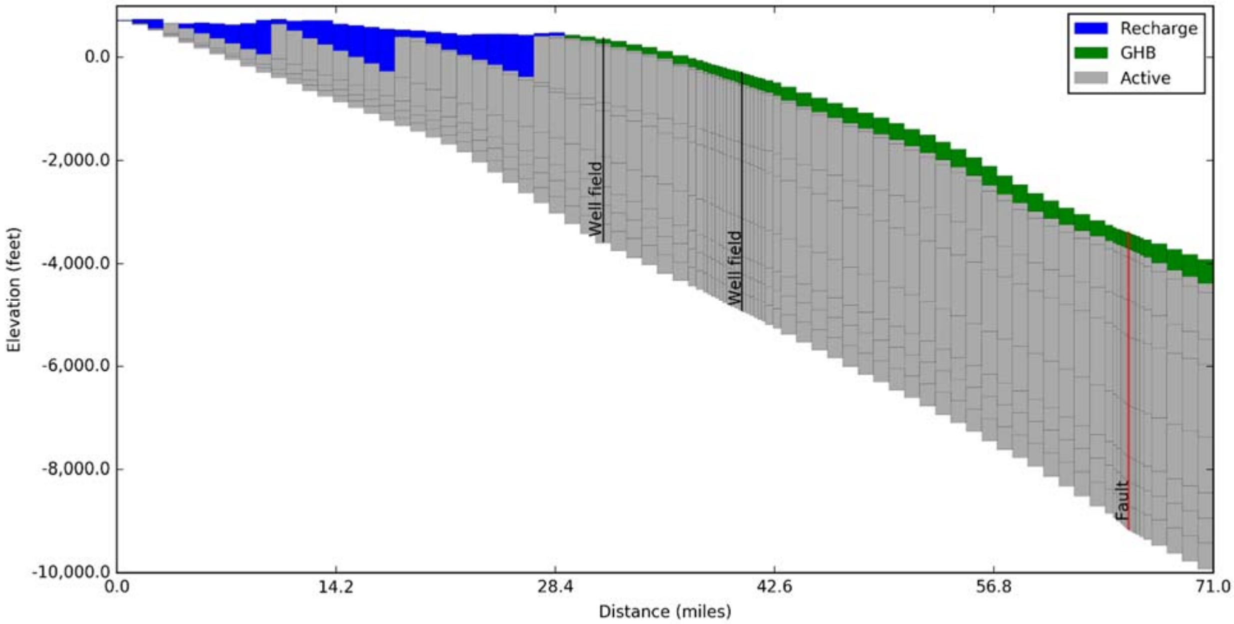


Figure 6-2. **Vertical cross section through PPA #1 that shows the nine model layers, model grids, and the hydraulic boundary conditions, the two well fields and one fault zones used to construct the GAM-based and GHSM-based groundwater models. This cross section is used to model the pumping from the up-dip well field in PPA #1. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.**

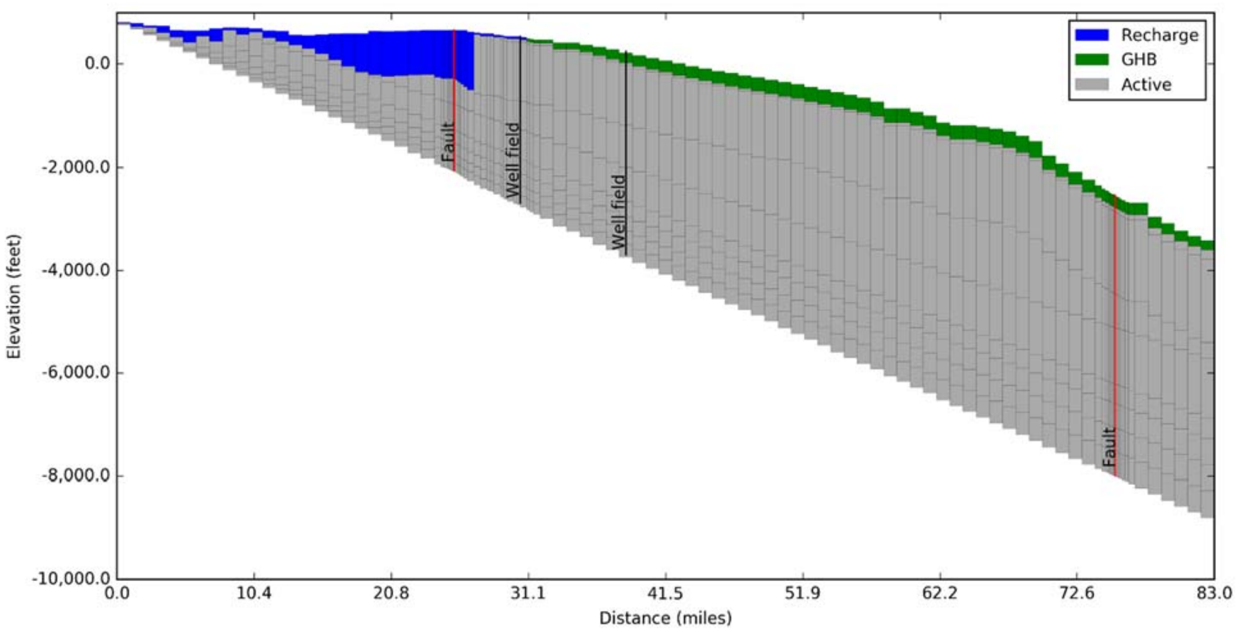


Figure 6-3. **Vertical cross section through PPA #2 that shows the nine model layers, model grids, and the hydraulic boundary conditions, the two well fields and two fault zones used to construct the GAM-based and GHSM-based groundwater models. This cross section is used to model the pumping from the up-dip well field in PPA #2. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30.**

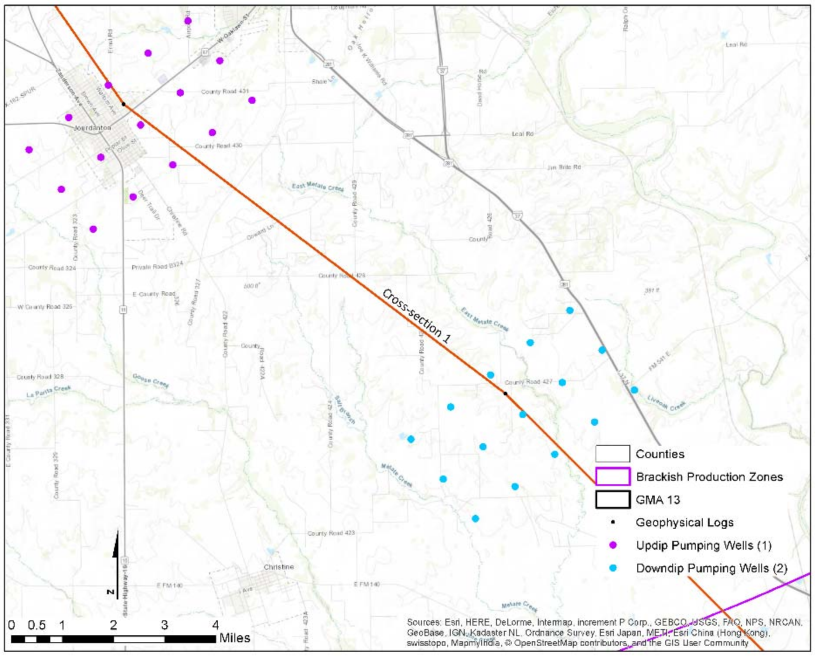


Figure 6-4. Location of the two well fields along cross section #1. Both well fields are illustrated using the 15 well network used to pump 30,000 AFY.

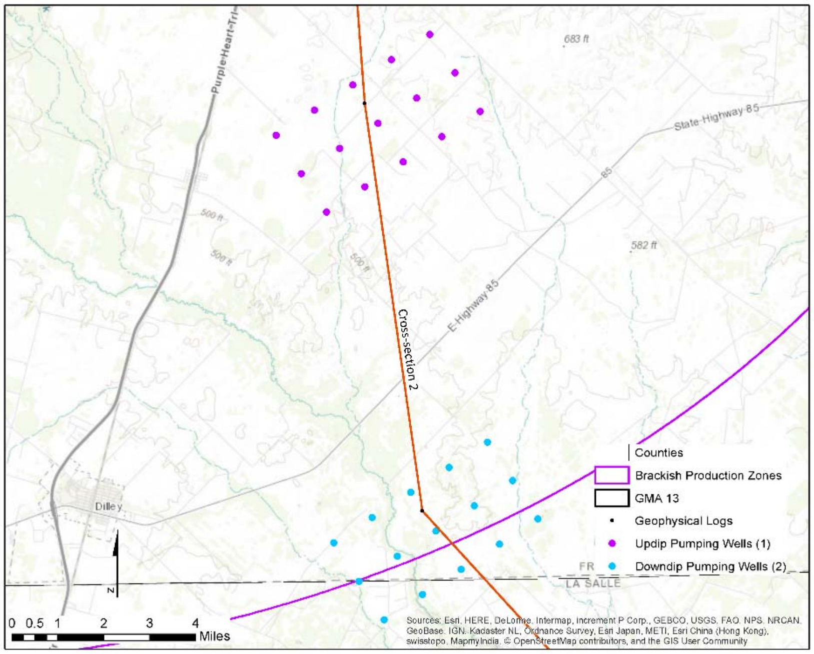


Figure 6-5. Location of the two well fields along cross section #2. Both well fields are illustrated using the 15 well network used to pump 30,000 AFY.

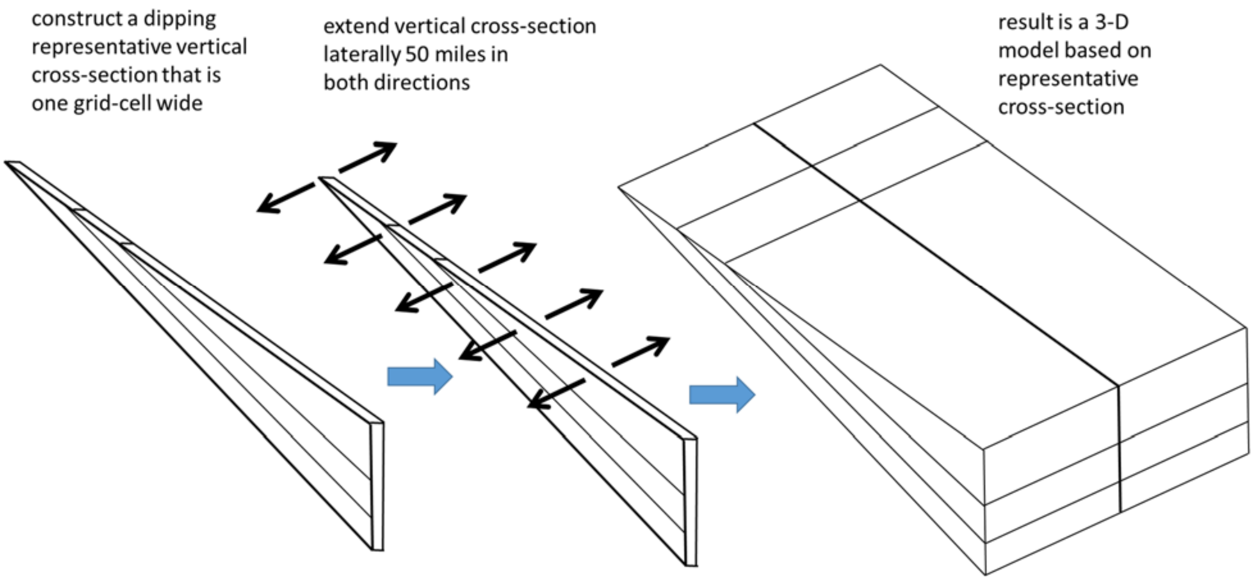


Figure 6-6. **Schematic showing the lateral outward replication of a vertical cross section, which is one grid-cell wide, to construct a three-dimensional model that covers a distance of 50 miles on both sides of the original cross section.**

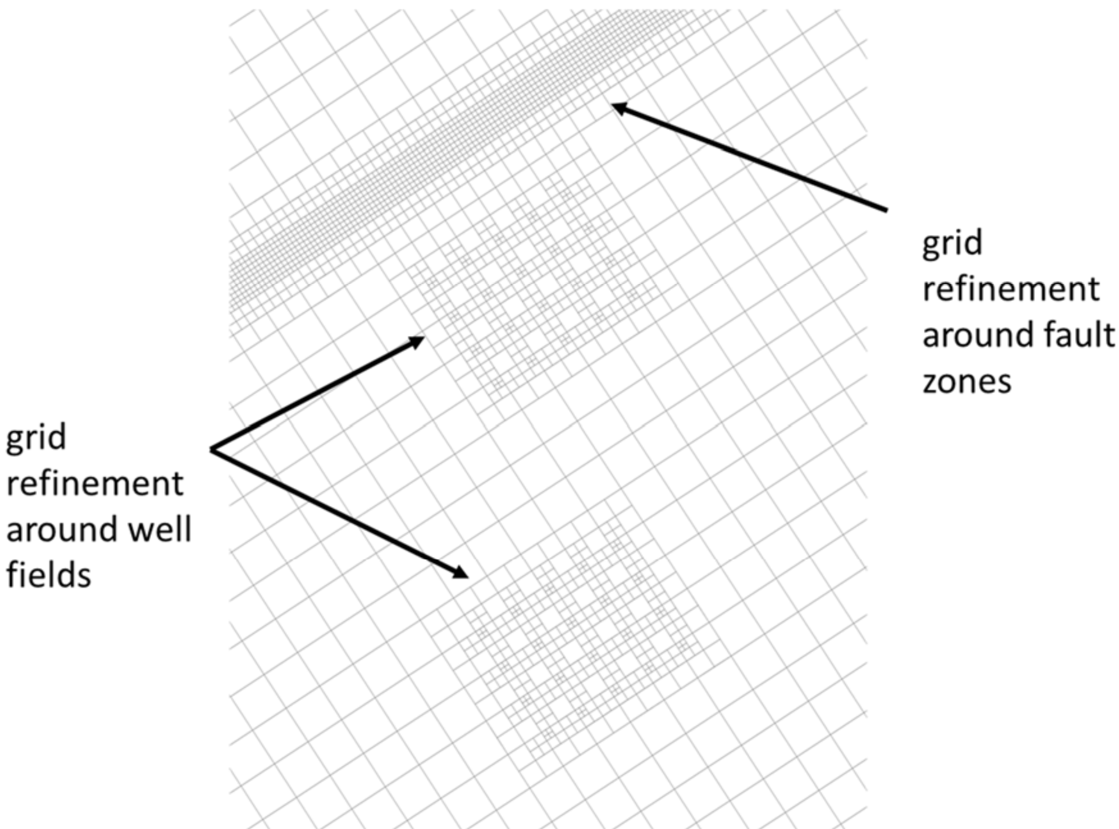
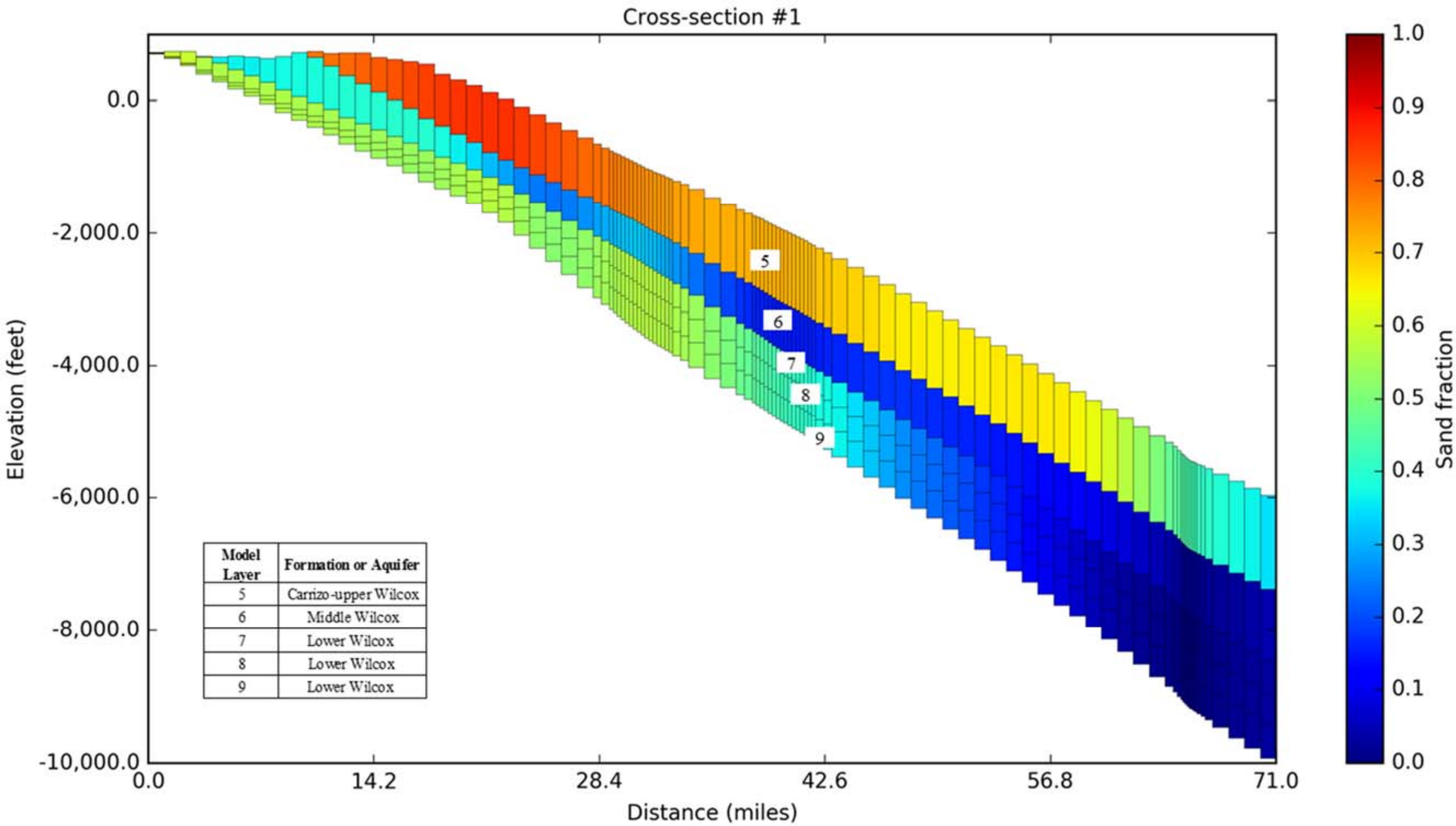
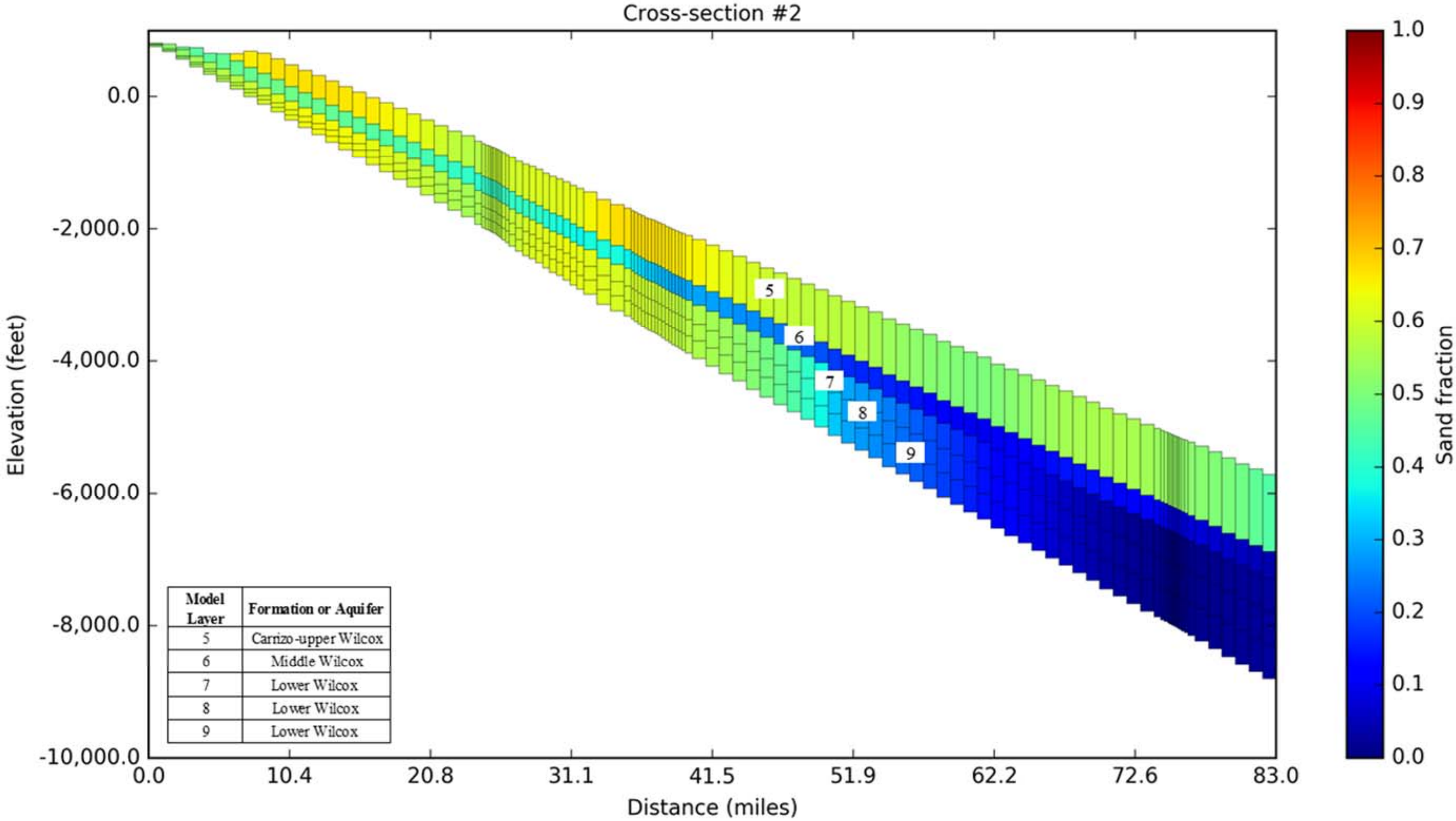


Figure 6-7. **Aerial view of the groundwater model for PPA #1 showing the type of grid refinement that occurs in the vicinity of the well fields and faults to reduce from 1-mile by 1-mile grid cells to 1/8-mile by 1/8-mile grid cells. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.**



Model Layer	Formation or Aquifer
5	Carrizo-upper Wilcox
6	Middle Wilcox
7	Lower Wilcox
8	Lower Wilcox
9	Lower Wilcox

Figure 6-8. Sand fraction for model layers 5, 6, 7, 8, and 9 for a vertical cross section cut through the three-dimensional model for PPA #1. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. Absence of faults in the vicinity prevents groundwater mixing, and the shale-dominated middle Wilcox acts as a potential hydrogeologic barrier, but the presence of fresh groundwater in some parts of PPA #1 may still lead to significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers.



Model Layer	Formation or Aquifer
5	Carrizo-upper Wilcox
6	Middle Wilcox
7	Lower Wilcox
8	Lower Wilcox
9	Lower Wilcox

Figure 6-9. Sand fraction for model layers 5, 6, 7, 8, and 9 for a vertical cross section cut through the three-dimensional model for PPA #2. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30. PPA #2 contains some fresh groundwater, and the updip fault may facilitate groundwater mixing, while the locally sandy nature of the middle Wilcox forms an ineffective hydrogeologic barrier. So significant impacts to water availability or freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers may not be preventable.

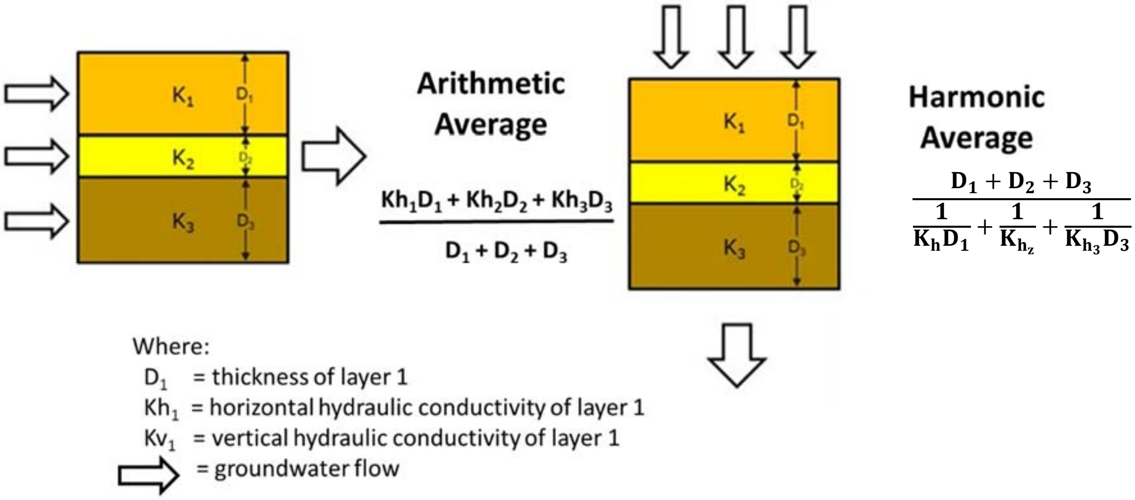


Figure 6-10. **Schematic showing the application of an arithmetic average and a harmonic average to calculate equivalent horizontal and vertical hydraulic conductivities based on the assumption of one-dimension flow through uniform layered media.**

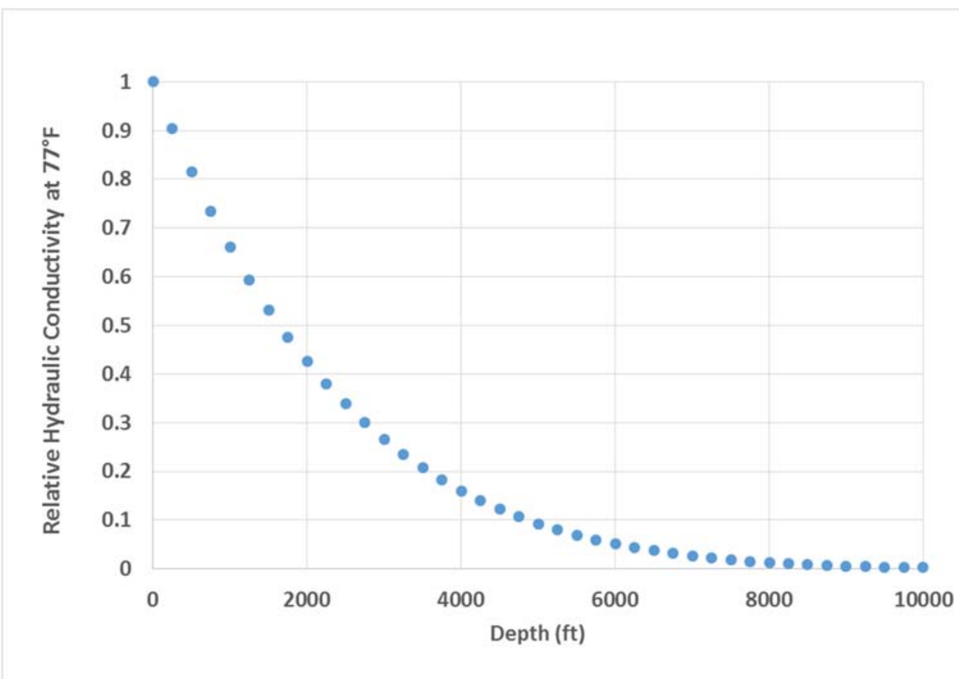


Figure 6-11. **Relationship used by the geohydrostratigraphic Model to account for hydraulic conductivity decrease with depth caused by a decrease in porosity with depth.**

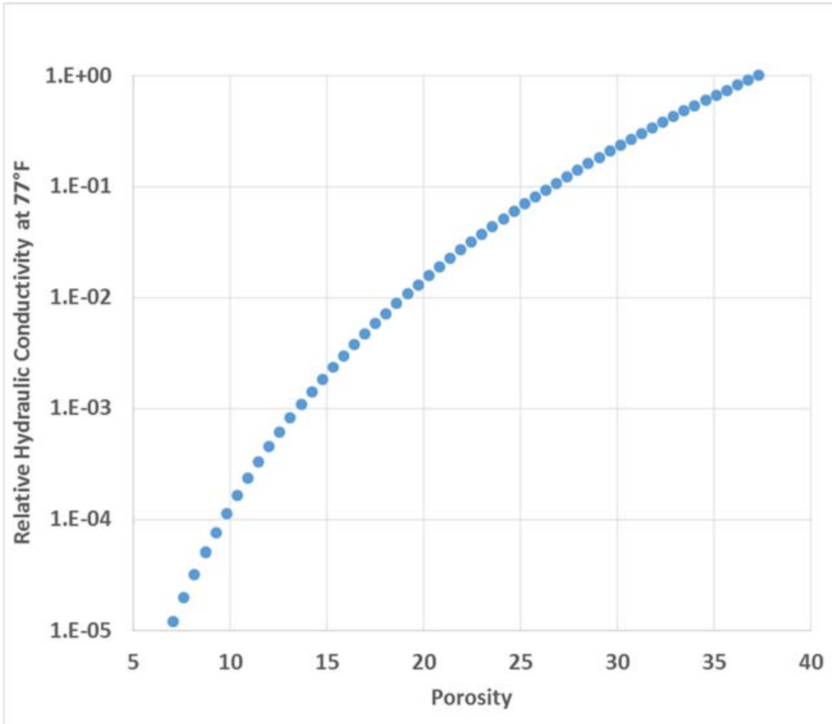


Figure 6-12. **Change in relative hydraulic conductivity as a function of change in porosity based on data from Dutton and Loucks (2014).**

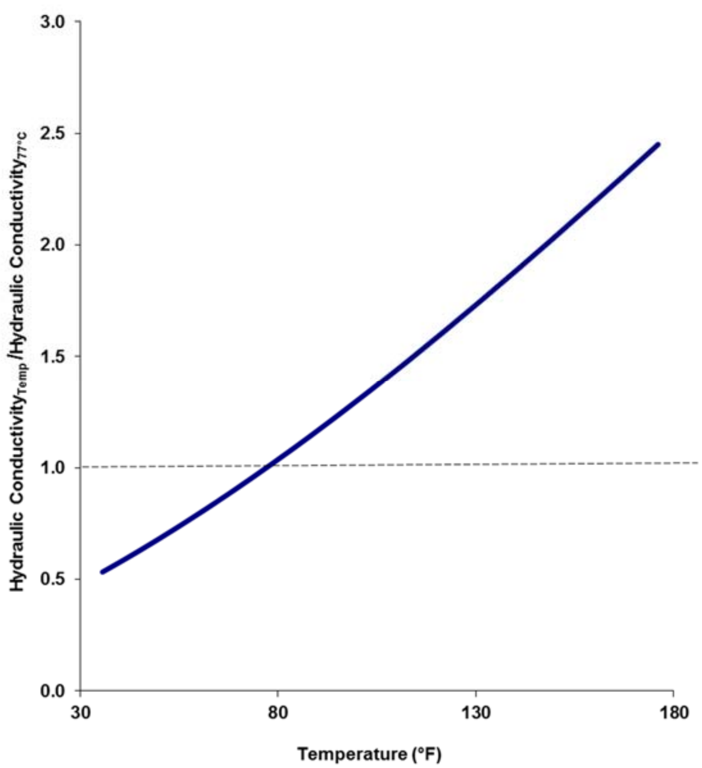


Figure 6-13. **Relative change in hydraulic conductivity values caused by the temperature dependence of the density and viscosity of water.**

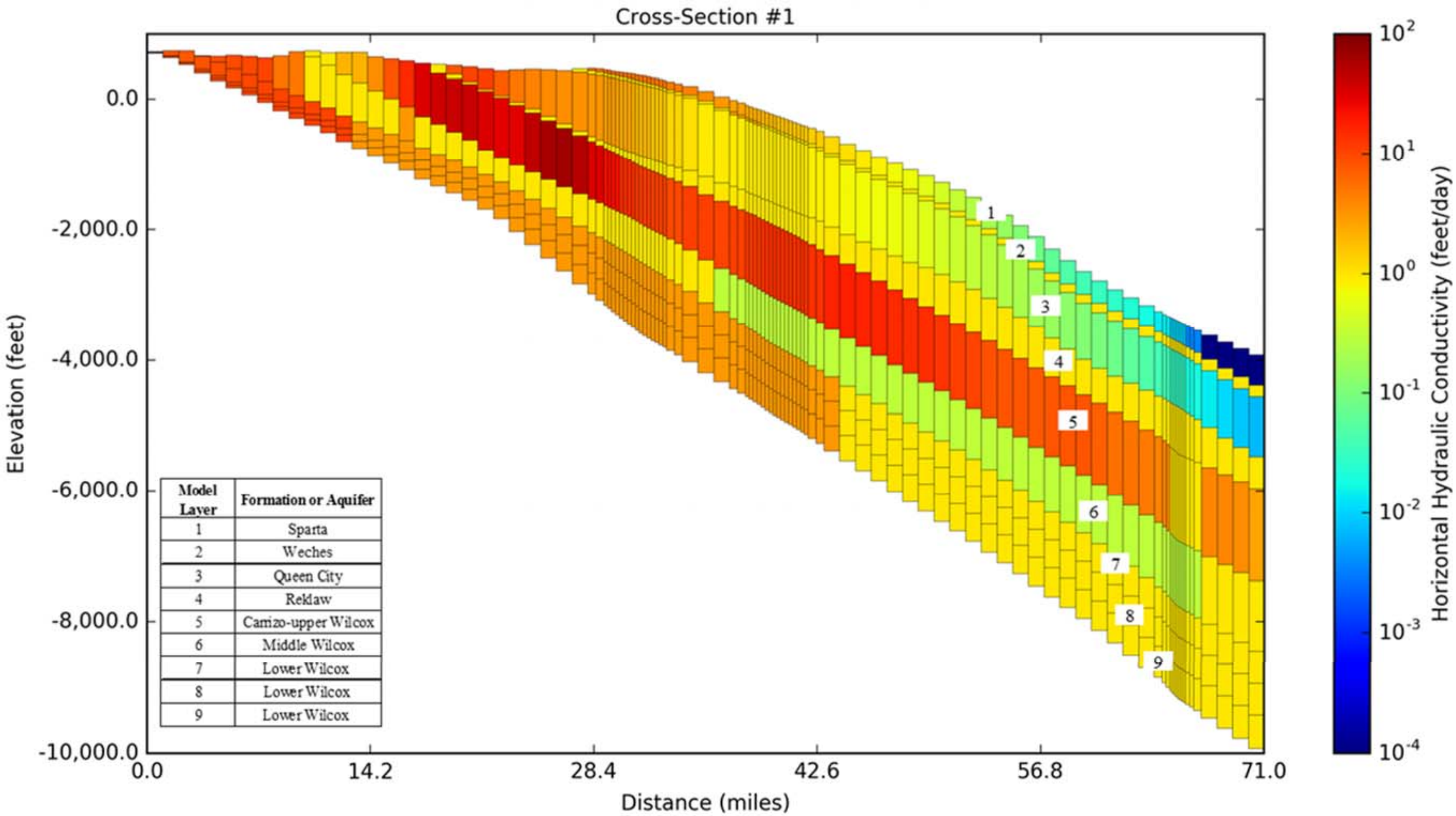


Figure 6-14. **Horizontal hydraulic conductivity values in the groundwater model for PPA #1 with properties that are GAM-based for model layers 1 to 9. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. Absence of faults in the vicinity prevents groundwater mixing, and the shale-dominated middle Wilcox acts as a potential hydrogeologic barrier, but the presence of fresh groundwater in some parts of PPA #1 may still lead to significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers.**

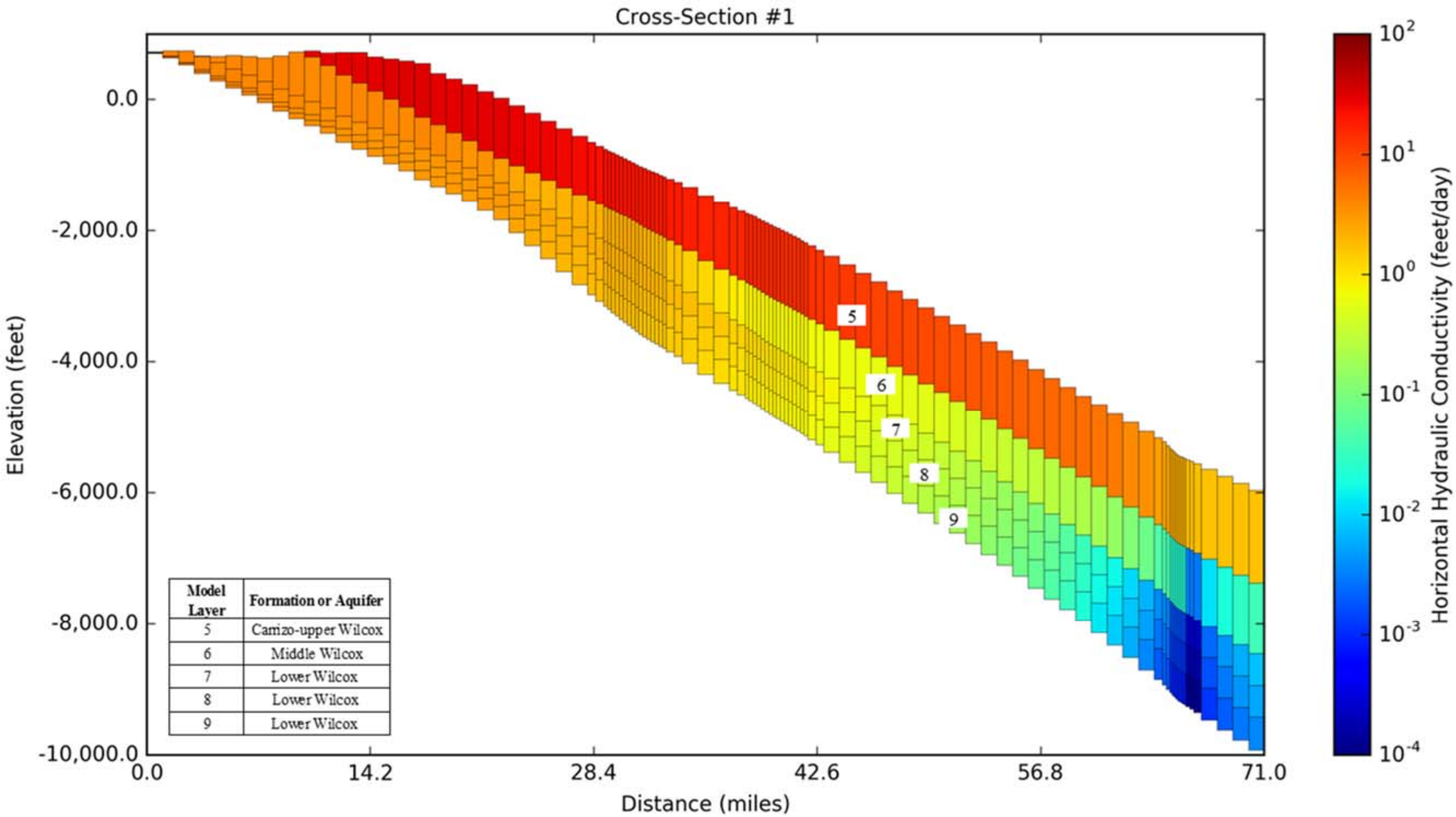


Figure 6-15. **Horizontal hydraulic conductivity values in the groundwater model for PPA #1 with properties that are GHSM-based for model layers 5 to 9. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. Absence of faults in the vicinity prevents groundwater mixing, and the shale-dominated middle Wilcox acts as a potential hydrogeologic barrier, but the presence of fresh groundwater in some parts of PPA #1 may still lead to significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers.**

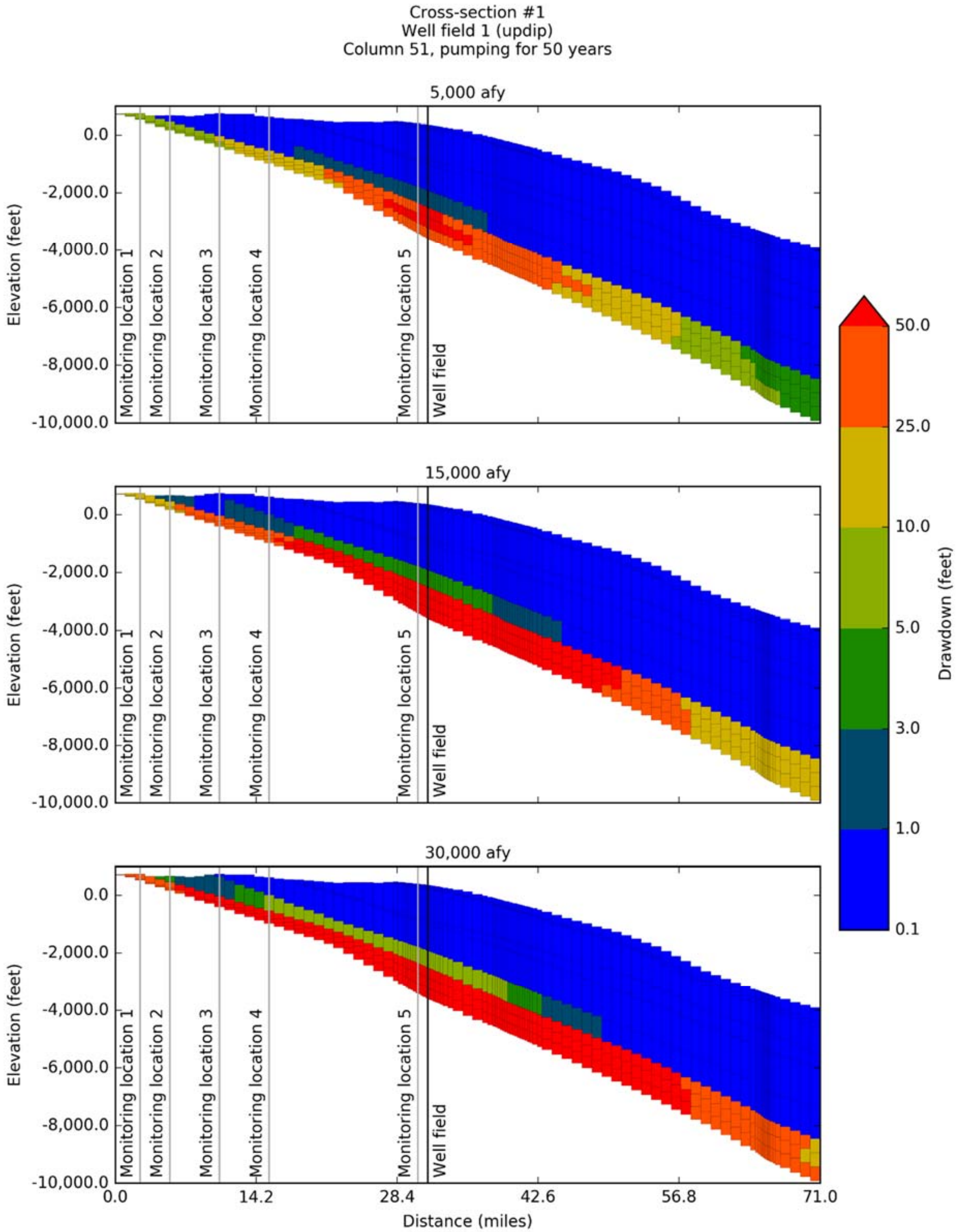


Figure 6-16. Simulated drawdown at 50 years after pumping the up dip Well Field #1 located in PPA #1 at 5,000 AFY, 15,000 AFY, and 30,000 AFY produced by the groundwater model with GAM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.

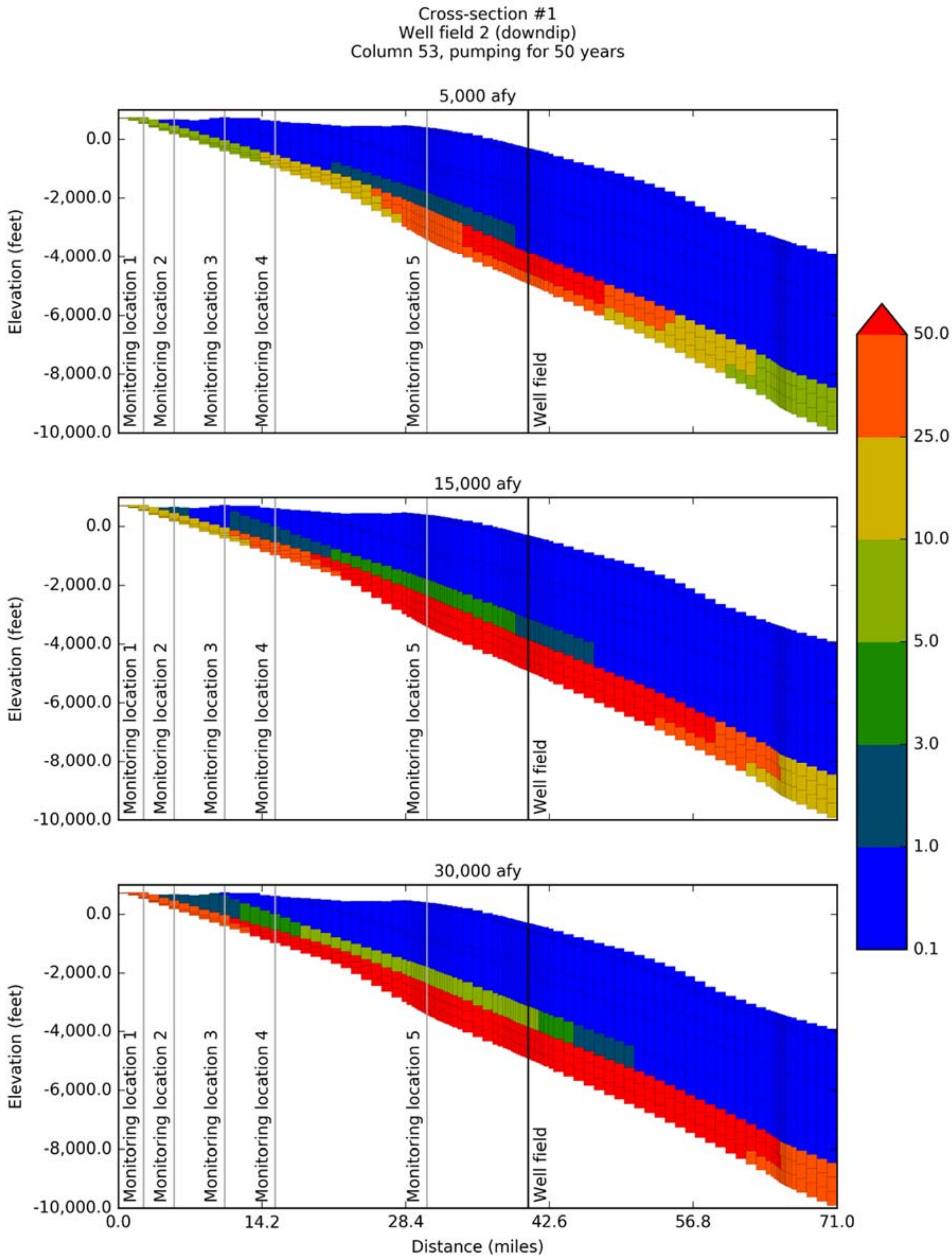


Figure 6-17. **Simulated drawdown at 50 years after pumping the up dip Well Field #2 located in PPA #1 at 5,000 AFY, 15,000 AFY, and 30,000 AFY produced by the groundwater model with GAM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.**

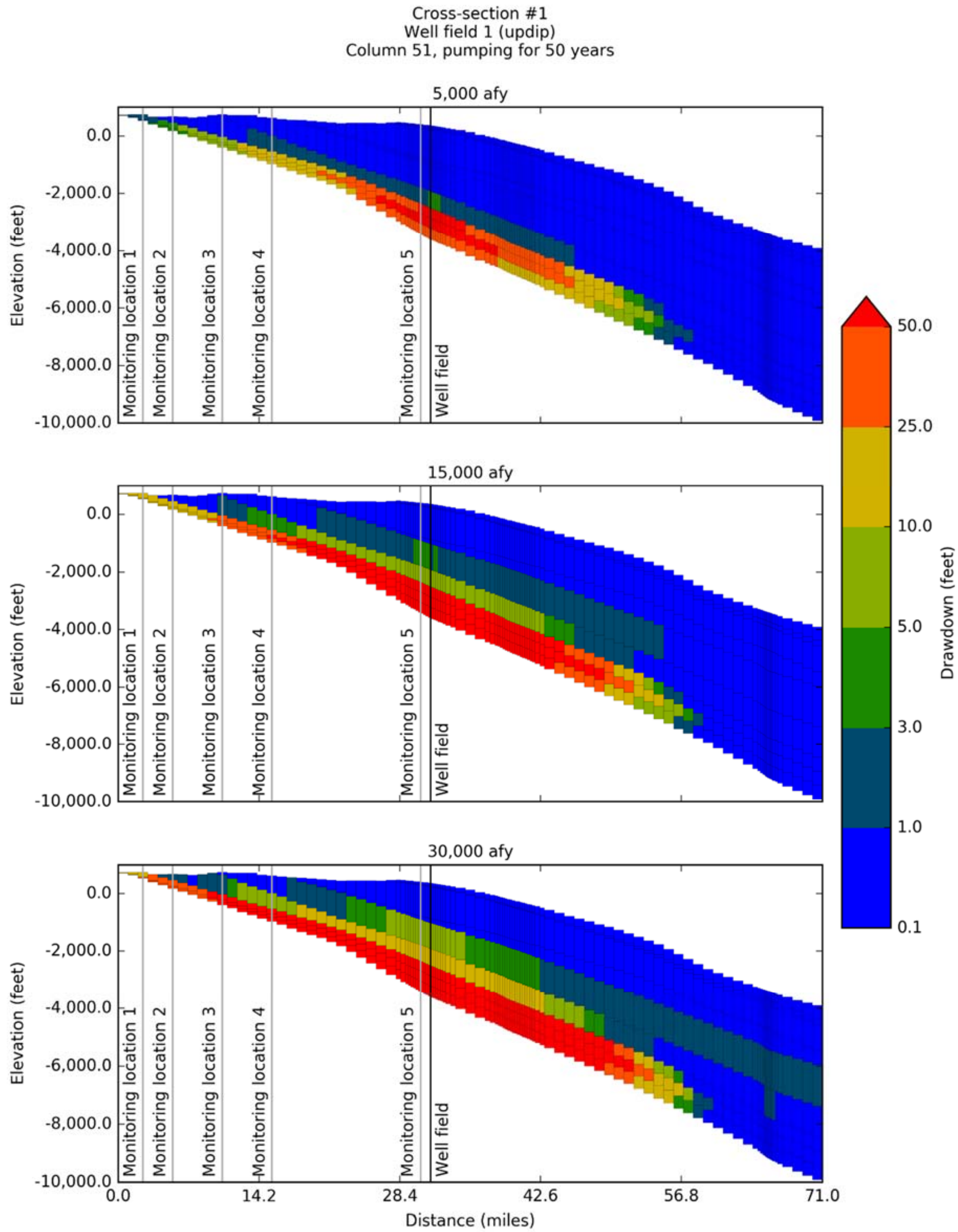


Figure 6-18. Simulated drawdown at 50 years after pumping the up dip Well Field #1 located in PPA #1 at 5,000 AFY, 15,000 AFY, and 30,000 AFY produced by the groundwater model with GHSM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.

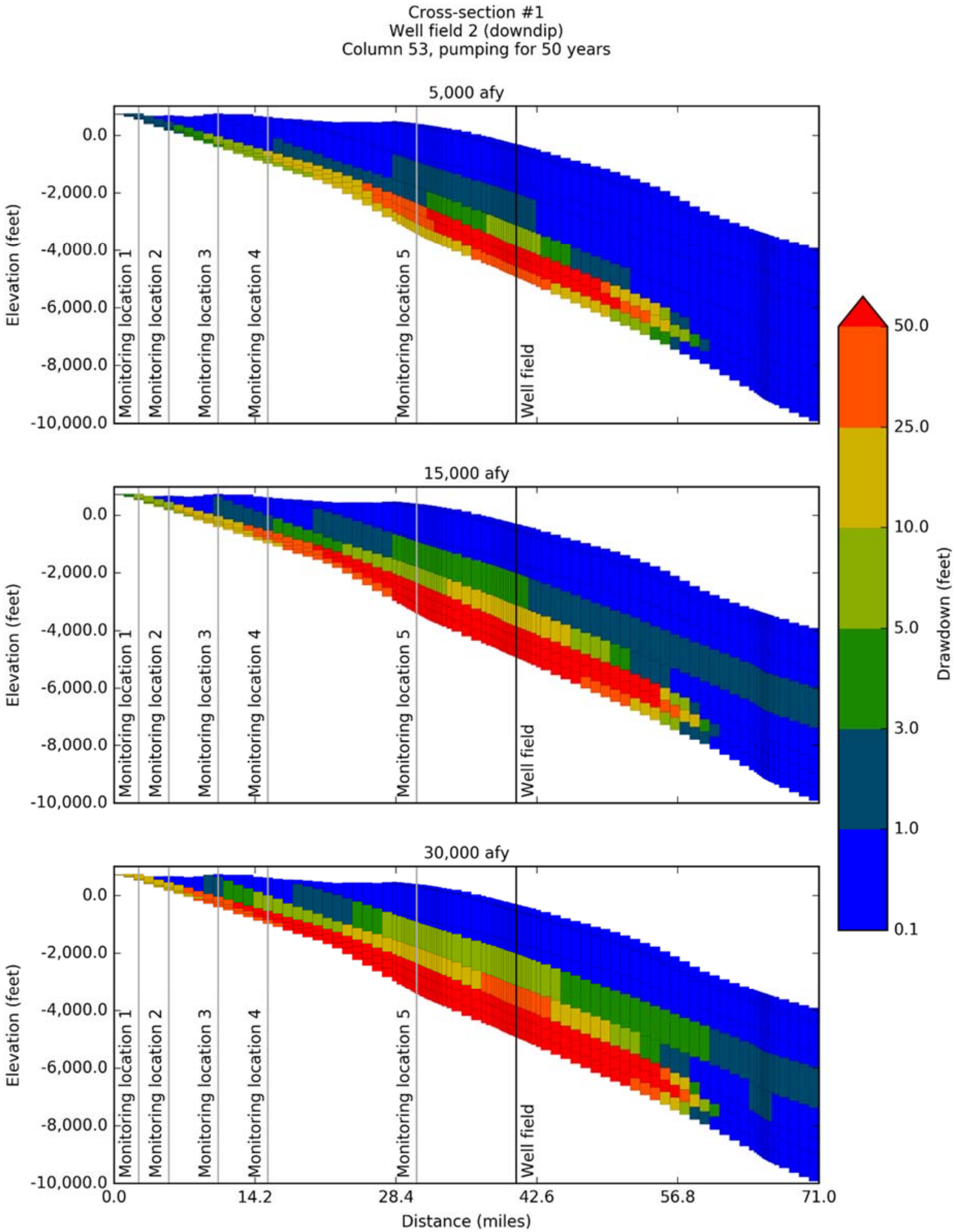


Figure 6-19. **Simulated drawdown at 50 years after pumping the up dip Well Field #2 located in PPA #1 at 5,000 AFY, 15,000 AFY, and 30,000 AFY produced by the groundwater model with GHSM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.**

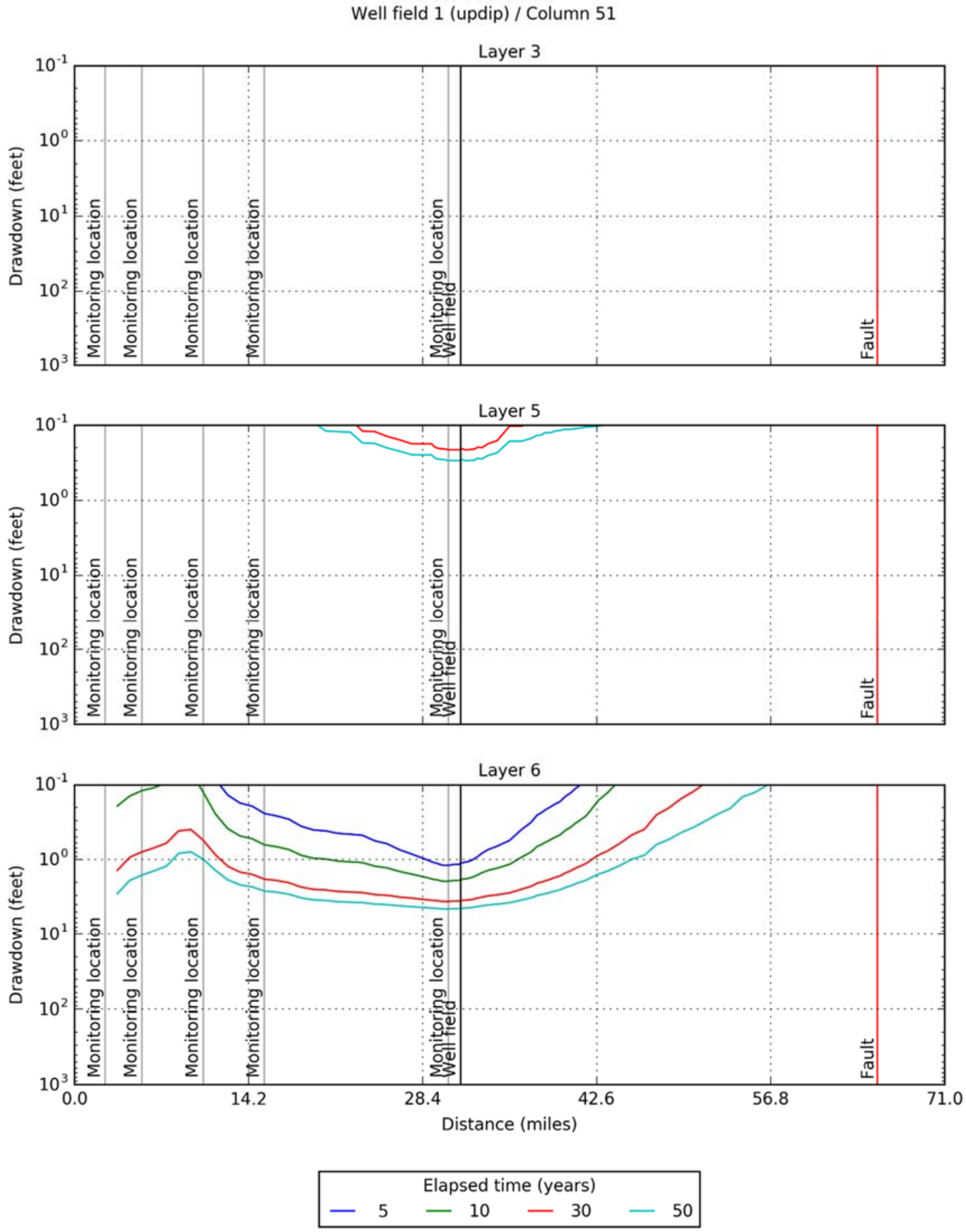


Figure 6-20. Simulated drawdown at 5, 10, 30, and 50 years for model layers 3, 5, and 6 after pumping the up dip Well Field #1 located in PPA #1 at 15,000 AFY produced by the groundwater model with GAM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. Absence of faults in the vicinity prevents groundwater mixing, and the shale-dominated middle Wilcox acts as a potential hydrogeologic barrier, but the presence of fresh groundwater in some parts of PPA #1 may still lead to significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers.

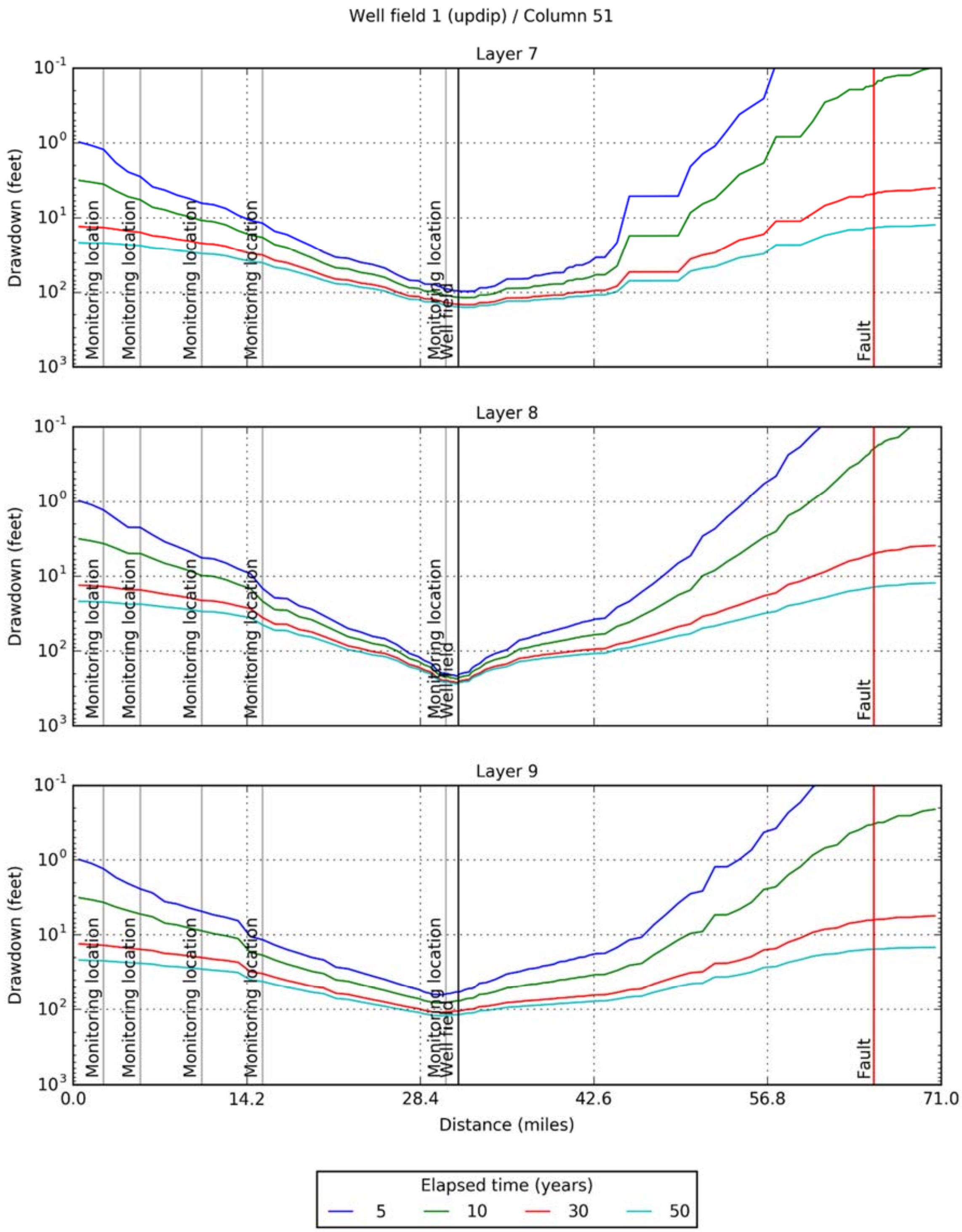


Figure 6-21. **Simulated drawdown at 5, 10, 30, and 50 years for model layers 7, 8, and 9 after pumping the up dip Well Field #1 located in PPA #1 at 15,000 AFY produced by the groundwater model with GAM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. Absence of faults in the vicinity prevents groundwater mixing, and the shale-dominated middle Wilcox acts as a potential hydrogeologic barrier, but the presence of fresh groundwater in some parts of PPA #1 may still lead to significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers.**

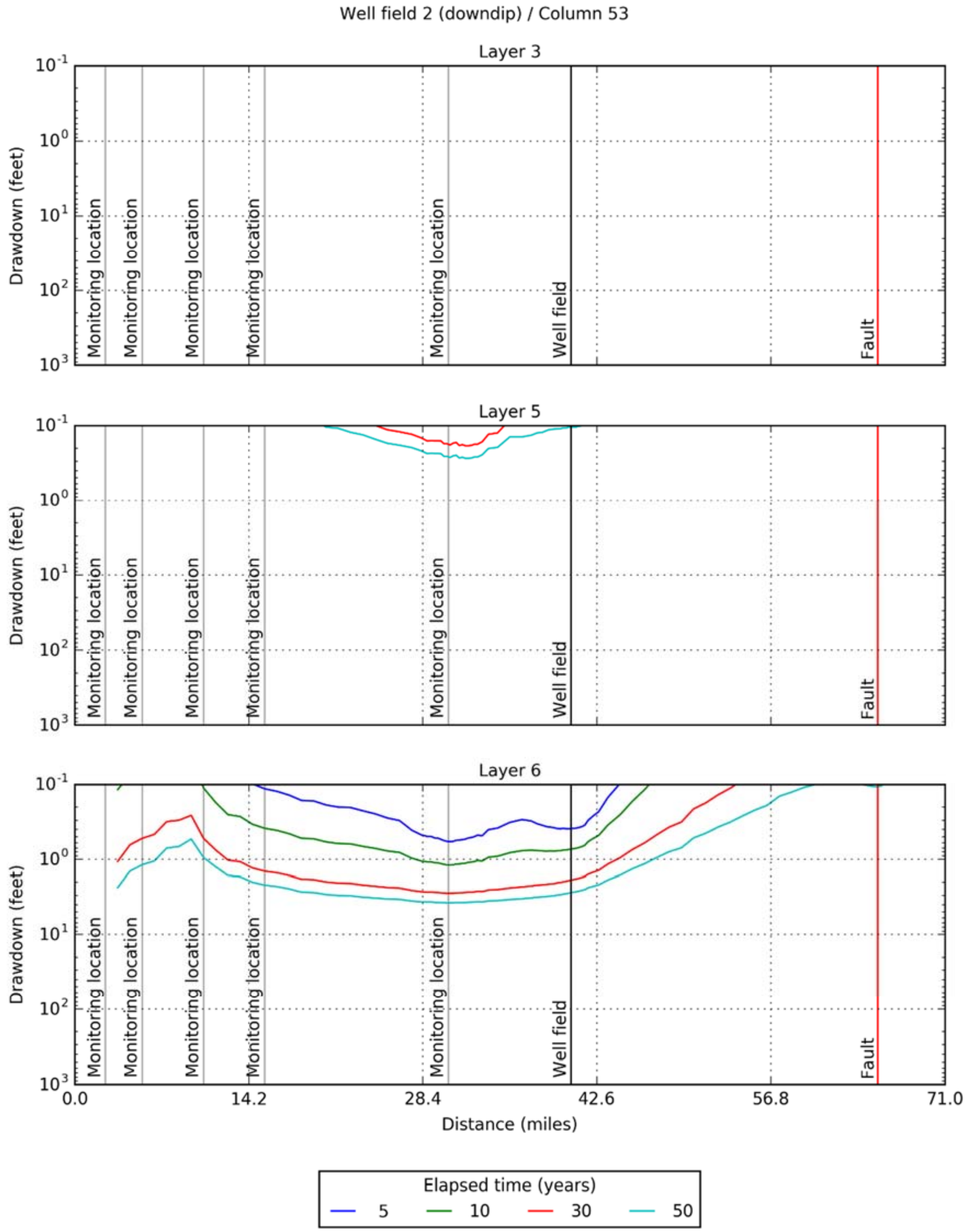


Figure 6-22. **Simulated drawdown at 5, 10, 30, and 50 years for model layers 3, 5, and 6 after pumping the down dip Well Field #2 located in PPA #1 at 15,000 AFY produced by the groundwater model with GAM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. Absence of faults in the vicinity prevents groundwater mixing, and the shale-dominated middle Wilcox acts as a potential hydrogeologic barrier, but the presence of fresh groundwater in some parts of PPA #1 may still lead to significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers.**

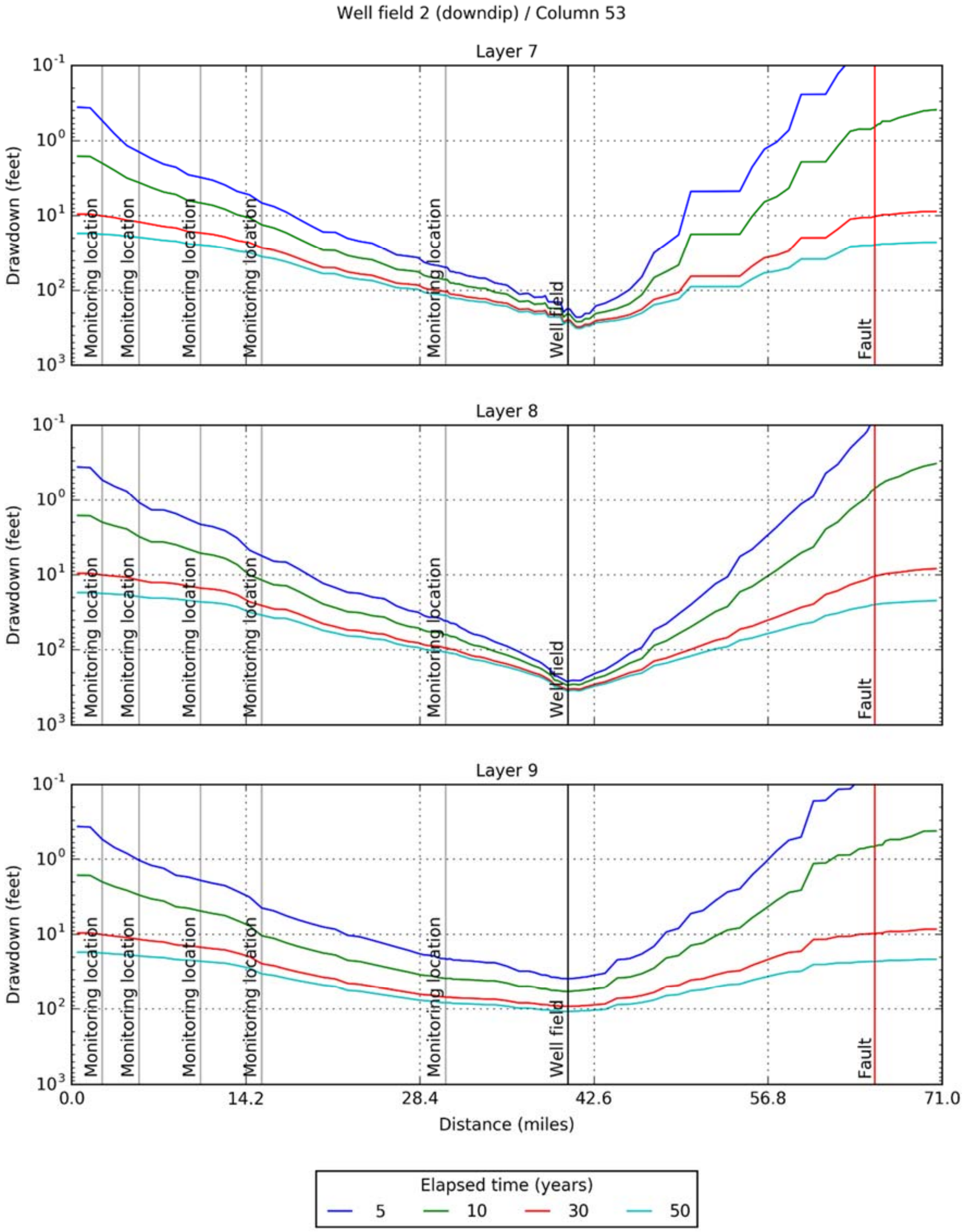


Figure 6-23. Simulated drawdown at 5, 10, 30, and 50 years for model layers 7, 8, and 9 after pumping the down dip Well Field #2 located in PPA #1 at 15,000 AFY produced by the groundwater model with GAM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. Absence of faults in the vicinity prevents groundwater mixing, and the shale-dominated middle Wilcox acts as a potential hydrogeologic barrier, but the presence of fresh groundwater in some parts of PPA #1 may still lead to significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers.

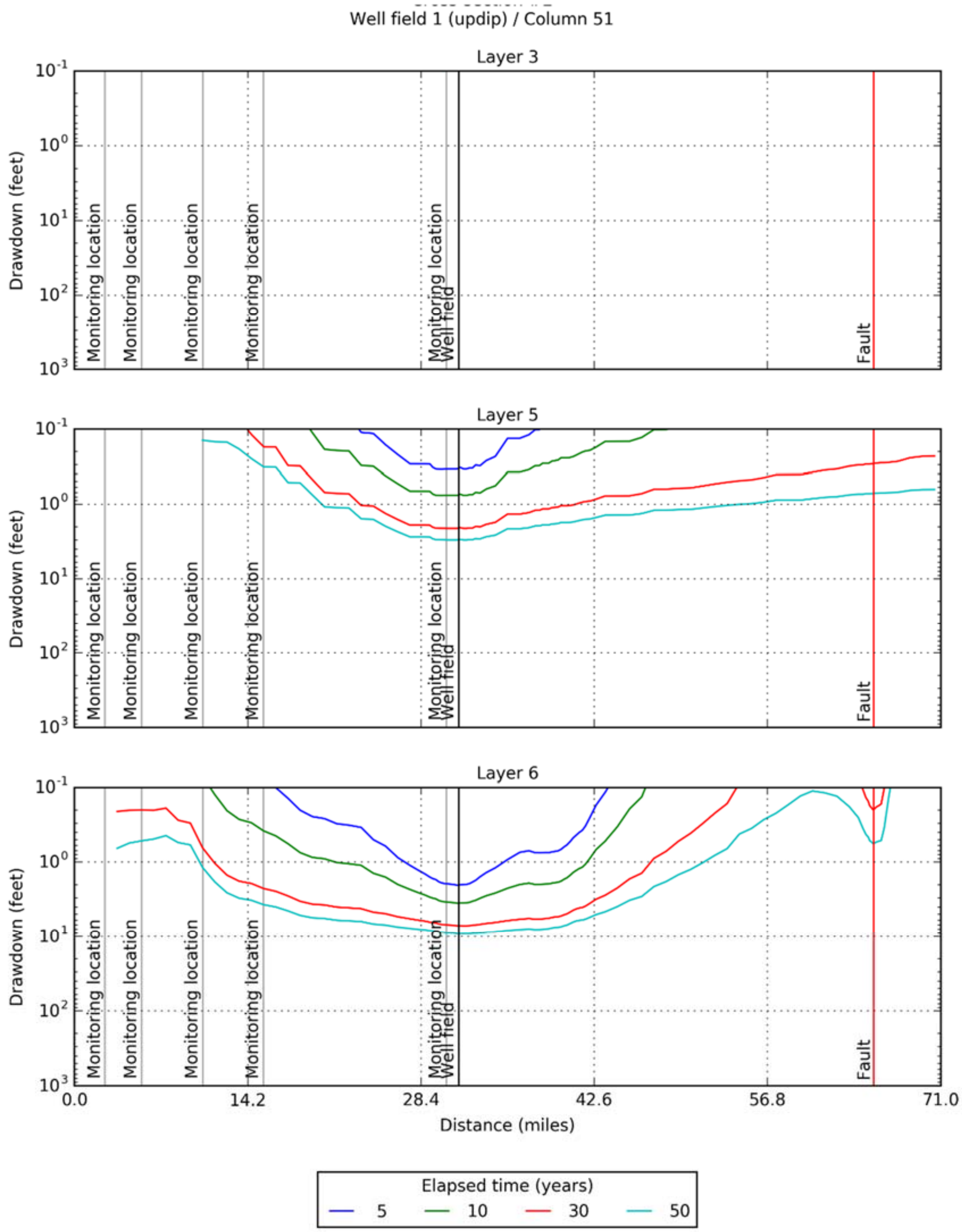


Figure 6-24. **Simulated drawdown at 5, 10, 30, and 50 years for model layers 3, 5, and 6 after pumping the up dip Well Field #1 located in PPA #1 at 15,000 AFY produced by the groundwater model with GHSM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. Absence of faults in the vicinity prevents groundwater mixing, and the shale-dominated middle Wilcox acts as a potential hydrogeologic barrier, but the presence of fresh groundwater in some parts of PPA #1 may still lead to significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers.**

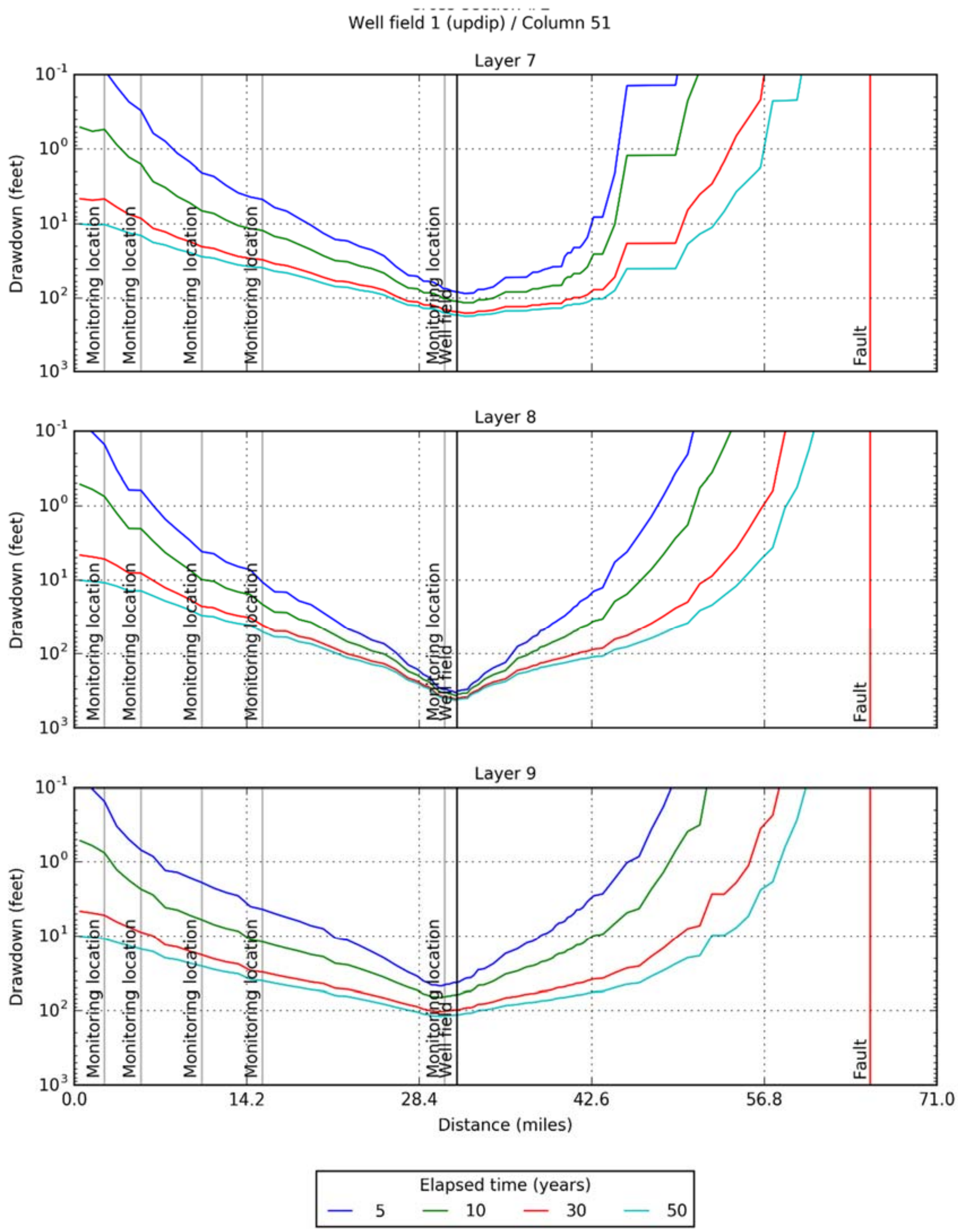


Figure 6-25. **Simulated drawdown at 5, 10, 30, and 50 years for model layers 7, 8, and 9 after pumping the up dip Well Field #1 located in PPA #1 at 15,000 AFY produced by the groundwater model with GHSM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. Absence of faults in the vicinity prevents groundwater mixing, and the shale-dominated middle Wilcox acts as a potential hydrogeologic barrier, but the presence of fresh groundwater in some parts of PPA #1 may still lead to significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers.**

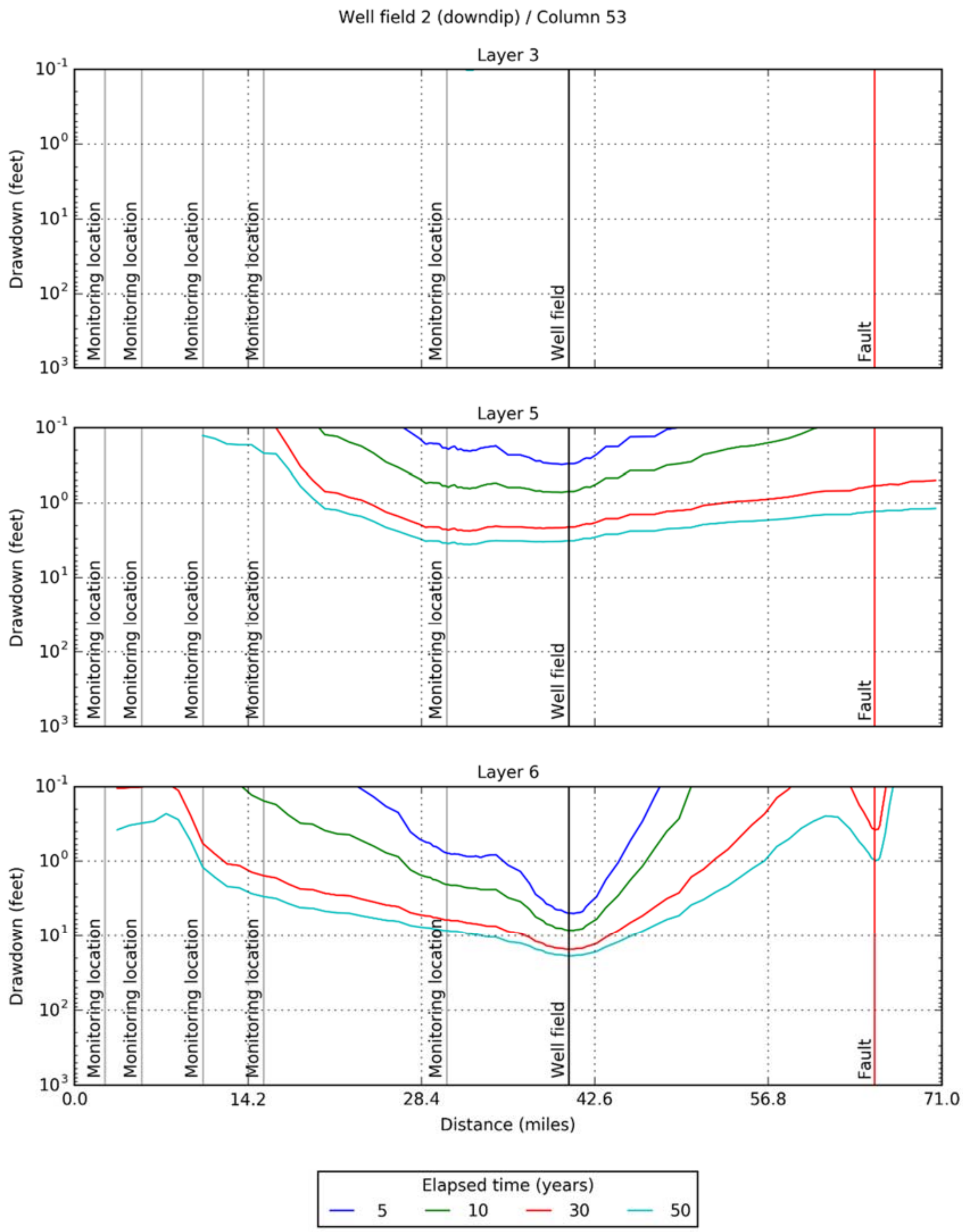


Figure 6-26. **Simulated drawdown at 5, 10, 30, and 50 years for model layers 3, 5, and 6 after pumping the down dip Well Field #2 located in PPA #1 at 15,000 AFY produced by the groundwater model with GHSM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. Absence of faults in the vicinity prevents groundwater mixing, and the shale-dominated middle Wilcox acts as a potential hydrogeologic barrier, but the presence of fresh groundwater in some parts of PPA #1 may still lead to significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers.**

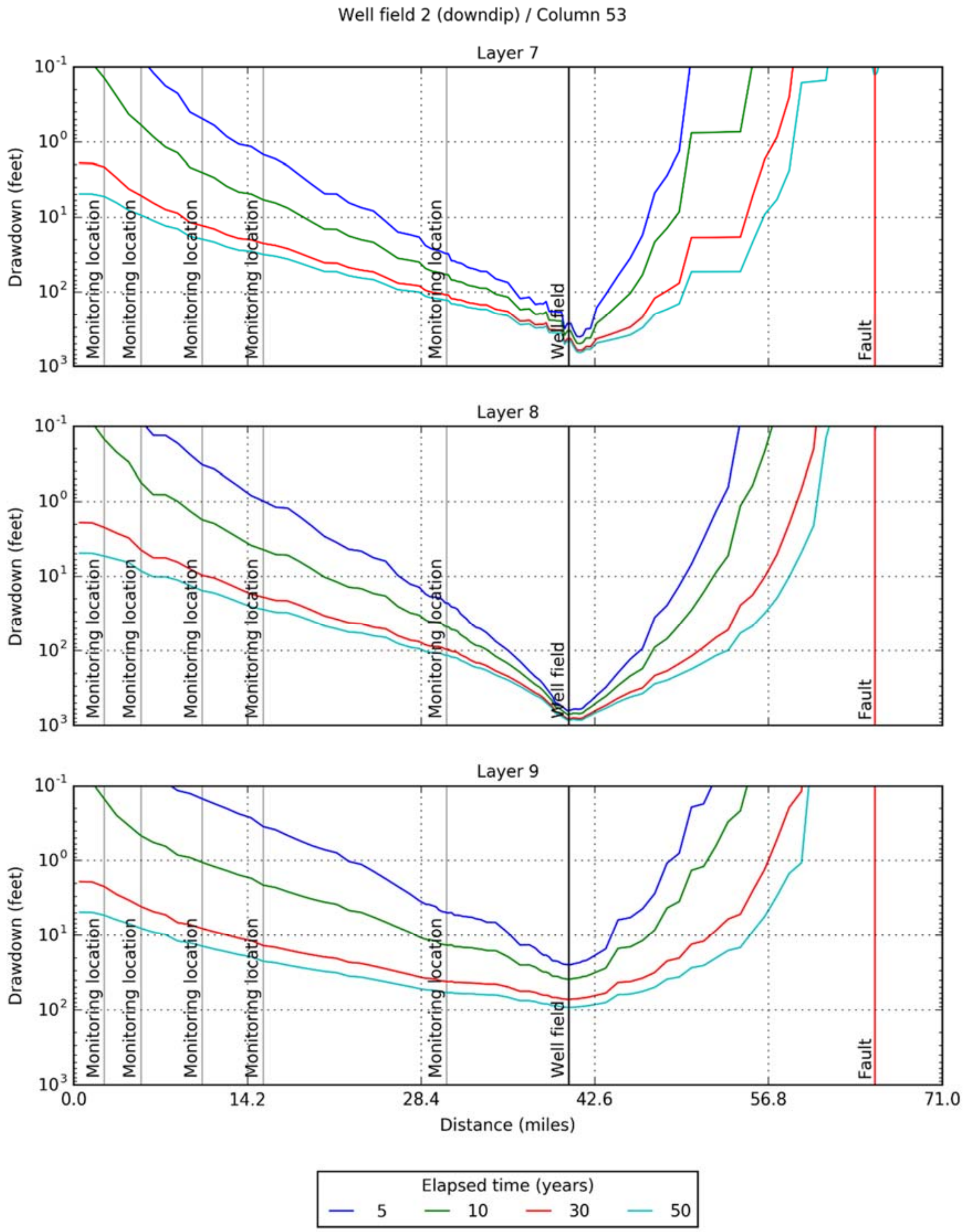
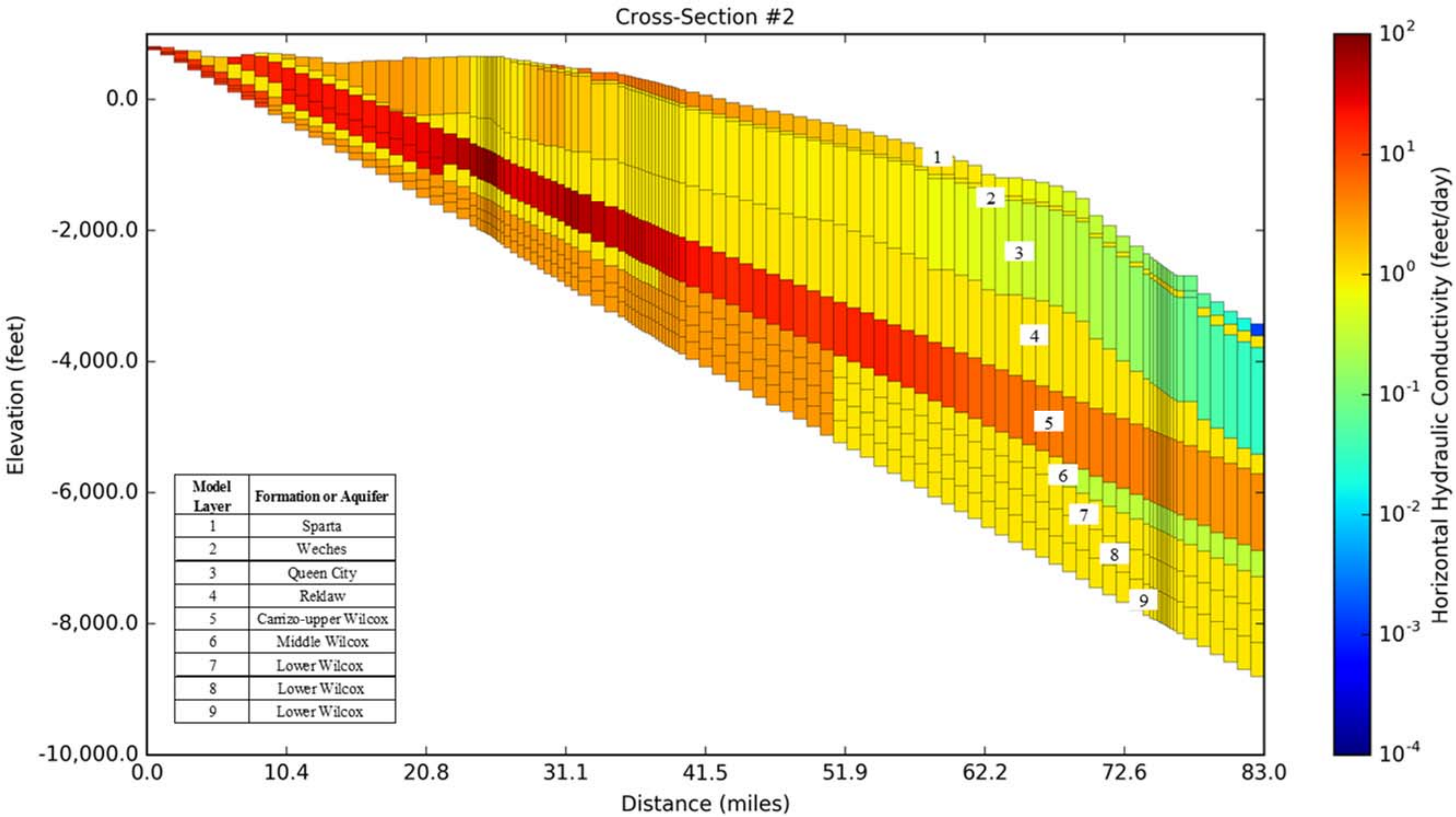


Figure 6-27. **Simulated drawdown at 5, 10, 30, and 50 years for model layers 7, 8, and 9 after pumping the down dip Well Field #2 located in PPA #1 at 15,000 AFY produced by the groundwater model with GHSM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #1 was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. Absence of faults in the vicinity prevents groundwater mixing, and the shale-dominated middle Wilcox acts as a potential hydrogeologic barrier, but the presence of fresh groundwater in some parts of PPA #1 may still lead to significant impacts to freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers.**



Model Layer	Formation or Aquifer
1	Sparta
2	Weches
3	Queen City
4	Reklaw
5	Carrizo-upper Wilcox
6	Middle Wilcox
7	Lower Wilcox
8	Lower Wilcox
9	Lower Wilcox

Figure 6-28. **Horizontal hydraulic conductivity values in the groundwater model for PPA #2 with properties that are GAM-based for model layers 1 to 9. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30. PPA #2 contains some fresh groundwater, and the updip fault may facilitate groundwater mixing, while the locally sandy nature of the middle Wilcox forms an ineffective hydrogeologic barrier. So significant impacts to water availability or freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers may not be preventable.**

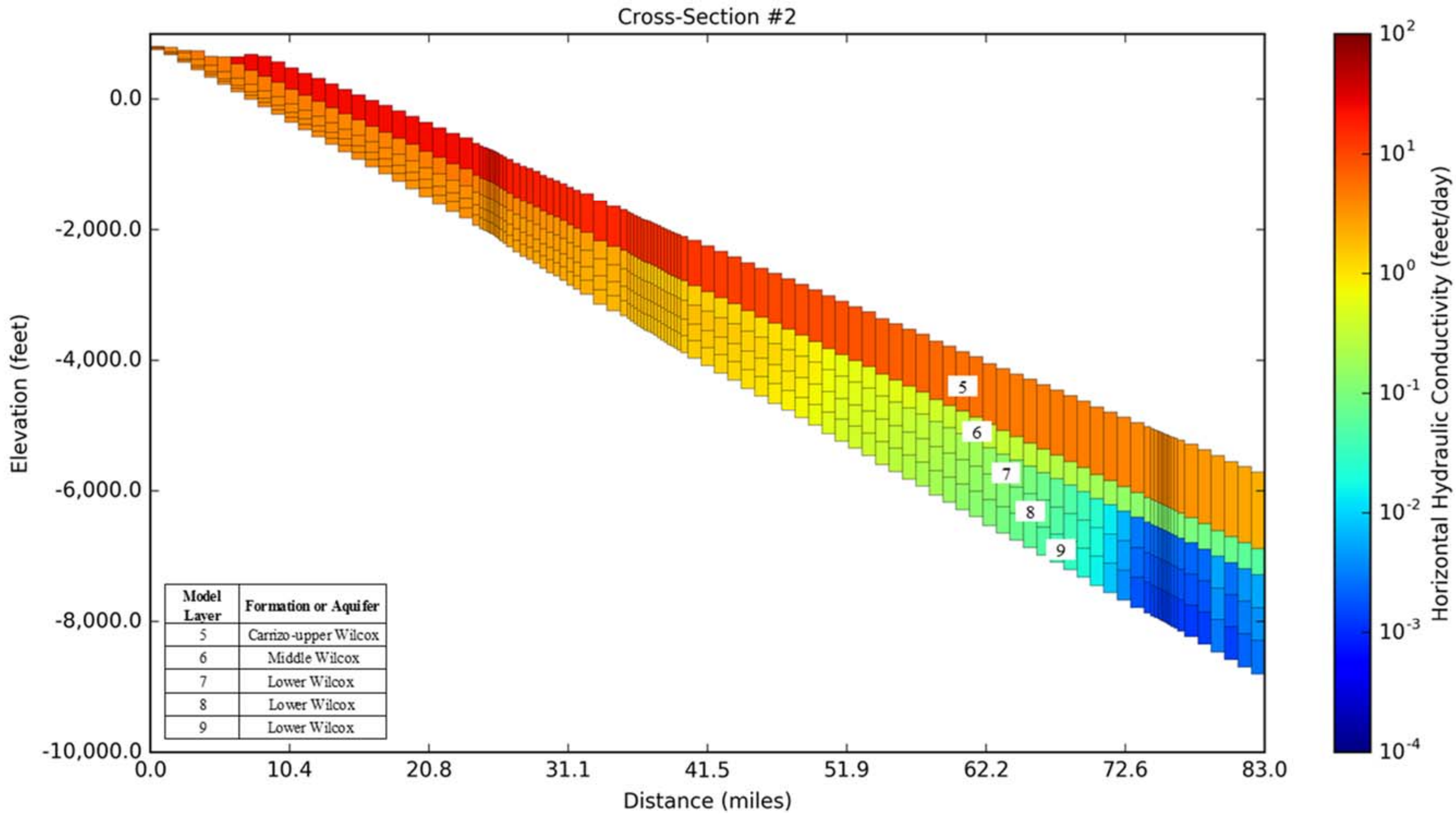


Figure 6-29. **Horizontal hydraulic conductivity values in the groundwater model for PPA #2 with properties that are GHSM-based for model layers 5 to 9. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30. PPA #2 contains some fresh groundwater, and the updip fault may facilitate groundwater mixing, while the locally sandy nature of the middle Wilcox forms an ineffective hydrogeologic barrier. So significant impacts to water availability or freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers may not be preventable.**

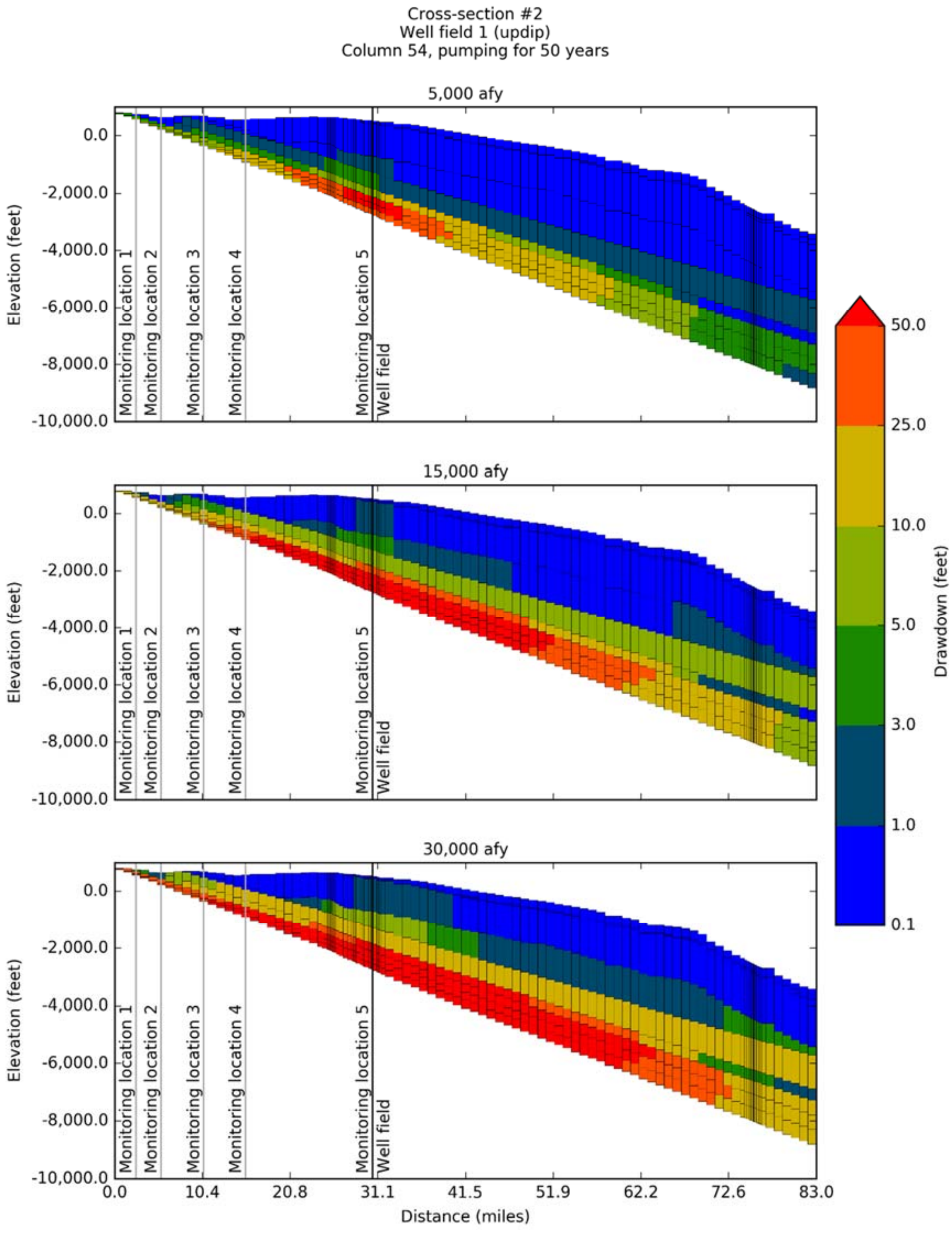


Figure 6-30. **Simulated drawdown at 50 years after pumping the up dip Well Field #1 located in PPA #2 at 5,000 AFY, 15,000 AFY, and 30,000 AFY produced by the groundwater model with GAM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30. PPA #2 contains some fresh groundwater, and the updip fault may facilitate groundwater mixing, while the locally sandy nature of the middle Wilcox forms an ineffective hydrogeologic barrier. So significant impacts to water availability or freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers may not be preventable.**

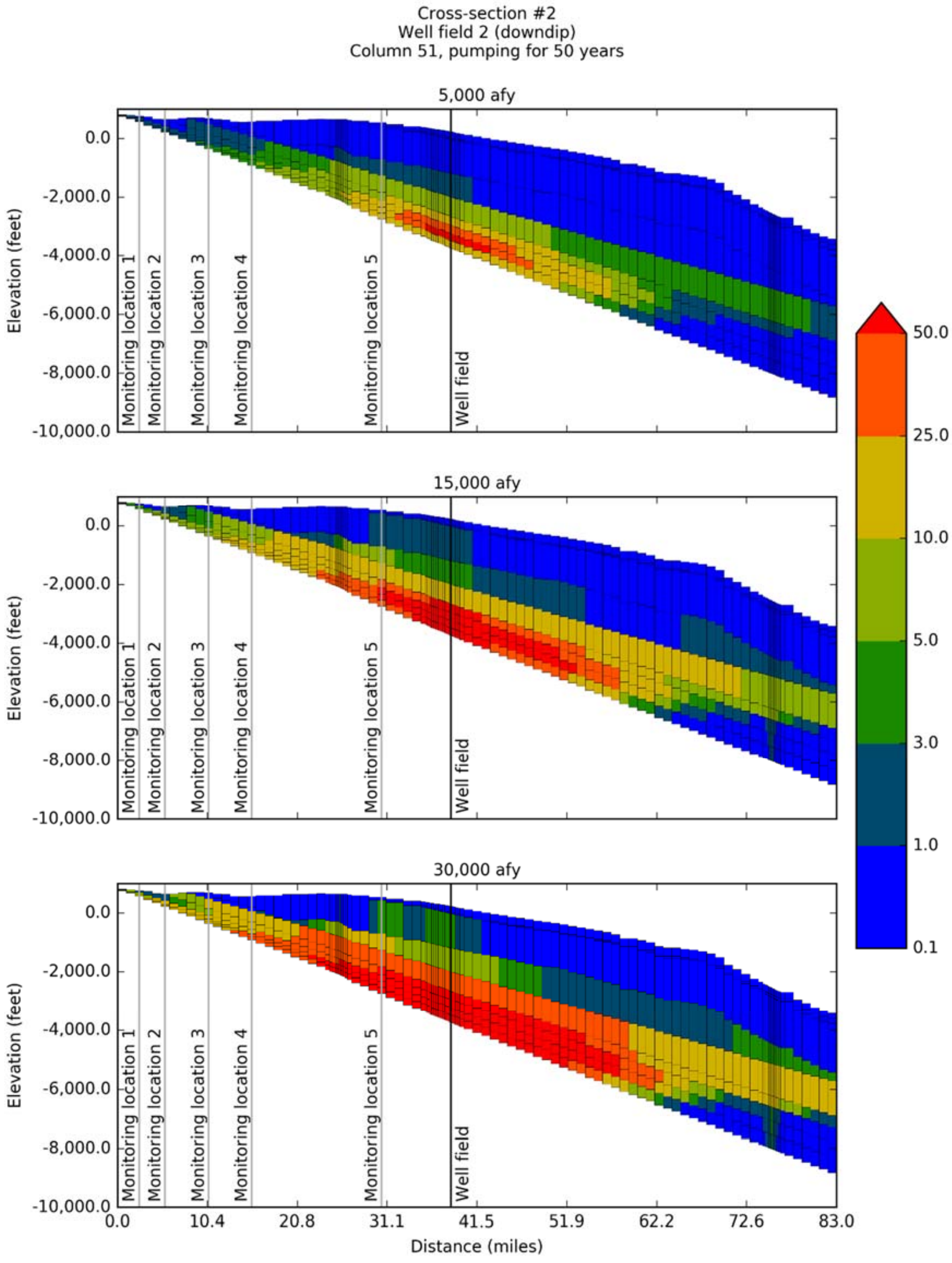


Figure 6-31. **Simulated drawdown at 50 years after pumping the up dip Well Field #2 located in PPA #2 at 5,000 AFY, 15,000 AFY, and 30,000 AFY produced by the groundwater model with GAM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30.**

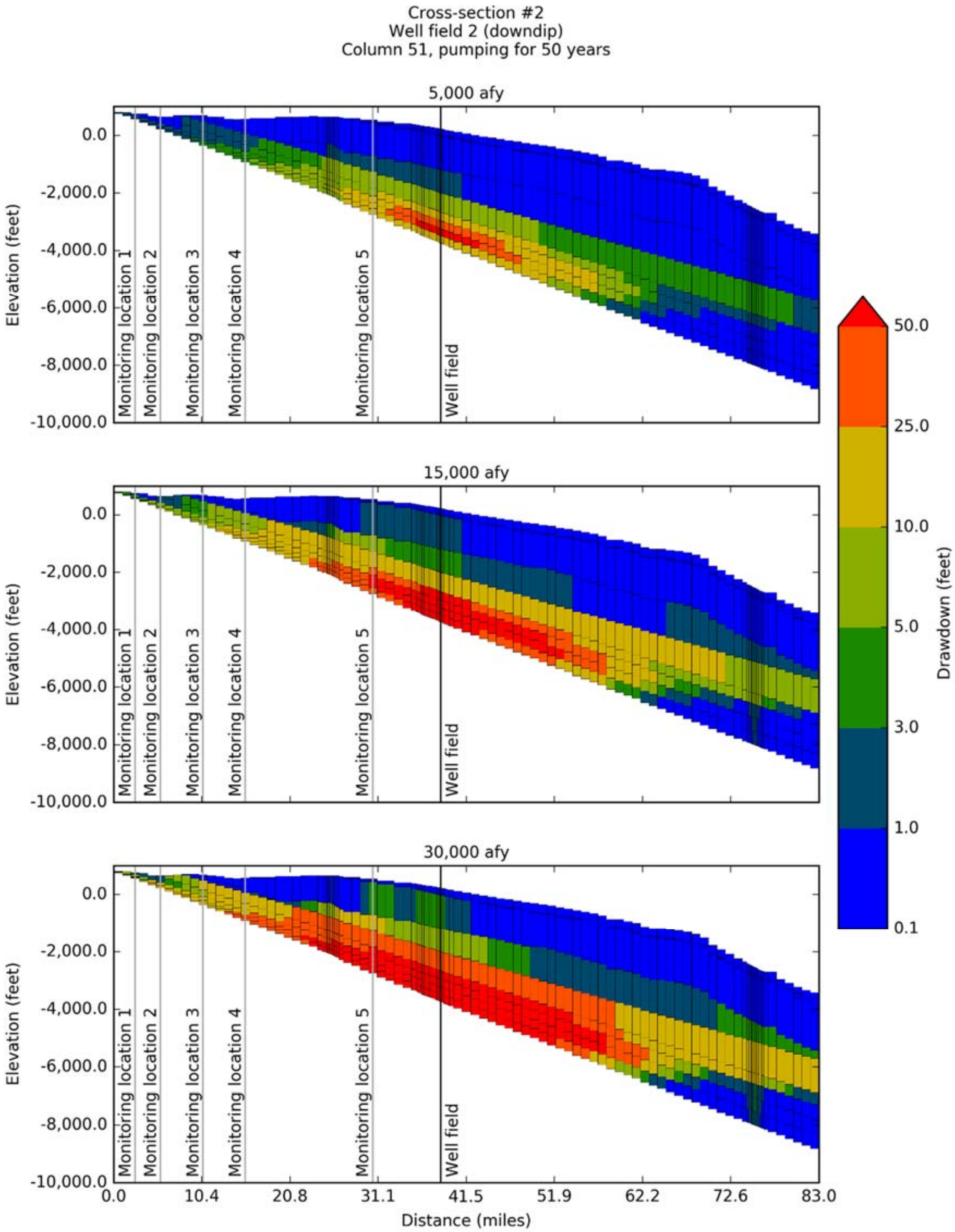


Figure 6-32. **Simulated drawdown at 50 years after pumping the up dip Well Field #1 located in PPA #2 at 5,000 AFY, 15,000 AFY, and 30,000 AFY produced by the groundwater model with GHSM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30.**

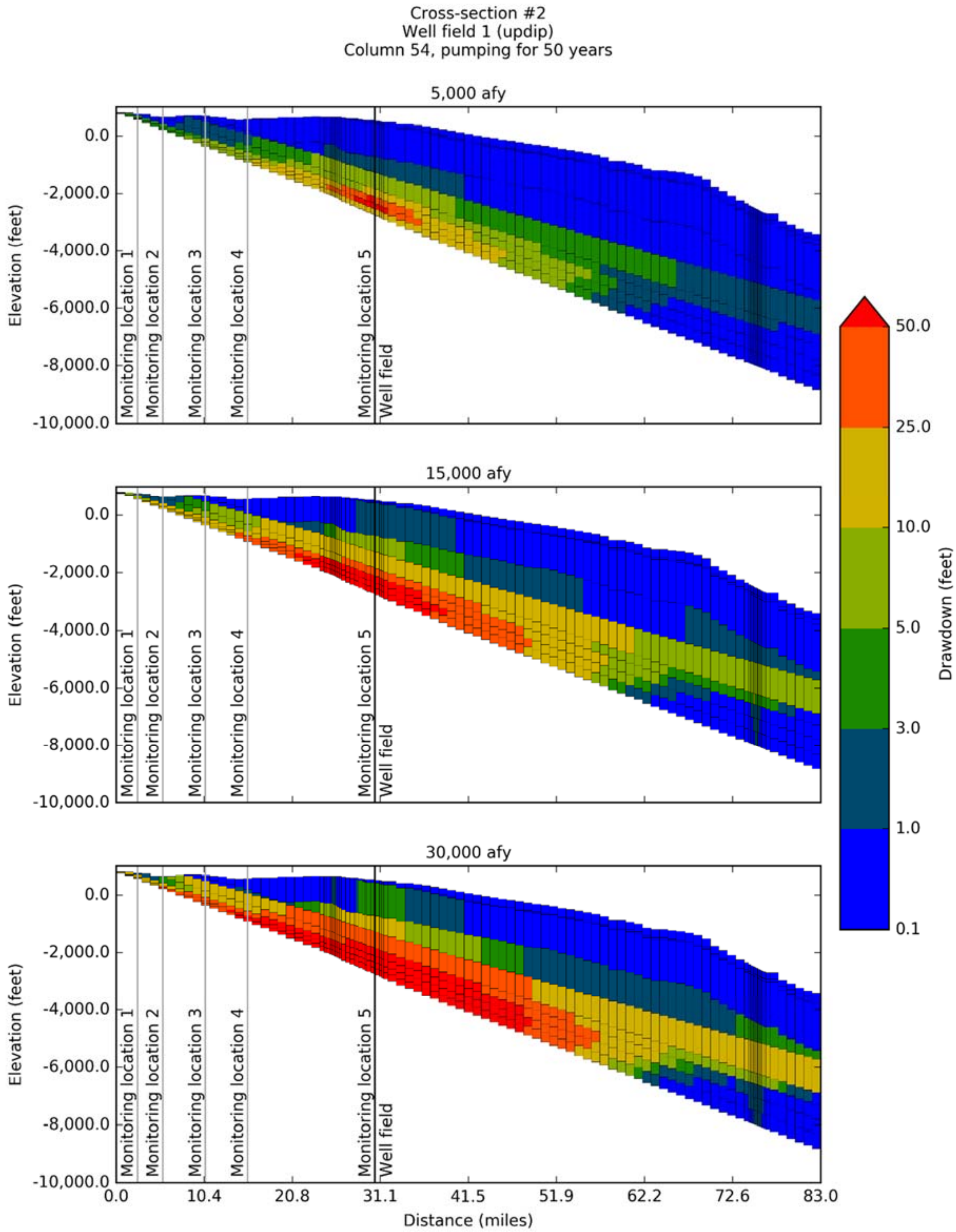


Figure 6-33. **Simulated drawdown at 50 years after pumping the up dip Well Field #2 located in PPA #2 at 5,000 AFY, 15,000 AFY, and 30,000 AFY produced by the groundwater model with GHSM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30.**

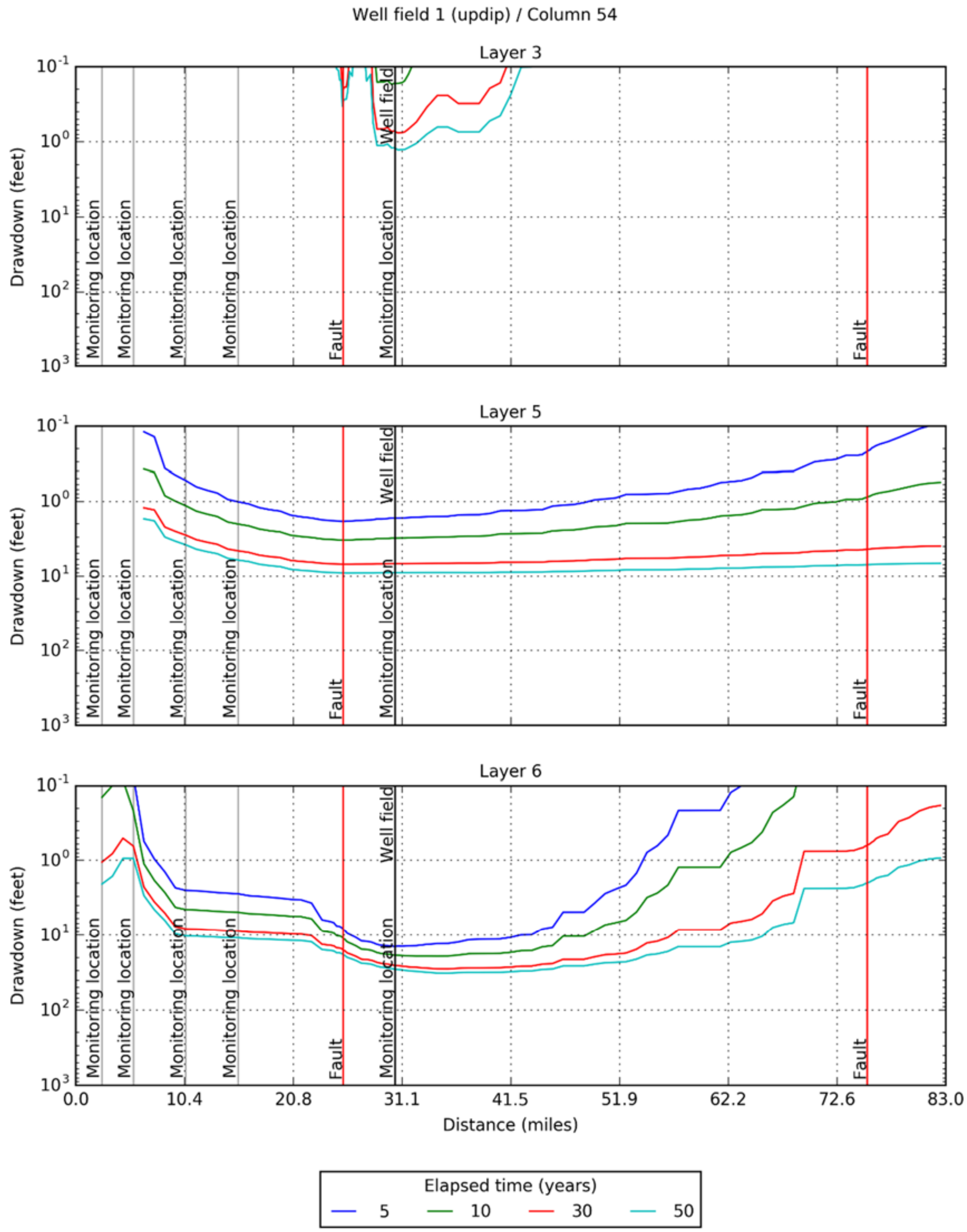


Figure 6-34. **Simulated drawdown at 5, 10, 30, and 50 years for model layers 3, 5, and 6 after pumping the up dip Well Field #1 located in PPA #2 at 15,000 AFY produced by the groundwater model with GAM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30. PPA #2 contains some fresh groundwater, and the updip fault may facilitate groundwater mixing, while the locally sandy nature of the middle Wilcox forms an ineffective hydrogeologic barrier. So significant impacts to water availability or freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers may not be preventable.**

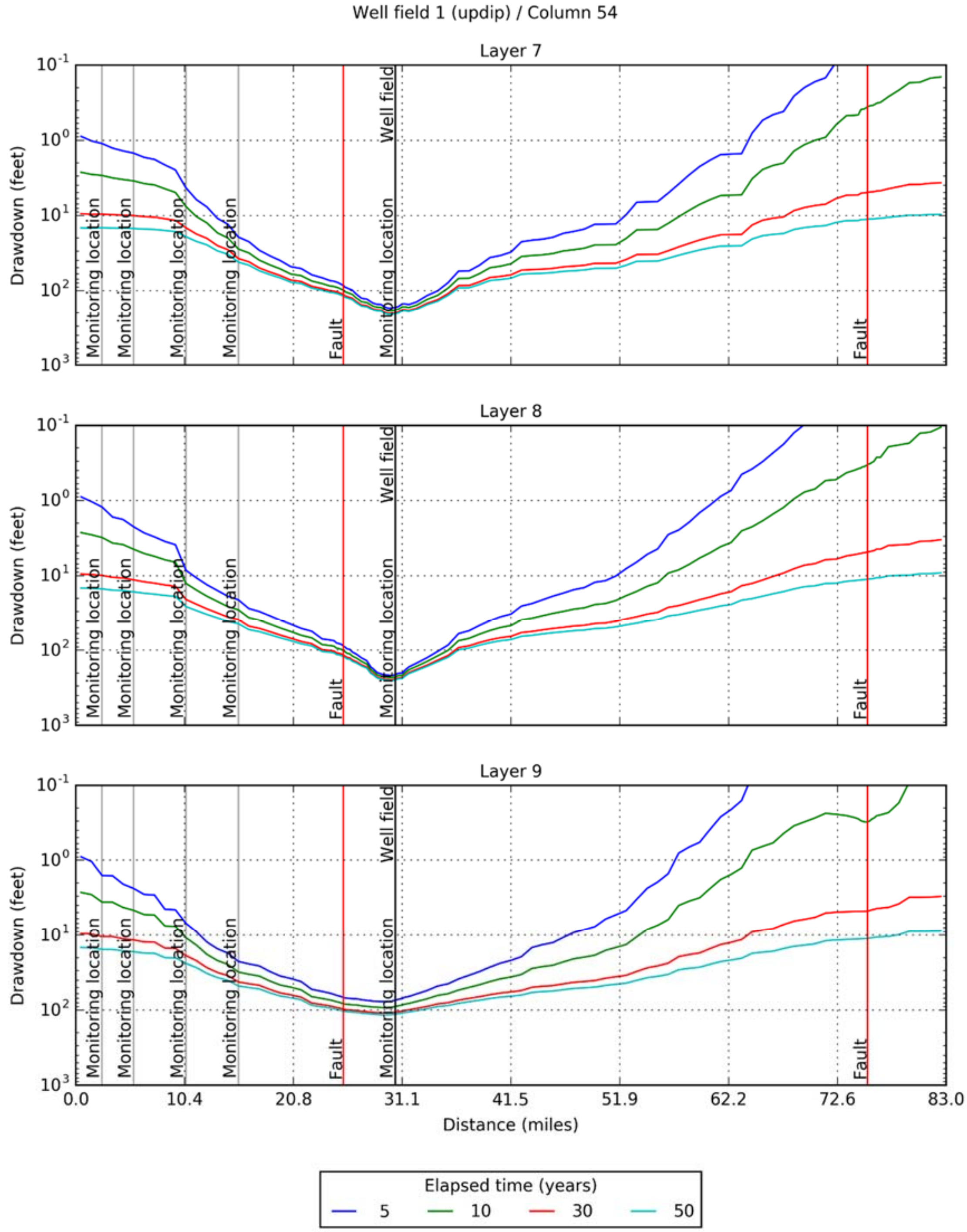


Figure 6-35. Simulated drawdown at 5, 10, 30, and 50 years for model layers 7, 8, and 9 after pumping the up dip Well Field #1 located in PPA #2 at 15,000 AFY produced by the groundwater model with GAM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30. PPA #2 contains some fresh groundwater, and the updip fault may facilitate groundwater mixing, while the locally sandy nature of the middle Wilcox forms an ineffective hydrogeologic barrier. So significant impacts to water availability or freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers may not be preventable.

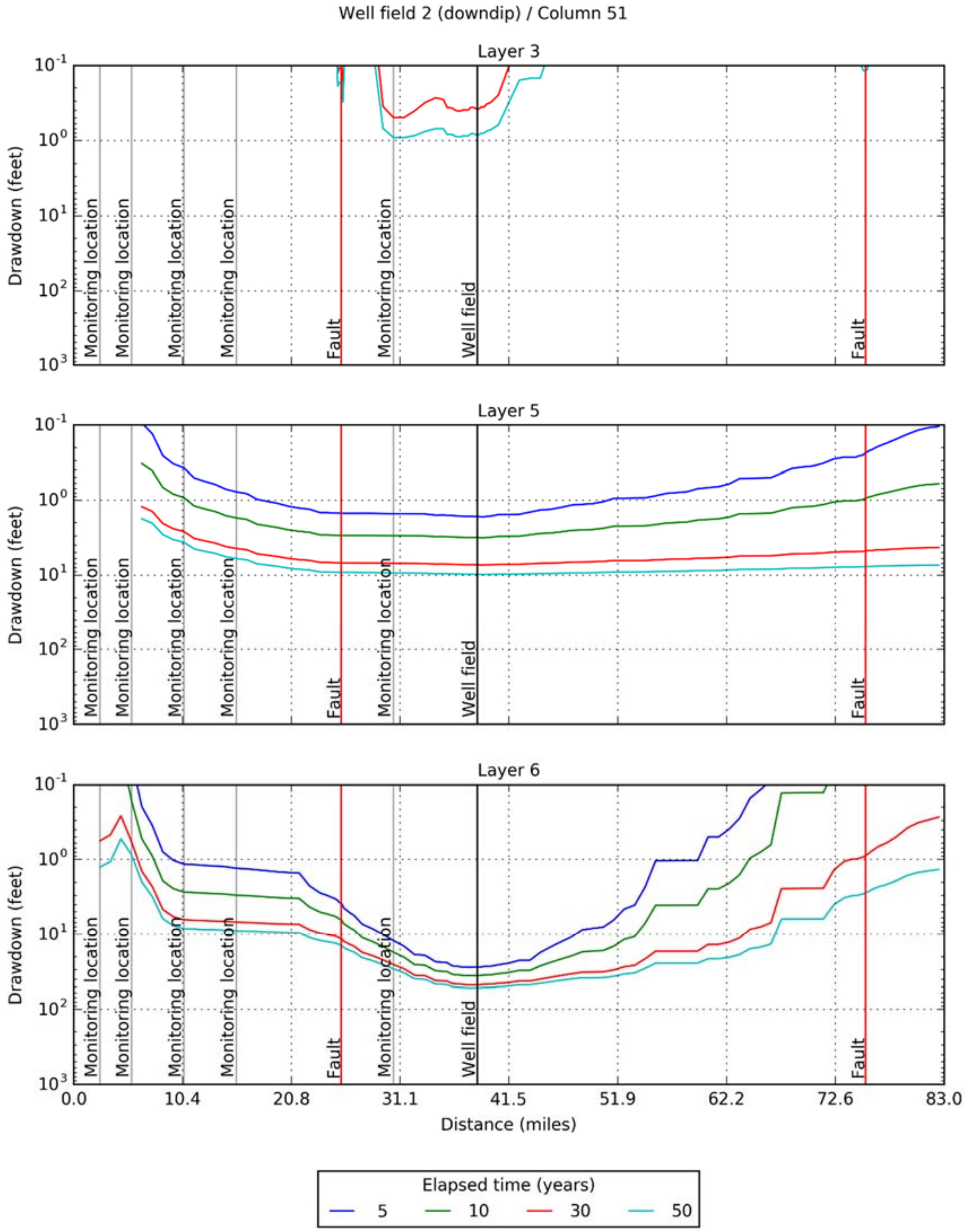


Figure 6-36. Simulated drawdown at 5, 10, 30, and 50 years for model layers 3, 5, and 6 after pumping the up dip Well Field #2 located in PPA #2 at 15,000 AFY produced by the groundwater model with GAM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30. PPA #2 contains some fresh groundwater, and the updip fault may facilitate groundwater mixing, while the locally sandy nature of the middle Wilcox forms an ineffective hydrogeologic barrier. So significant impacts to water availability or freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers may not be preventable.

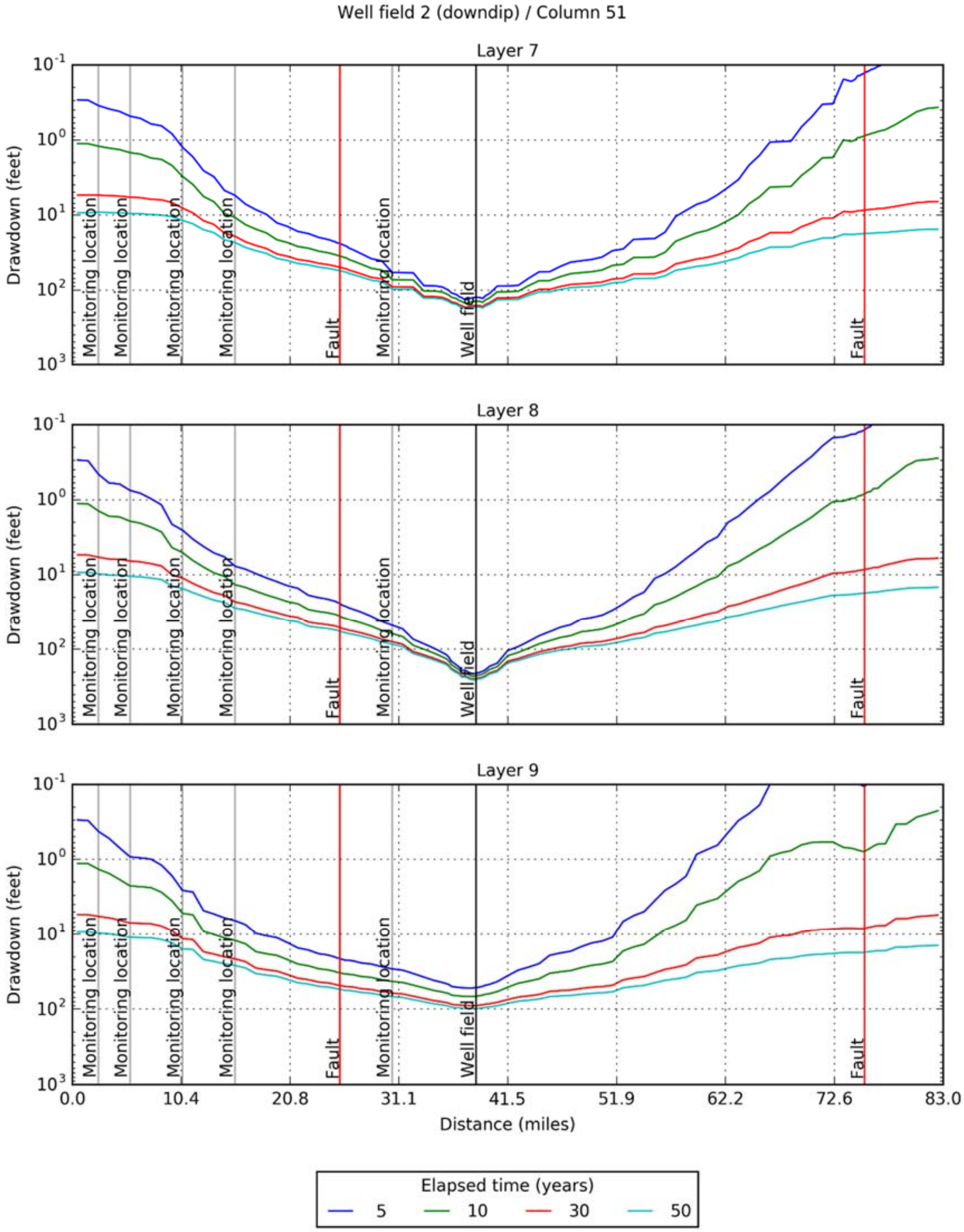


Figure 6-37. Simulated drawdown at 5, 10, 30, and 50 years for model layers 7, 8, and 9 after pumping the up dip Well Field #2 located in PPA #2 at 15,000 AFY produced by the groundwater model with GAM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30. PPA #2 contains some fresh groundwater, and the updip fault may facilitate groundwater mixing, while the locally sandy nature of the middle Wilcox forms an ineffective hydrogeologic barrier. So significant impacts to water availability or freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers may not be preventable.

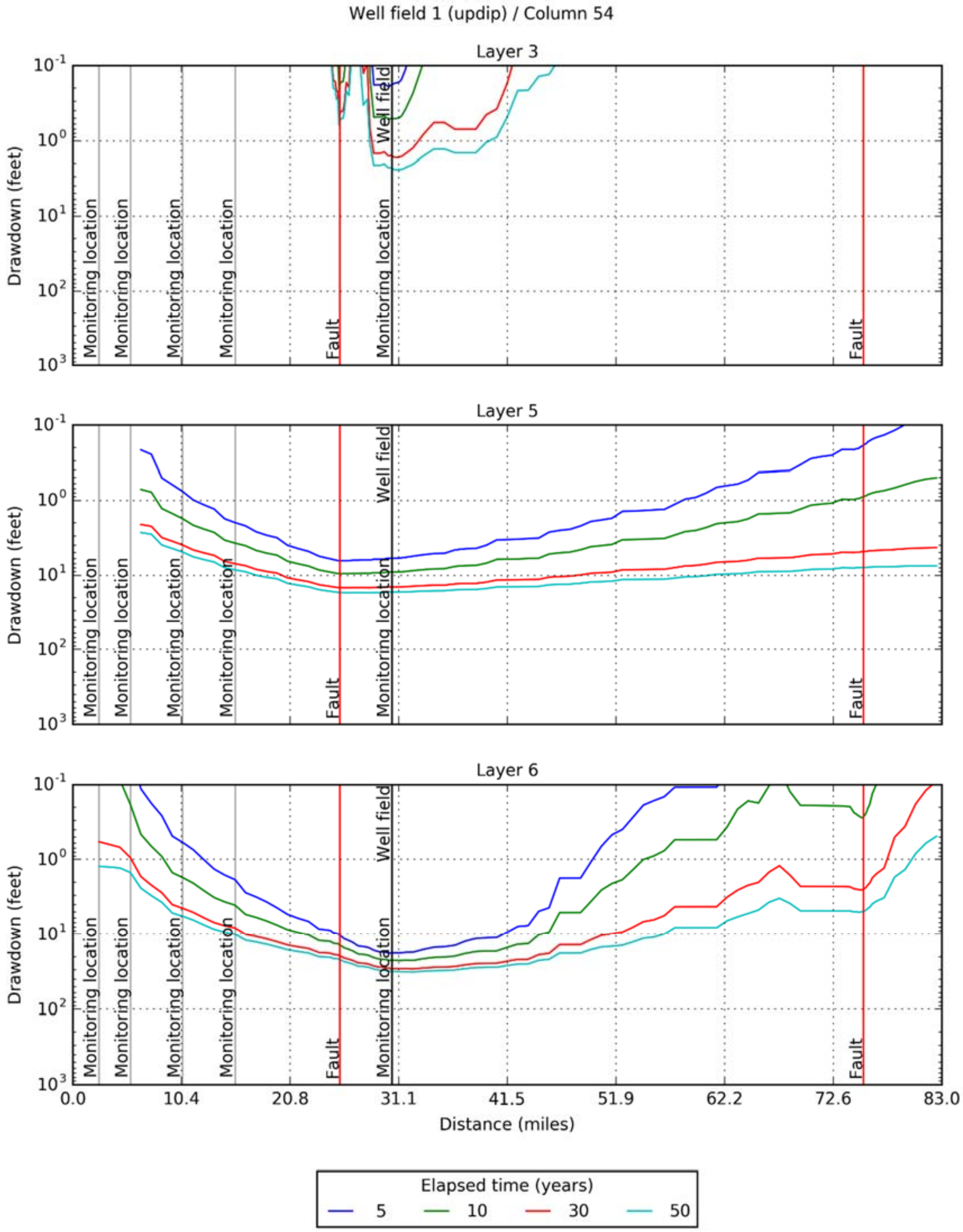


Figure 6-38. **Simulated drawdown at 5, 10, 30, and 50 years for model layers 3, 5, and 6 after pumping the up dip Well Field #1 located in PPA #2 at 15,000 AFY produced by the groundwater model with GHSM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30. PPA #2 contains some fresh groundwater, and the updip fault may facilitate groundwater mixing, while the locally sandy nature of the middle Wilcox forms an ineffective hydrogeologic barrier. So significant impacts to water availability or freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers may not be preventable.**

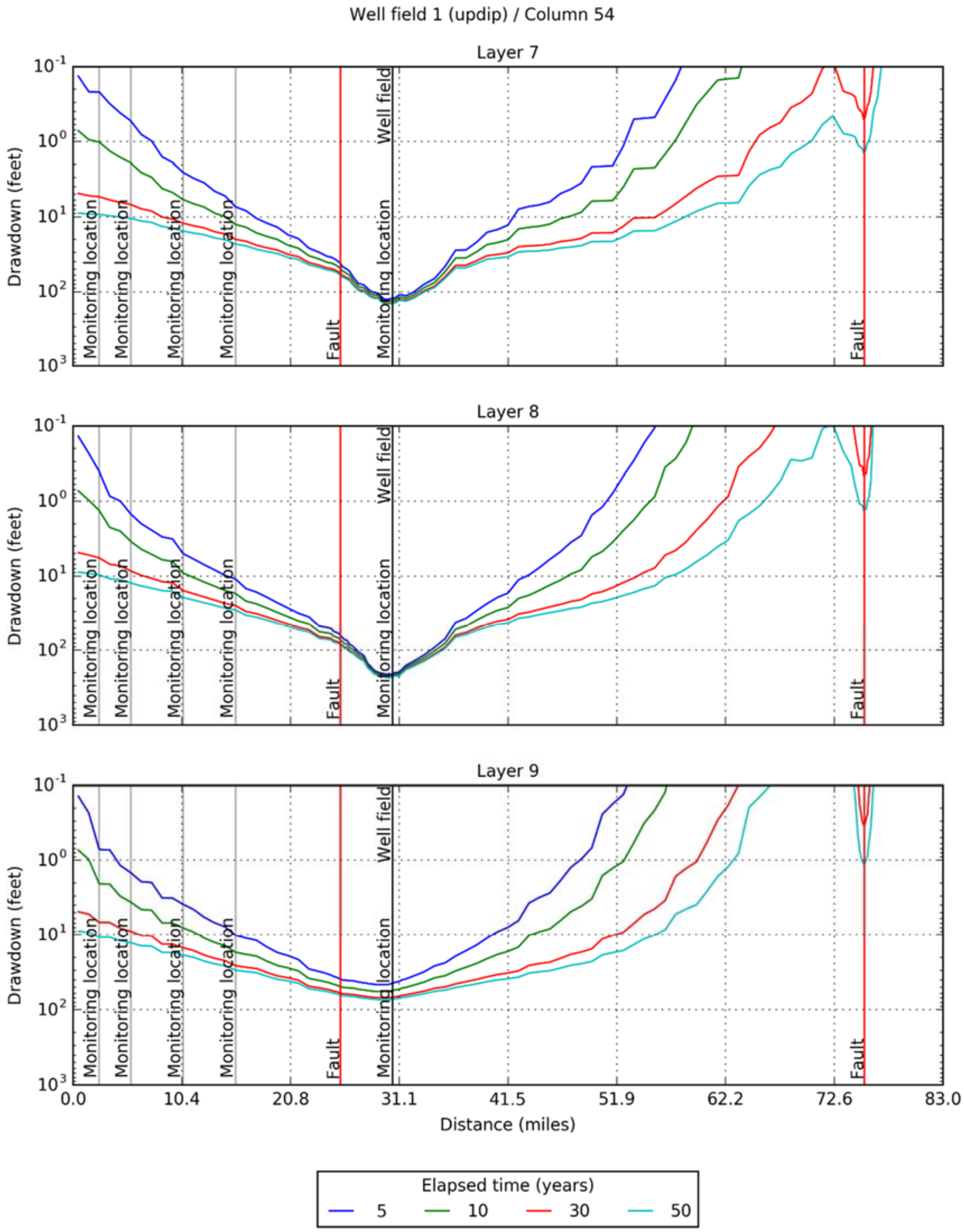


Figure 6-39. **Simulated drawdown at 5, 10, 30, and 50 years for model layers 7, 8, and 9 after pumping the up dip Well Field #1 located in PPA #2 at 15,000 AFY produced by the groundwater model with GHSM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30. PPA #2 contains some fresh groundwater, and the updip fault may facilitate groundwater mixing, while the locally sandy nature of the middle Wilcox forms an ineffective hydrogeologic barrier. So significant impacts to water availability or freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers may not be preventable.**

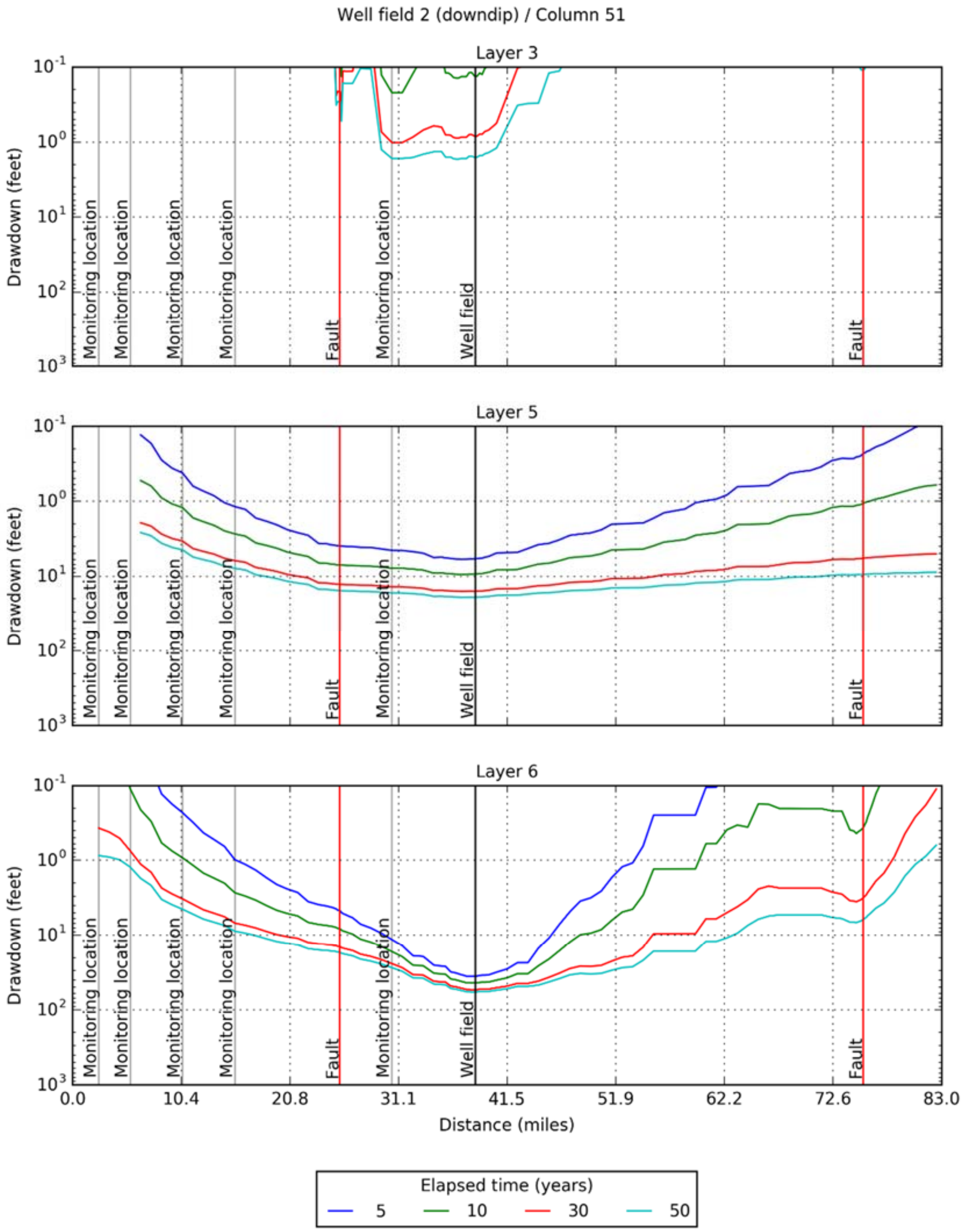


Figure 6-40. **Simulated drawdown at 5, 10, 30, and 50 years for model layers 3, 5, and 6 after pumping the up dip Well Field #2 located in PPA #2 at 15,000 AFY produced by the groundwater model with GHSM- based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30. PPA #2 contains some fresh groundwater, and the updip fault may facilitate groundwater mixing, while the locally sandy nature of the middle Wilcox forms an ineffective hydrogeologic barrier. So significant impacts to water availability or freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers may not be preventable.**

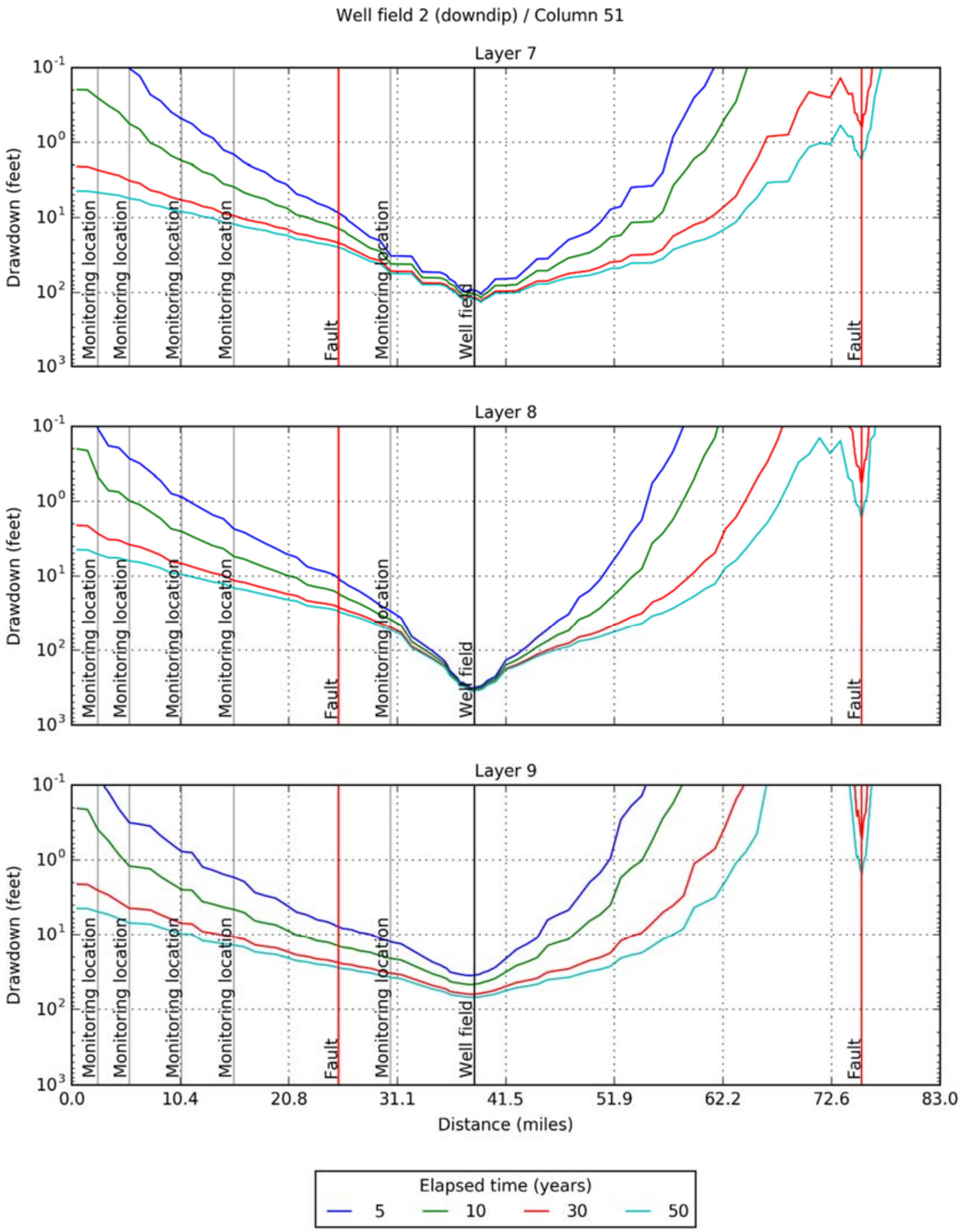


Figure 6-41. Simulated drawdown at 5, 10, 30, and 50 years for model layers 7, 8, and 9 after pumping the up dip Well Field #2 located in PPA #2 at 15,000 AFY produced by the groundwater model with GHSM-based hydraulic properties for Carrizo-Wilcox Aquifer. Although PPA #2 was evaluated, geoscientific analyses indicated that it did not meet all required criteria for a PPA per House Bill 30. PPA #2 contains some fresh groundwater, and the updip fault may facilitate groundwater mixing, while the locally sandy nature of the middle Wilcox forms an ineffective hydrogeologic barrier. So significant impacts to water availability or freshwater resource availability or quality in any part of the Carrizo-Wilcox or adjacent aquifers may not be preventable.

6.3 Queen City and Sparta Aquifers

This section describes the construction and application of a three-dimensional groundwater model to simulate pumping from hypothetical wells fields located in the PPA identified in Section 4 for the Queen City and Sparta aquifers. **Figure 6-42** shows the location of the PPA.

6.3.1 Development of Three-Dimensional Groundwater Models

The groundwater models used to simulate pumping from the PPA for the Queen City and Sparta aquifer were developed using the MODFLOW-USG code (Panday and others, 2013). Section 6.1 Section 6.2.3 provides a brief description of the code.

The modeling objectives and approach for modeling pumping from the Queen City and Sparta aquifers is similar to that described in Section 6.1, except that only the GHSM-based groundwater model was developed. A GAM-based groundwater was not developed because at the time the groundwater models were being developed, there was another PPA proposed besides the one shown in Figure 6-42. The other PPA was located in south Webb and northern Zapata counties outside of the model domain of the southern QCSP GAM. The lack of GAM coverage in proposed PPA in Webb and Zapata counties a GAM-based model was not developed. The GHSM-based groundwater model was constructed using the four-step procedure described in Section 6.2.3.1 “Construction of Three-Dimensional Models for the Potential Production Areas.”

Figure 6-42 shows the PPA for the Queen City and Sparta aquifers the cross section #1 that was used to develop two-dimensional, vertical cross sectional grid in **Figure 6-43** for PPA #1. The groundwater model developed to simulate pumping in PPA #1 includes the seven model layers that listed in **Table 6-28.** The elevations for the top and bottom surfaces for the model layers were obtained from three different models. The elevations for the top and bottom surfaces for the Sparta Aquifer, Weches Formation, and Queen City Aquifer, and Reklaw Formation were extracted from the Southern QCSP GAM (Kelly and others, 2004). The elevations for the top surface for the Cook formation was extracted from the Yegua-Jackson GAM (Deeds and others, 2010). The elevations for the bottom surface for the Carrizo-upper Wilcox aquifer were developed using the stratigraphic picks provided in Section 4. For the grid cells located at the most down-dip extent of each model layer, a no-flow boundary condition is imposed. This assumption is the same assumption used in the Southern QCSP GAM (Kelley and others, 2004).

In Figure 6-43, the down dip portion of Cook Mountain formation serves as a general head boundary (GHB) to simulate upward flow from the confined portions of the Sparta and Queen City aquifer during predevelop conditions and downward flow during pumping conditions. Because of its low permeability, the Cook Formation should not be contributing much of the groundwater to the well field. In the vicinity of the well fields, the middle Wilcox is primarily clay and has a low permeability. It is treated as a no-flow boundary because the highly permeable Carrizo-upper Wilcox aquifer above it will provide serves as a major water supply reservoir.

Three of the model layers represent formations that are predominantly clay. These formations are the Cook Mountain, Reklaw, and Weches formations. These formations were presume to have low permeability and were assigned a hydraulic conductivity of 1 ft/day. . This approach is similar to the approach used by southern QCSP GAM which assigned the same hydraulic conductivity values of 1 ft/day to the Weches and Reklaw formations.

Table 6-28. Seven model layers in the groundwater models developed along Transects 1 shown in Figure 6-77.

Model Layer	Description
1	Cook Mountain
2	Sparta
3	Weches
4	Upper Queen City
5	Lower Queen City
6	Reklaw
7	Carrizo-upper Wilcox

6.3.2 Well Fields

Figure 6-42 shows the location two well fields in PPA #1. The locations of the well fields for the Sparta Aquifer and the Queen City Aquifer are the same except for the model layer. The well fields for the Sparta Aquifer and the Queen City Aquifer are in Model Layers 2 and 4, respectively. **Table 6-29** provides the distance down dip to the two well fields. The distance is measured from the start of the cross section or the up-dip extend of the groundwater model to the centroid of the well field. In the Sparta Aquifer, the well fields that produce 2,000, 6,000 and 10,000 AFY consists of 3, 9, and 15 wells, respectively. In the Queen City Aquifer, the well fields used to produce 4,000, 12,000 and 20,000 AFY consist of 3, 9, and 15 wells, respectively. For each pumping scenario, all of the wells pump at the same rate which is provided in **Table 6-30**.

Different pumping rates were selected for the two aquifers because of their different hydraulic properties and thickness. Larger projects were selected for the Queen City Aquifer because of it higher transmissivity values. The range in productions was based on the size of the water projects anticipated for the Queen City and the Sparta aquifer in GMA #13.

Table 6-29. Down dip distance to the center of the well fields from the up-dip extend of the groundwater model

Potential Brackish Production Area	Distance from Up-Dip Extend of Groundwater Model to Well Field	
	Up-Dip Well Field	Down-Dip Well Field
#2	43 miles	61 miles

Table 6-30. Number of wells and average pumping rates for the modeled well fields.

Aquifer	Total Pumping (AFY)	Number of Wells	Pumping Rate (gpm) Per Well
Sparta	2,000	3	413
	6,000	9	413
	10,000	15	413
Queen City	4,000	3	826
	12,000	9	826
	20,000	15	826

6.3.3 Development of a Geohydrostratigraphic Model for the Queen City and Sparta Aquifers

For this study, the purpose of a GHSM is to provide transmissive and storage properties for the Queen City and Sparta aquifers based on the continuous profiles of sand and clay sequences calculated from the geophysical logs in the vicinity of cross sections #1. The process of building a GHSM involves developing relationships among the different geologic data sets, such as sand fraction and porosity that can be used to estimate aquifer properties such as hydraulic conductivity and specific storage. Once these relationships have been developed, then the continuous lithology data can be transformed via the GHSM to a continuous set of hydraulic properties.

A simple GHSM that has been commonly used to guide the development of groundwater model is to use sand thickness as an indicator of transmissivity. This practice is often used in developing regional scale groundwater models. More advanced applications of GHSM consider other factors besides sand thickness, such as porosity, depositional environment, depth, and temperature. Examples of GHSM that have been used to guide the development of groundwater models in Texas include: a groundwater transport models for Former Kelly Air Force Base in Bexar County (Young and others, 2003), water availability models for the Catahoula formation in Montgomery County, (LGB Guyton and INTERA, 2012); the Lower Colorado River Basin model in the Central Texas Gulf Coast (Young and Kelley, 2006; Young and others, 2009); and groundwater availability models for the Yegua-Jackson Aquifer (Deeds and others, 2010); Central Queen City/Sparta GAM (Dutton and others, 2003), the Southern Queen City/Sparta (Deeds and others, 2003), and the Northern Trinity and Woodbine Aquifers (Kelley and others, 2014).

6.3.3.1 Estimation of Horizontal Hydraulic Conductivity from Sand Fraction

To develop a relationship between sand fraction and hydraulic conductivity, we used three sources of information. One information source was maps of sand fraction for Sparta and Queen City aquifers shown in **Figures 6-46** and **6-47** that were generated as part of this study (see Section 4). Another source of information was maps of horizontal conductivity values for the Queen City and Sparta aquifers from the Southern QCSP GAM (Deeds and others, 2003) shown in Figures 6-46 and 6-47. The third source of information was estimates of hydraulic conductivity from field data shown in **Figure 6-48.** Figure 6-48 shows hydraulic conductivity values associated with the Sparta Aquifer and hydraulic conductivity values associated with the Queen City Aquifer. These values include hydraulic conductivity values used by Deeds and others (2003), and additional hydraulic conductivity values developed data obtained from TWDB database of submitted driller logs.

Using information in Figures 6-46 through 6-48, we developed **Equations 6-7** and **6-8** to calculate hydraulic conductivity for the Sparta and Queen City aquifers based on sand fractions developed for the Sparta and Queen City aquifers in Section 4. **Table 6-31** compares the hydraulic conductivity values generated by Equations 6-7 and 6-8 using for percentiles of sand fractions determined for the area underlying the footprint of the measured hydraulic conductivity values in Figure 6-48. Table 6-31 also provides the percentiles for the hydraulic conductivity values calculated from field data and the percentiles for the hydraulic conductivity values from the southern QCSP GAM for the area underlying the footprint of the measured hydraulic conductivity values in Figure 6-48. All three sets of hydraulic conductivity values provide similar values. The three sets of hydraulic conductivity values, however, are not as consistent. The highest and the lowest hydraulic conductivity values for each percentile is the field-based and the GAM-based hydraulic conductivity values, respectively. The hydraulic conductivity values generated from Equation 6-8 generally provide a better match to the field based than the GAM-based hydraulic conductivity values. In general, the hydraulic conductivity values calculated from field data was given more weight than the GAM-based hydraulic conductivity values except for the some of the high values of hydraulic conductivity estimated from specific capacity tests.

In our data evaluation for the Queen City Aquifer that supported the development of Equations 6-8, the 80th and 90th percentile Queen City hydraulic conductivity values based on field data were considered to be over estimates. The method used to calculate the Queen City hydraulic conductivity values involves dividing the transmissivity value calculated from a specific capacity test by the well screen length (Razack and others, 1991). Young and Kelley (2006) and Kelly and others (2014) has shown that this method will produce hydraulic conductivity values that are too high and unrepresentative for the aquifer where the screen lengths are much shorter than the aquifer thickness.

$$K_{sparta} = 10.74 * S_{fsp} + 0.2 \qquad \text{Equation 6-7}$$

$$K_{queen\ city} = 34.2 * S_{fqu} - 1.35 \qquad \text{Equation 6-8}$$

Where:

K_{sparta} = Sparta Aquifer hydraulic conductivity (ft/day)
$K_{Queen\ City}$ = Queen City hydraulic conductivity (ft/day)
S_{fsp} = sand fraction for the Sparta Aquifer
S_{fqc} = sand fraction for the Queen City Aquifer

Table 6-31. Relationship between hydraulic conductivity and sand fraction for the Sparta Aquifer and the Queen City Aquifer based on field data and calculated hydraulic conductivity values using Equations 6-7 and 6-8.

Percentile	Sparta Aquifer				Queen City Aquifer			
	Sand Fraction	Hydraulic Conductivity (ft/day)			Sand Fraction	Hydraulic Conductivity (ft/day)		
		Field Data	Southern QCSP GAM	From Equation 6-8		Field Data	Southern QCSP GAM	From Equation 6-8
10th	0.03	1.0	1.6	0.5	0.12	1.3	0.9	2.7
20th	0.05	1.3	2.4	0.8	0.15	2.1	1.1	3.8
30th	0.08	1.3	3.0	1.1	0.18	3.0	1.3	4.7
40th	0.12	1.6	3.7	1.5	0.20	4.4	1.6	5.4
50th	0.16	1.7	4.6	1.9	0.23	6.4	1.8	6.6
60th	0.23	1.9	4.9	2.6	0.29	9.5	1.9	8.4
70th	0.29	2.1	5.2	3.3	0.34	15.0	2.1	10.3
80th	0.33	3.0	5.3	3.8	0.38	25.0	2.4	11.6
90th	0.39	3.3	5.5	4.4	0.43	39.4	3.2	13.3

6.3.3.2 Calculation of Horizontal Hydraulic Conductivity for Individual for Layers

Equation 6-9 was used to calculate the horizontal hydraulic conductivity for grid cells in the groundwater model for the Queen City and Sparta aquifers. This approach is similar to the approach used to calculate horizontal hydraulic conductivity for the Carrizo-Wilcox Aquifer that is discussed in Section 6.2.4.3.

$$K_H = K_{baseline} * A_{porosity} * A_{temperature} \qquad \text{(Equation 6-9)}$$

where

- K_H = horizontal hydraulic conductivity of the grid cell
- $K_{baseline}$ = baseline value of horizontal hydraulic conductivity calculated from sand fraction using Equation 6-7 or Equation 6-8
- $A_{porosity}$ = adjustments to account for the relationship between permeability and porosity based on Dutton and Loucks (2014)
- $A_{temperature}$ = adjustments to account for the change in the viscosity and density of water with depth

6.3.3.3 Calculation of Effective Vertical Hydraulic Conductivity for a Model Layer

The GHSM will estimate the horizontal and vertical hydraulic conductivity for a model layer based on the assumption of one-dimension flow through uniform layered media. For this condition, the equivalent horizontal and vertical hydraulic conductivity values (Kx and Kz, respectively) can be obtained using basic averaging equations (Maliva, 2016; Freeze and Cherry, 1979; Domenico and Schwartz, 1990). The equivalent horizontal hydraulic conductivity is the arithmetic mean of the horizontal hydraulic conductivity of the individual layers. The equivalent vertical hydraulic conductivity is the harmonic mean of the vertical hydraulic conductivity of the individual layers. **Figure 6-10** is a schematic showing the application of an arithmetic average and the harmonic average to calculate equivalent horizontal and vertical hydraulic conductivities based on one-dimensional vertical flow through layered media. For one-dimensional flow, the effective hydraulic conductivity is the weighted harmonic mean of the hydraulic conductivity of the different layers. For a two-layer aquifer consisting of a sand and clay layer, **Equation 6-11** calculates the harmonic average.

$$Kz_{effective} = (D_s + D_c)/[(D_s/Kz_s) + (D_c/Kz_c)] \quad \text{(Equation 6-11)}$$

where:

$Kz_{effective}$	=	equivalent vertical hydraulic conductivity for the media
D_s	=	total thickness of sand
D_c	=	total thickness of clay
K_{Hc}	=	hydraulic conductivity of clay
K_{Hs}	=	hydraulic conductivity of sand
Kz_c	=	vertical hydraulic conductivity of clay
Kz_s	=	vertical hydraulic conductivity of sand

The GHSM determines the vertical hydraulic conductivity of grid cell by using **Equation 6-11**. The thickness of the sand, D_s, is calculated by multiplying the sand fraction by the cell thickness. The clay thickness, D_c, is calculated by subtracting the sand thickness from the cell thickness. The vertical hydraulic conductivity of sand, Kz_s, is calculated by dividing the horizontal hydraulic conductivity of the sand layer by 10. The vertical hydraulic conductivity of clay, Kz_c, is set to 0.028 feet per day (ft/day) (0.00001 centimeter per second [cm/s]) for the vertical hydraulic conductivity of clay.

6.3.3.4 Calculation of Specific Storage for a Model Layer

The GHSM uses the modified version of the model of Shestakov (2002) to estimate specific storage values. Section 6.2.4.5 describes the approach and equations used by the GHSM model to calculate specific storage based on depth, sand fraction, and porosity.

6.3.4 Simulated drawdowns from Well Fields Located in Potential Production Area #1

This section describes the application of a groundwater model to simulate the drawdowns caused by pumping Potential Production Area #1 at two proposed well fields. The section begins with an overview of the aquifer properties in the model and then provides simulated drawdowns for the following four pumping scenarios: pumping the Sparta Aquifer at Well Field #1; pumping the Sparta Aquifer at Well Field #2; pumping the Queen City Aquifer at Well Field #1; pumping the Queen City Aquifer at Well Field #2.

6.3.4.1 Construction of Groundwater Model for PPA #1

The aquifer hydraulic properties for groundwater model developed for PPA #1 are based on geological conditions in the vicinity of cross section #1. Figure 6-49 illustrates the spatial distribution of sand fraction along cross section #1. The three-dimensional model has been developed using the same grid and properties long strike until the model is 100 miles wide. The model grid was expanded to 100 miles in order to prevent the no-flow conditions along the edges of the model from affecting the development of the cone-of-depression during 50 years of pumping. **Table 6-32** provides the values for Kx, Kz, and Ss produced by the GHSM for model layers 2, 3, 4, and 7 and extracted from the Southern QCSP GAM for model layers 3 and 5. The hydraulic conductivity values or the Cook Mountain formation (model layer 1) were set based on the properties for the Reklaw and Weches formation, which are represented by model layers 3 and 6, respectively. **Figures 6-50** and **6-51** show the spatial distribution of Kx and Kz along a vertical slice through the model.

Table 6-32. Average values for Kx (feet per day), Kz (feet per day), and Ss (1/feet) by model layer for 10-mile reaches along dip for the groundwater model for PPA #1.

Reach (miles)	Property	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
0-10	Kx	NP	NP	NP	NP	5.0	1.0	12.4
	Kz	NP	NP	NP	NP	3.14E-03	1.00E-04	1.40E-03
	Ss	NP	NP	NP	NP	5.87E-04	5.41E-03	1.52E-04
10-20	Kx	NP	NP	NP	4.5	4.3	1.0	22.4
	Kz	NP	NP	NP	3.06E-03	3.14E-03	1.00E-04	2.97E-03
	Ss	NP	NP	NP	1.09E-03	1.13E-04	6.44E-06	5.58E-06
20-30	Kx	1.0	2.2	1.0	8.8	8.2	1.0	23.6
	Kz	1.00E-04	3.13E-03	1.00E-04	3.79E-03	3.90E-03	1.00E-04	3.97E-03
	Ss	5.24E-06	4.37E-04	2.51E-03	7.18E-05	1.27E-05	5.52E-06	2.85E-06
30-40	Kx	1	4.68371	1	11.1867	10.30601	1	21.30864
	Kz	1.00E-04	4.53E-03	1.00E-04	4.37E-03	4.48E-03	1.00E-04	3.70E-03
	Ss	4.66E-06	3.62E-05	6.79E-06	1.40E-05	7.64E-06	4.66E-06	2.36E-06
40-50	Kx	1.0	4.5	1.0	12.5	11.5	1.0	19.8
	Kz	1.00E-04	4.42E-03	1.00E-04	4.78E-03	4.88E-03	1.00E-04	3.25E-03
	Ss	4.25E-06	2.86E-05	6.30E-06	1.20E-05	6.82E-06	4.25E-06	2.47E-06
50-60	Kx	1.0	3.2	1.0	14.7	13.6	1.0	13.8
	Kz	1.00E-04	3.76E-03	1.00E-04	5.62E-03	5.69E-03	1.00E-04	2.11E-03
	Ss	3.24E-06	1.97E-05	4.91E-06	7.79E-06	5.20E-06	3.24E-06	2.87E-06
60-70	Kx	1.0	2.8	1.0	13.7	12.7	1.0	13.7
	Kz	1.00E-04	3.58E-03	1.00E-04	5.33E-03	5.37E-03	1.00E-04	2.15E-03
	Ss	2.63E-06	1.79E-05	4.21E-06	7.56E-06	5.30E-06	2.63E-06	2.65E-06
70-80	Kx	1.0	2.9	1.0	13.4	12.7	1.0	14.9
	Kz	1.00E-04	3.64E-03	1.00E-04	5.31E-03	5.35E-03	1.00E-04	2.56E-03
	Ss	1.88E-06	1.54E-05	3.02E-06	7.10E-06	5.41E-06	1.85E-06	2.11E-06

The simulated drawdown from pumping the well fields in PPA #1 were monitored at five locations. The monitoring locations are designated based on the number of miles down dip they are from the start of cross section #1. The five locations used to monitor drawdown from the well field in the

Queen City are located at down dip distances of 18, 22, 26, 30, and 34 miles from the origin of the cross section. The five locations used to monitor drawdown from the well field in the Queen City are located at down dip distances of 22, 26, 30, 34, and 38 miles from the origin of the cross section. At each of these monitoring locations, drawdown in four model layers are tabulated after 30 and 50 years of pumping. These four model layers are Sparta (layer 2), Upper Queen City (layer 4), Lower Queen City (layer 5) and Carrizo-upper Wilcox (layer 7). **Table 6-33** lists the top and bottom elevations associated with these four model layers at the five monitoring locations.

Table 6-33. Locations and elevation (in feet above mean sea level [amsl]) where drawdowns were monitored for the simulated pumping at Well Field #1 and Well Field #2 in Potential Production Area #1.

Aquifer Pumped	Monitoring Location (miles down dip)	Ground Surface (ft, amsl)	Top & Bottom of Model Layer	Sparta	Upper Queen City	Lower Queen City	Carrizo-Upper Wilcox
				Layer 2	Layer 4	Layer 5	Layer 7
Queen City	18	650.934	Top	NP	NP	651	-282
			Bottom	NP	NP	-246	-1095
	22	625.727	Top	NP	626	281	-501
			Bottom	NP	281	-408	-1320
	26	566.197	Top	566	410	-117	-727
			Bottom	451	-117	-664	-1541
	30	523.3919	Top	416	194	-379	-977
			Bottom	243	-379	-952	-1848
	34	457.8074	Top	287	26	-609	-1261
			Bottom	76	-609	-1243	-2227
Sparta	22	625.727	Top	NP	626	281	-501
			Bottom	NP	281	-408	-1320
	26	566.197	Top	566	410	-117	-727
			Bottom	451	-117	-664	-1541
	30	523.3919	Top	416	194	-379	-977
			Bottom	243	-379	-952	-1848
	34	457.8074	Top	287	26	-609	-1261
			Bottom	76	-609	-1243	-2227
	38	467.0128	Top	65	-200	-862	-1552
			Bottom	-158	-862	-1523	-2540

Note: NP = not present

6.3.5 Simulated Drawdown Produced by Pumping from Potential Production Area #1

Figures 6-52 to **6-55** show simulated drawdowns caused by pumping the Queen City Aquifer at 4,000, 12,000, and 20,000 AFY for 30 years and 50 years at well field #1 and well field #2. The simulated drawdowns are plotted along cross section #1 for all seven model layers. **Figures 6-56** to **6-57** show simulated drawdowns for 5, 10, 30, and 50 years for model layers 2, 4, and 5 caused by pumping the Queen City Aquifer at well field #1 and well field #2. In **Figures 6-52** through **6-57**, there are five monitoring locations up dip of the two well fields. At these five monitoring locations, **Tables 6-34** and **6-35** provide simulated drawdowns for model layers 2, 4, 5, and 7 caused by pumping 12,000 AFY from well field #1 and well field #2, respectively.

Among the notable observations are the following:

- Except for areas near the up-dip boundary of the outcrops where storage coefficients are large, the model exhibits a linear response between the increase in the pumping rate and the increase in the aquifer drawdown for times greater than 30 years.
- Similar drawdowns occur near the center of pumping for both well fields at times greater than 30 years. For the pumping rate of 12,000 AFY, this drawdown amount is 100 to 120 ft
- About 90% of the drawdown that occurs at 50 years near the well fields occur during the first 5 years of pumping
- After 50 years of pumping at well field #1 at 12,000 AFY, the drawdown in the upper Queen City, the lower Queen City, Sparta, and Carrizo-upper Wilcox is 33, 26, 21, and 14 ft, respectively at a distance that is 11 miles up dip from the well field and 34 miles down dip from the outcrop of the Carrizo-Wilcox Aquifer.
- After 50 years of pumping at well field #1 at 12,000 AFY, the drawdown in the upper Queen City, lower Queen City, and Carrizo-upper Wilcox is 0.7, 2.1, and 8.6 ft, respectively at a distance that is 21 miles up dip from the well field and 22 miles down dip from the outcrop of the Carrizo-Wilcox Aquifer.
- After 50 years of pumping at well field #2 at 12,000 AFY, the drawdown in the upper Queen City, the lower Queen City, Sparta, and Carrizo-upper Wilcox is 5.4, 5.3, 4.9, and 3.4 ft, respectively at a distance that is 27 miles up dip from the well field and 34 miles down dip from the outcrop of the Carrizo-Wilcox Aquifer.
- After 50 years of pumping at well field #2 at 12,000 AFY, the drawdown in the upper Queen City, lower Queen City, and Carrizo-upper Wilcox is 0.2, 0.3, and 2.2 ft, respectively at a distance that is 39 miles up dip from the well field and 22 miles down dip from the outcrop of the Carrizo-Wilcox Aquifer.

Table 6-34. Simulated drawdown at monitoring locations after pumping the Queen City Aquifer at Well Field #1 in PPA #1 for 30 years and 50 years.

Monitoring Location (miles)	Pumping Rate (AFY)	Sparta	Upper Queen City	Lower Queen City	Carrizo-Upper Wilcox
		Layer 2	Layer 4	Layer 5	Layer 7
30 Years					
18	4,000	Not Present	Not Present	0.0	1.0
	12,000	Not Present	Not Present	0.1	2.9
	20,000	Not Present	Not Present	0.1	4.7
22	4,000	Not Present	0.1	0.3	2.0
	12,000	Not Present	0.3	1.0	6.0
	20,000	Not Present	0.6	1.6	9.7
26	4,000	0.4	2.2	2.3	2.4
	12,000	1.1	6.5	7.1	7.3
	20,000	1.9	10.9	11.8	11.6
30	4,000	2.4	5.0	5.3	2.8
	12,000	7.0	15.0	15.9	8.4
	20,000	11.6	25.0	26.4	13.4
34	4,000	5.6	9.2	7.0	3.4
	12,000	16.3	27.9	21.0	10.2
	20,000	27.2	46.2	34.9	16.4
50 Years					
18	4,000	Not Present	Not Present	0.1	1.5
	12,000	Not Present	Not Present	0.2	4.5
	20,000	Not Present	Not Present	0.3	7.3
22	4,000	Not Present	0.2	0.7	2.8
	12,000	Not Present	0.7	2.1	8.6
	20,000	Not Present	1.2	3.4	13.9
26	4,000	0.8	3.1	3.5	3.3
	12,000	2.4	9.3	10.6	10.1
	20,000	4.0	15.6	17.6	16.3
30	4,000	3.2	6.4	6.8	3.8
	12,000	9.5	19.3	20.6	11.4
	20,000	15.8	32.1	34.2	18.5
34	4,000	7.0	11.0	8.6	4.4
	12,000	20.6	33.1	26.1	13.5
	20,000	34.5	54.9	43.3	21.8

Table 6-35. Simulated drawdown at monitoring locations after pumping the Queen City Aquifer at Well Field #2 in PPA #1 for 30 years and 50 years.

Monitoring Location (miles)	Pumping Rate (AFY)	Sparta	Upper Queen City	Lower Queen City	Carrizo-Upper Wilcox
		Layer 2	Layer 4	Layer 5	Layer 7
30 Years					
18	4,000	Not Present	Not Present	0.0	0.1
	12,000	Not Present	Not Present	0.0	0.4
	20,000	Not Present	Not Present	0.0	0.7
22	4,000	Not Present	0.0	0.0	0.3
	12,000	Not Present	0.0	0.1	0.9
	20,000	Not Present	0.1	0.1	1.6
26	4,000	0.0	0.1	0.2	0.4
	12,000	0.1	0.4	0.7	1.1
	20,000	0.1	0.7	1.1	1.9
30	4,000	0.3	0.5	0.4	0.5
	12,000	0.9	1.5	1.3	1.4
	20,000	1.4	2.5	2.2	2.4
34	4,000	0.7	0.8	0.8	0.5
	12,000	2.2	2.4	2.3	1.6
	20,000	3.6	4.0	3.9	2.7
50 Years					
18	4,000	Not Present	Not Present	0.0	0.4
	12,000	Not Present	Not Present	0.0	1.1
	20,000	Not Present	Not Present	0.1	1.8
22	4,000	Not Present	0.1	0.1	0.7
	12,000	Not Present	0.2	0.3	2.2
	20,000	Not Present	0.3	0.4	3.6
26	4,000	0.1	0.4	0.7	0.8
	12,000	0.3	1.3	2.1	2.6
	20,000	0.5	2.2	3.5	4.2
30	4,000	0.7	1.3	1.2	1.0
	12,000	2.2	3.8	3.5	3.1
	20,000	3.7	6.3	5.8	5.1
34	4,000	1.6	1.8	1.8	1.1
	12,000	4.9	5.4	5.3	3.4
	20,000	8.1	9.1	8.8	5.6

Figures 6-58 to **6-59** show simulated drawdowns caused by pumping the Sparta Aquifer at 2,000; 6,000; and 10,000 AFY for 30 and 50 years at well field #1 and well field #2. The simulated drawdowns are plotted along cross section #1 for all seven model layers. **Figures 6-60** to **6-61** show simulated drawdowns for 5, 10, 30, and 50 years for model layers 2, 4, and 5 caused by pumping the Sparta Aquifer at well field #1 and well field #2. In **Figures 6-62** through **6-63**, there are five monitoring locations up dip of the two well fields. At these locations, **Tables 6-36** and **6-37** provide simulated drawdowns for model layers 2, 4, 5, and 7 caused by pumping 6,000 AFY from well field #1 and well field #2, respectively.

Among the notable observations are the following:

- Except for areas near the up-dip boundary of the outcrops where storage coefficients are large, the model exhibits a linear response between the increase in the pumping rate and the increase in the aquifer drawdown for times greater than 30 years.
- Greater drawdowns occur near the center of pumping at well field #1 than at well field #2 at times greater than 30 years. For the pumping rate of 6,000 AFY, this drawdown is about 90 ft at well field #1 and is about 120 ft at well field #2.
- About 90% of the drawdown that occurs at 50 years near the well fields occur during the first 5 years of pumping.
- After 50 years of pumping at well field #1 at 6,000 AFY, the drawdown in the Sparta, upper Queen City, the lower Queen City, and Carrizo-upper Wilcox is 37, 13.6, 13.4, and 4 ft, respectively at a distance that is 9 miles up dip from the well field and 34 miles down dip from the outcrop of the Carrizo-Wilcox Aquifer.
- After 50 years of pumping at well field #1 at 6,000 AFY, the drawdown in the Sparta, upper Queen City, lower Queen City, and Carrizo-upper Wilcox is 2.4, 3.4, 3.4, and 2.4 ft, respectively at a distance that is 21 miles up dip from the well field and 22 miles down dip from the outcrop of the Carrizo-Wilcox Aquifer.
- After 50 years of pumping at well field #2 at 6,000 AFY, the drawdown in the Sparta, upper Queen City, the lower Queen City, and Carrizo-upper Wilcox is 6.3, 3.5, 3.1, and 1.0 ft, respectively at a distance that is 27 miles up dip from the well field and 34 miles down dip from the outcrop of the Carrizo-Wilcox Aquifer.
- After 50 years of pumping at well field #2 at 6,000 AFY, the drawdown in the Sparta, upper Queen City, lower Queen City, and Carrizo-upper Wilcox is 0.3, 0.5, 0.8, and 0.7 ft, respectively at a distance that is 39 miles up dip from the well field and 22 miles down dip from the outcrop of the Carrizo-Wilcox Aquifer.

Table 6-36. Simulated drawdown at monitoring locations after pumping the Sparta Aquifer at Well Field #1 in PPA #1 for 30 years and 50 years.

Monitoring Location (miles)	Pumping Rate (AFY)	Sparta	Upper Queen City	Lower Queen City	Carrizo-Upper Wilcox
		Layer 2	Layer 4	Layer 5	Layer 7
30 Years					
22	2,000	Not Present	0.0	0.1	0.4
	6,000	Not Present	0.1	0.3	1.3
	10,000	Not Present	0.2	0.4	2.1
26	2,000	0.4	0.7	0.7	0.5
	6,000	1.3	2.2	2.1	1.5
	10,000	2.1	3.7	3.5	2.6
30	2,000	2.7	1.6	1.6	0.6
	6,000	8.3	4.9	4.7	1.8
	10,000	13.6	8.2	7.9	3.0
34	2,000	6.7	2.9	2.1	0.7
	6,000	20.5	8.7	6.2	2.2
	10,000	33.4	14.4	10.3	3.6
38	2,000	10.9	3.7	3.7	0.9
	6,000	33.6	11.2	11.1	2.6
	10,000	54.3	18.6	18.3	4.4
50 Years					
18	2,000	Not Present	0.1	0.2	0.7
	6,000	Not Present	0.2	0.6	2.1
	10,000	Not Present	0.4	1.0	3.4
22	2,000	0.8	1.1	1.1	0.8
	6,000	2.4	3.4	3.4	2.4
	10,000	4.0	5.6	5.7	4.0
26	2,000	3.3	2.3	2.2	0.9
	6,000	10.1	6.8	6.6	2.7
	10,000	16.5	11.3	11.1	4.6
30	2,000	7.7	3.7	2.8	1.1
	6,000	23.4	11.0	8.3	3.2
	10,000	38.3	18.2	13.8	5.3
34	2,000	12.0	4.5	4.5	1.3
	6,000	36.9	13.6	13.4	3.8
	10,000	59.7	22.6	22.2	6.2

Table 6-37. Simulated drawdown at monitoring locations after pumping the Sparta Aquifer at Well Field #2 in PPA #1 for 30 years and 50 years.

Monitoring Location (miles)	Pumping Rate (AFY)	Sparta	Upper Queen City	Lower Queen City	Carrizo-Upper Wilcox
		Layer 2	Layer 4	Layer 5	Layer 7
30 Years					
22	2,000	Not Present	0.0	0.0	0.1
	6,000	Not Present	0.0	0.0	0.2
	10,000	Not Present	0.0	0.0	0.4
26	2,000	0.0	0.1	0.1	0.1
	6,000	0.1	0.2	0.2	0.3
	10,000	0.1	0.3	0.4	0.5
30	2,000	0.3	0.2	0.2	0.1
	6,000	1.0	0.6	0.5	0.4
	10,000	1.7	1.0	0.8	0.6
34	2,000	0.8	0.3	0.3	0.1
	6,000	2.5	1.0	0.9	0.4
	10,000	4.2	1.6	1.4	0.6
38	2,000	1.2	0.6	0.5	0.2
	6,000	3.8	1.8	1.5	0.5
	10,000	6.3	3.0	2.5	0.7
50 Years					
18	2,000	Not Present	0.0	0.0	0.2
	6,000	Not Present	0.1	0.1	0.6
	10,000	Not Present	0.1	0.1	1.0
22	2,000	0.1	0.2	0.3	0.2
	6,000	0.3	0.5	0.8	0.7
	10,000	0.5	0.9	1.3	1.2
26	2,000	0.7	0.5	0.4	0.3
	6,000	2.1	1.6	1.3	0.9
	10,000	3.5	2.6	2.2	1.4
30	2,000	1.5	0.7	0.7	0.3
	6,000	4.6	2.3	2.0	0.9
	10,000	7.7	3.7	3.3	1.6
34	2,000	2.1	1.2	1.0	0.3
	6,000	6.3	3.5	3.1	1.0
	10,000	10.6	5.9	5.1	1.7

6.3.5.1 Sensitivity Analysis on the Simulated Drawdown for Potential Production Area #1

Table 6-2 lists the sixteen model runs that comprise the sensitivity analysis. The primary focus of the sensitivity analysis was on specific storage (Ss), vertical hydraulic conductivity (Kz), and horizontal hydraulic conductivity (Kh). These three parameters were increased and decrease by a factor of 3. In the report discussion, the baseline simulation is referred as a Run 0. Sensitivity Model Runs 1 through 8 involved varying only one model parameter. Sensitivity Model Runs 9 through 16 involved varying three hydraulic properties at the same time. The only runs involving a change in the recharge rate are Model Runs 7 and 8.

The results of the sensitivity runs are summarized in four tables. The output from each sensitivity run is drawdown at the five monitoring locations for the Queen City Aquifer are shown in Figure 6-52 and the five monitoring locations for the Sparta Aquifer are shown in Figure 6-58. **Table 6-38** summarizes simulated drawdown results at the monitoring location for pumping the Queen City Aquifer at 12,000 AFY at well field #1 for 30 and 50 years. **Table 6-39** summarizes simulated drawdown results at the monitoring location for pumping the Queen City Aquifer at 12,000 AFY at well field #2 for 30 and 50 years. **Table 6-40** summarizes simulated drawdown results at the monitoring location for pumping the Sparta Aquifer at 6,000 AFY at well field #1 for 30 and 50 years. **Table 6-41** summarizes simulated drawdown results at the monitoring location for pumping the Sparta Aquifer at 6,000 AFY at well field #2 for 30 and 50 years. Among the notable observations are the following:

- The drawdowns at the monitoring wells are less sensitive to changes in recharge rates (Runs 7 and 8).
- For the condition of pumping the upper Queen City Aquifer at 12,000 AFY for 50 years at well field #1 (**Table 6-38**):
  - o The predicted range in the upper Queen City Aquifer at an up dip distance of 9 miles up dip from the well field is between 12.0 and 34.4 ft. The base case run predicted a drawdown of 26.1 ft.
  - o The predicted range in the upper Queen City Aquifer at an up dip distance of 21 miles up dip from the well field is between 0.3 and 3.3 ft. The base case run predicted a drawdown of 2.1 ft.
- For the condition of pumping the upper Queen City Aquifer at 12,000 AFY for 50 years at well field #2 (Table 6-39):
  - o The predicted range in the upper Queen City Aquifer at an up dip distance of 27 miles up dip from the well field is between 0.4 and 12.7 ft. The base case run predicted a drawdown of 5.3 ft.
  - o The predicted range in the upper Queen City Aquifer at a up dip distance of 39 miles up dip from the well field is between <0.1 and 2.4 ft. The base case run predicted a drawdown of 0.3 ft.
- For the condition of pumping the Sparta Aquifer at 6,000 AFY for 50 years at well field #1 (Table 6-40):

  - The predicted range in the upper Queen City at an up dip distance of 5 miles up dip from the well field is between 20.2 and 50.1 ft. The base case run predicted a drawdown of 36.9 ft.
  - The predicted range in the upper Queen City at an up dip distance of 17 miles up dip from the well field is between 0.3 and 5.0 ft. The base case run predicted a drawdown of 2.4 ft.
- For the condition of pumping the Sparta Aquifer at 6,000 AFY for 50 years at well field #2:
  - The predicted range in the upper Queen City at an up dip distance of 23 miles up dip from the well field is between 0.7 and 9.9 ft. The base case run predicted a drawdown of 6.3 ft.
  - The predicted range in the upper Queen City at a up dip distance of 35 miles up dip from the well field is between <0.1 and 1.7 ft. The base case run predicted a drawdown of 0.3 ft.

Table 6-38. Results from a sensitivity analysis of simulated drawdowns caused by pumping 12,000 AFY from the Queen City Aquifer at Well Field #1 located in PPA #1 at five monitoring locations for model layers 2, 4, 5, and 7.

Monitoring	30 years				50 years			
Location 18 miles	**Layer 2**	**Layer 4**	**Layer 5**	**Layer 7**	**Layer 2**	**Layer 4**	**Layer 5**	**Layer 7**
Run 00	NP	NP	0.1	2.9	NP	NP	0.2	4.5
Run 01	NP	NP	0.2	3.8	NP	NP	0.3	5.6
Run 02	NP	NP	<0.1	2.0	NP	NP	0.1	3.2
Run 03	NP	NP	0.1	2.4	NP	NP	0.1	3.9
Run 04	NP	NP	0.1	3.1	NP	NP	0.2	4.7
Run 05	NP	NP	0.1	3.6	NP	NP	0.1	5.5
Run 06	NP	NP	0.2	2.0	NP	NP	0.4	3.1
Run 07	NP	NP	0.1	2.9	NP	NP	0.2	4.5
Run 08	NP	NP	0.1	2.9	NP	NP	0.2	4.5
Run 09	NP	NP	0.1	1.5	NP	NP	0.1	2.4
Run 10	NP	NP	<0.1	0.9	NP	NP	0.1	1.6
Run 11	NP	NP	0.4	3.0	NP	NP	0.5	4.3
Run 12	NP	NP	0.4	2.2	NP	NP	0.5	3.3
Run 13	NP	NP	<0.1	2.9	NP	NP	0.1	4.5
Run 14	NP	NP	<0.1	2.0	NP	NP	0.1	3.4
Run 15	NP	NP	0.1	4.9	NP	NP	0.2	7.2
Run 16	NP	NP	0.1	4.0	NP	NP	0.2	6.1

Monitoring	30 years				50 years			
Location 22 miles	**Layer 2**	**Layer 4**	**Layer 5**	**Layer 7**	**Layer 2**	**Layer 4**	**Layer 5**	**Layer 7**
Run 00	NP	0.3	1.0	6.0	NP	0.7	2.1	8.6
Run 01	NP	0.7	2.5	7.8	NP	1.1	3.3	10.5
Run 02	NP	0.1	0.1	4.1	NP	0.2	0.4	6.1
Run 03	NP	0.4	0.9	5.0	NP	0.7	2.2	7.4
Run 04	NP	0.6	0.9	6.6	NP	1.4	1.8	9.1
Run 05	NP	<0.1	0.6	7.5	NP	0.1	1.2	10.6
Run 06	NP	2.3	2.1	4.2	NP	3.8	3.1	5.9
Run 07	NP	0.6	1.0	6.0	NP	1.4	2.2	8.6
Run 08	NP	0.3	1.0	6.0	NP	0.6	2.0	8.6
Run 09	NP	0.5	0.5	3.2	NP	1.4	1.3	4.7
Run 10	NP	0.4	0.3	1.9	NP	0.8	1.0	3.1
Run 11	NP	2.7	3.4	5.9	NP	3.9	4.3	7.9
Run 12	NP	1.5	3.6	4.4	NP	2.4	4.3	6.1
Run 13	NP	<0.1	0.2	6.1	NP	0.1	0.4	8.7
Run 14	NP	<0.1	0.1	4.3	NP	<0.1	0.3	6.6
Run 15	NP	0.3	1.2	10.1	NP	0.5	1.9	13.5
Run 16	NP	0.2	1.7	8.2	NP	0.4	2.9	11.5

Monitoring	30 years				50 years			
Location 26 miles	**Layer 2**	**Layer 4**	**Layer 5**	**Layer 7**	**Layer 2**	**Layer 4**	**Layer 5**	**Layer 7**
Run 00	1.1	6.5	7.1	7.3	2.4	9.3	10.6	10.1
Run 01	1.6	10.2	11.7	9.2	2.9	12.0	14.0	12.3
Run 02	0.7	1.7	1.6	5.0	1.6	4.0	4.0	7.3
Run 03	1.2	7.2	6.8	5.9	2.5	10.2	10.8	8.6
Run 04	1.1	6.3	7.0	7.9	2.3	9.1	10.1	10.8
Run 05	1.2	3.3	4.1	9.0	2.7	6.5	7.9	12.5
Run 06	0.9	7.5	8.0	4.9	1.7	9.4	10.2	6.8
Run 07	1.1	6.5	7.1	7.3	2.4	9.3	10.6	10.1
Run 08	1.1	6.5	7.1	7.3	2.4	9.2	10.5	10.1
Run 09	0.5	4.0	3.8	3.8	1.2	6.3	6.4	5.5
Run 10	0.6	4.8	2.8	2.3	1.3	7.4	5.2	3.6
Run 11	1.2	10.6	11.0	7.0	2.1	12.1	12.7	9.1
Run 12	1.2	12.0	10.9	5.1	2.1	13.4	12.5	7.1
Run 13	0.7	0.4	1.0	7.5	1.7	1.5	2.3	10.4
Run 14	0.8	0.3	0.6	5.2	2.0	1.2	1.6	7.8
Run 15	1.6	7.7	9.1	12.1	3.2	10.1	12.0	15.9
Run 16	1.9	8.4	9.8	9.8	3.7	11.0	13.5	13.4

Monitoring	30 years				50 years			
Location 30 miles	**Layer 2**	**Layer 4**	**Layer 5**	**Layer 7**	**Layer 2**	**Layer 4**	**Layer 5**	**Layer 7**
Run 00	7.0	15.0	15.9	8.4	9.5	19.3	20.6	11.4
Run 01	8.6	20.5	21.9	10.5	11.0	23.3	25.1	13.8
Run 02	4.8	6.4	6.6	5.9	7.1	10.9	11.5	8.3
Run 03	7.4	16.9	15.8	6.8	10.1	21.4	21.1	9.7
Run 04	6.7	14.4	15.4	9.2	9.1	18.6	19.8	12.2
Run 05	8.3	11.1	12.0	10.5	11.6	17.0	18.3	14.2
Run 06	4.8	13.3	14.0	5.6	6.3	15.7	16.7	7.7
Run 07	7.0	15.0	15.9	8.4	9.5	19.3	20.6	11.5
Run 08	7.0	15.0	15.9	8.4	9.4	19.2	20.5	11.4
Run 09	3.4	8.0	8.5	4.5	4.8	11.2	11.8	6.3
Run 10	3.7	9.6	6.8	2.7	5.2	13.0	10.2	4.1
Run 11	5.7	16.6	17.5	7.9	7.3	18.5	19.6	10.2
Run 12	6.0	18.9	17.1	5.8	7.6	20.7	19.1	7.8
Run 13	5.3	2.8	3.3	8.7	8.0	6.7	7.4	12.0
Run 14	6.5	2.6	2.5	6.1	9.7	6.6	6.4	8.9
Run 15	9.7	18.5	19.7	13.9	12.7	22.6	24.0	18.0
Run 16	11.5	21.5	21.8	11.2	14.9	26.1	26.9	15.1

Monitoring	30 years				50 years			
Location 34 miles	**Layer 2**	**Layer 4**	**Layer 5**	**Layer 7**	**Layer 2**	**Layer 4**	**Layer 5**	**Layer 7**
Run 00	16.3	27.9	21.0	10.2	20.6	33.1	26.1	13.5
Run 01	19.5	34.4	27.3	12.6	23.5	38.1	30.8	16.0
Run 02	12.0	17.0	10.8	7.3	16.1	23.3	16.5	10.1
Run 03	17.4	31.7	20.9	8.3	22.0	37.2	26.4	11.3
Run 04	15.5	26.6	20.4	11.2	19.7	31.6	25.2	14.5
Run 05	20.4	27.2	18.3	13.0	26.0	34.9	25.2	17.1
Run 06	10.8	20.9	16.9	6.7	13.4	23.7	19.7	8.9
Run 07	16.3	27.9	21.0	10.2	20.6	33.1	26.1	13.5
Run 08	16.3	27.9	21.0	10.2	20.6	33.1	26.0	13.5
Run 09	7.9	14.4	11.2	5.5	10.4	17.9	14.7	7.4
Run 10	8.6	17.1	9.1	3.3	11.3	21.0	12.6	4.8
Run 11	12.5	24.1	20.7	9.2	15.1	26.3	22.9	11.7
Run 12	13.2	27.8	19.7	6.7	15.9	29.9	21.9	8.8
Run 13	13.8	12.6	7.0	11.1	18.8	20.3	13.0	14.7
Run 14	16.7	13.9	5.9	7.7	22.7	22.9	12.0	10.9
Run 15	22.7	34.8	26.4	17.0	27.9	40.0	31.2	21.4
Run 16	27.0	42.4	28.9	13.6	32.9	48.3	34.4	17.7

Note: NP = Not Present; 0.0 represents a drawdown that is less than 0.1 foot

Table 6-39. Results from a sensitivity analysis of simulated drawdowns caused by pumping 12,000 AFY from the Queen City Aquifer at Well Field #2 located in PPA #1 at five monitoring locations for model layers 2, 4, 5, and 7.

Monitoring Location 18 miles	30 years Layer 2	30 years Layer 4	30 years Layer 5	30 years Layer 7	50 years Layer 2	50 years Layer 4	50 years Layer 5	50 years Layer 7
Run 00	NP	NP	<0.1	0.4	NP	NP	<0.1	1.1
Run 01	NP	NP	<0.1	1.1	NP	NP	0.1	2.4
Run 02	NP	NP	<0.1	0.2	NP	NP	<0.1	0.4
Run 03	NP	NP	<0.1	0.4	NP	NP	<0.1	1.0
Run 04	NP	NP	<0.1	0.5	NP	NP	<0.1	1.2
Run 05	NP	NP	<0.1	0.4	NP	NP	<0.1	1.0
Run 06	NP	NP	0.1	0.6	NP	NP	0.2	1.3
Run 07	NP	NP	<0.1	0.4	NP	NP	<0.1	1.1
Run 08	NP	NP	<0.1	0.4	NP	NP	<0.1	1.1
Run 09	NP	NP	<0.1	0.2	NP	NP	<0.1	0.5
Run 10	NP	NP	<0.1	0.1	NP	NP	<0.1	0.4
Run 11	NP	NP	0.2	1.4	NP	NP	0.3	2.6
Run 12	NP	NP	0.2	1.2	NP	NP	0.3	2.3
Run 13	NP	NP	<0.1	0.2	NP	NP	<0.1	0.6
Run 14	NP	NP	<0.1	0.2	NP	NP	<0.1	0.5
Run 15	NP	NP	<0.1	0.9	NP	NP	<0.1	2.0
Run 16	NP	NP	<0.1	0.8	NP	NP	<0.1	1.8

Monitoring Location 22 miles	30 years Layer 2	30 years Layer 4	30 years Layer 5	30 years Layer 7	50 years Layer 2	50 years Layer 4	50 years Layer 5	50 years Layer 7
Run 00	NP	<0.1	0.1	0.9	NP	0.2	0.3	2.2
Run 01	NP	0.3	0.5	2.3	NP	0.7	1.1	4.4
Run 02	NP	<0.1	<0.1	0.3	NP	<0.1	<0.1	0.8
Run 03	NP	<0.1	<0.1	0.8	NP	0.2	0.2	2.0
Run 04	NP	<0.1	0.1	1.0	NP	0.2	0.2	2.3
Run 05	NP	<0.1	<0.1	0.9	NP	<0.1	0.1	2.0
Run 06	NP	0.6	0.4	1.2	NP	1.3	0.9	2.5
Run 07	NP	<0.1	0.1	0.9	NP	0.2	0.3	2.2
Run 08	NP	<0.1	0.1	0.9	NP	0.2	0.2	2.2
Run 09	NP	<0.1	<0.1	0.4	NP	0.2	0.1	1.0
Run 10	NP	<0.1	<0.1	0.3	NP	0.2	0.1	0.8
Run 11	NP	1.3	1.5	2.8	NP	2.1	2.2	4.6
Run 12	NP	1.4	1.6	2.4	NP	2.0	2.4	4.1
Run 13	NP	<0.1	<0.1	0.5	NP	<0.1	<0.1	1.1
Run 14	NP	<0.1	<0.1	0.4	NP	<0.1	<0.1	0.9
Run 15	NP	<0.1	0.1	1.9	NP	0.2	0.4	3.9
Run 16	NP	<0.1	0.1	1.6	NP	0.1	0.5	3.5

Monitoring Location 26 miles	30 years Layer 2	30 years Layer 4	30 years Layer 5	30 years Layer 7	50 years Layer 2	50 years Layer 4	50 years Layer 5	50 years Layer 7
Run 00	0.1	0.4	0.7	1.1	0.3	1.3	2.1	2.6
Run 01	0.2	2.2	3.6	2.8	0.6	3.7	6.1	5.1
Run 02	<0.1	<0.1	<0.1	0.4	0.1	0.1	0.2	1.0
Run 03	0.1	0.5	0.6	1.0	0.3	1.4	2.0	2.3
Run 04	0.1	0.4	0.7	1.2	0.3	1.3	2.1	2.7
Run 05	<0.1	0.1	0.2	1.1	0.2	0.4	0.8	2.3
Run 06	0.1	1.7	2.3	1.5	0.4	3.1	4.3	3.0
Run 07	0.1	0.4	0.7	1.1	0.3	1.3	2.1	2.6
Run 08	0.1	0.4	0.7	1.1	0.3	1.3	2.1	2.6
Run 09	<0.1	0.2	0.3	0.5	0.1	0.8	1.0	1.2
Run 10	<0.1	0.3	0.2	0.4	0.1	1.0	0.8	0.9
Run 11	0.3	4.5	5.8	3.3	0.7	6.0	7.6	5.3
Run 12	0.3	4.9	6.0	2.8	0.7	6.3	8.0	4.7
Run 13	<0.1	<0.1	<0.1	0.6	0.1	<0.1	0.1	1.3
Run 14	<0.1	<0.1	<0.1	0.4	0.1	<0.1	0.1	1.0
Run 15	0.1	0.7	1.4	2.3	0.5	1.7	3.3	4.5
Run 16	0.1	0.6	1.3	1.9	0.5	1.6	3.4	4.1

Monitoring Location 30 miles	30 years Layer 2	30 years Layer 4	30 years Layer 5	30 years Layer 7	50 years Layer 2	50 years Layer 4	50 years Layer 5	50 years Layer 7
Run 00	0.9	1.5	1.3	1.4	2.2	3.8	3.5	3.1
Run 01	2.1	5.9	5.5	3.3	4.2	9.0	8.8	6.0
Run 02	0.3	0.1	0.1	0.5	0.9	0.5	0.4	1.2
Run 03	0.9	1.7	1.2	1.2	2.3	4.1	3.4	2.7
Run 04	0.8	1.5	1.4	1.5	2.2	3.7	3.5	3.2
Run 05	0.7	0.4	0.5	1.4	2.0	1.5	1.5	2.8
Run 06	1.2	3.7	3.5	1.8	2.4	6.1	6.0	3.5
Run 07	0.9	1.5	1.3	1.4	2.2	3.8	3.5	3.1
Run 08	0.9	1.5	1.3	1.4	2.2	3.8	3.5	3.1
Run 09	0.4	0.7	0.6	0.7	1.0	1.9	1.7	1.5
Run 10	0.4	0.9	0.4	0.4	1.1	2.2	1.4	1.1
Run 11	2.3	7.9	7.8	3.9	3.8	10.0	10.0	6.2
Run 12	2.3	8.6	8.1	3.3	3.7	10.7	10.4	5.4
Run 13	0.3	<0.1	0.1	0.8	1.0	0.2	0.3	1.6
Run 14	0.4	<0.1	0.1	0.6	1.1	0.2	0.2	1.2
Run 15	1.5	2.6	2.4	2.8	3.7	5.7	5.3	5.4
Run 16	1.6	2.7	2.3	2.4	3.9	5.9	5.4	4.8

Monitoring Location 34 miles	30 years Layer 2	30 years Layer 4	30 years Layer 5	30 years Layer 7	50 years Layer 2	50 years Layer 4	50 years Layer 5	50 years Layer 7
Run 00	2.2	2.4	2.3	1.6	4.9	5.4	5.3	3.4
Run 01	4.8	8.1	7.8	3.7	8.7	12.0	11.8	6.5
Run 02	0.8	0.2	0.2	0.6	2.1	0.9	0.9	1.3
Run 03	2.3	2.7	2.2	1.4	5.0	5.8	5.2	3.0
Run 04	2.1	2.4	2.3	1.7	4.8	5.4	5.3	3.5
Run 05	1.9	0.8	0.8	1.5	4.6	2.6	2.6	3.1
Run 06	2.6	4.9	4.9	2.0	4.9	7.7	7.9	3.8
Run 07	2.2	2.4	2.3	1.6	4.9	5.4	5.3	3.4
Run 08	2.2	2.4	2.3	1.6	4.9	5.4	5.3	3.4
Run 09	0.9	1.1	1.1	0.7	2.2	2.6	2.7	1.6
Run 10	1.1	1.4	0.8	0.5	2.4	3.1	2.2	1.2
Run 11	4.9	9.7	9.8	4.2	7.5	12.1	12.3	6.6
Run 12	4.8	10.6	10.1	3.5	7.4	13.0	12.7	5.7
Run 13	0.9	0.1	0.2	0.9	2.3	0.5	0.6	1.8
Run 14	1.1	0.1	0.1	0.6	2.6	0.4	0.4	1.4
Run 15	3.8	4.1	3.9	3.1	8.1	8.3	7.9	5.9
Run 16	4.0	4.3	3.8	2.7	8.4	8.7	8.0	5.3

Note: NP = Not Present; 0.0 represents a drawdown that is less than 0.1 foot

Table 6-40. **Results from a sensitivity analysis of simulated drawdowns caused by pumping 6,000 AFY from the Sparta Aquifer at Well Field #1 located in PPA #1 at five monitoring locations for model layers 2, 4, 5, and 7.**

Monitoring	30 years				50 years			
Location 22 miles	Layer 2	Layer 4	Layer 5	Layer 7	Layer 2	Layer 4	Layer 5	Layer 7
Run 00	NP	0.1	0.3	1.3	NP	0.2	0.6	2.1
Run 01	NP	0.1	0.3	1.5	NP	0.3	0.7	2.3
Run 02	NP	0.1	0.2	0.9	NP	0.2	0.4	1.6
Run 03	NP	0.1	0.2	1.2	NP	0.2	0.6	1.9
Run 04	NP	0.1	0.3	1.3	NP	0.3	0.6	2.1
Run 05	NP	0.1	0.3	1.7	NP	0.3	0.7	2.7
Run 06	NP	0.1	0.2	0.8	NP	0.2	0.4	1.3
Run 07	NP	0.1	0.3	1.3	NP	0.2	0.6	2.1
Run 08	NP	0.1	0.2	1.3	NP	0.2	0.6	2.1
Run 09	NP	0.1	0.1	0.6	NP	0.1	0.3	1.1
Run 10	NP	<0.1	0.1	0.5	NP	0.1	0.3	0.9
Run 11	NP	0.1	0.2	1.0	NP	0.2	0.5	1.6
Run 12	NP	0.1	0.2	0.9	NP	0.2	0.5	1.4
Run 13	NP	0.1	0.2	1.3	NP	0.2	0.6	2.2
Run 14	NP	0.1	0.2	1.2	NP	0.2	0.5	2.0
Run 15	NP	0.2	0.4	2.0	NP	0.4	0.9	3.1
Run 16	NP	0.2	0.4	1.9	NP	0.3	0.9	3.0

Monitoring	30 years				50 years			
Location 26 miles	Layer 2	Layer 4	Layer 5	Layer 7	Layer 2	Layer 4	Layer 5	Layer 7
Run 00	1.3	2.2	2.1	1.5	2.4	3.4	3.4	2.4
Run 01	2.0	2.7	2.6	1.8	3.0	3.8	3.9	2.8
Run 02	0.4	1.5	1.4	1.1	1.2	2.5	2.6	1.9
Run 03	1.4	2.1	2.0	1.4	2.5	3.2	3.3	2.3
Run 04	1.3	2.2	2.1	1.6	2.4	3.4	3.5	2.5
Run 05	0.2	2.6	2.5	2.1	0.3	4.0	4.2	3.2
Run 06	3.6	1.6	1.4	1.0	5.0	2.3	2.3	1.6
Run 07	1.3	2.2	2.1	1.5	2.4	3.4	3.4	2.4
Run 08	0.8	2.2	2.1	1.5	1.2	3.4	3.4	2.4
Run 09	1.4	1.1	1.0	0.8	2.8	1.8	1.8	1.3
Run 10	1.4	1.0	0.9	0.7	2.9	1.7	1.7	1.1
Run 11	3.4	1.9	1.8	1.2	4.8	2.7	2.7	1.8
Run 12	3.6	1.8	1.7	1.1	5.0	2.5	2.5	1.7
Run 13	0.1	1.8	1.8	1.6	0.3	3.0	3.3	2.6
Run 14	0.1	1.6	1.6	1.4	0.3	2.9	3.0	2.4
Run 15	0.7	3.2	3.2	2.5	1.3	4.7	4.9	3.7
Run 16	0.8	3.1	3.1	2.3	1.4	4.5	4.8	3.5

Monitoring	30 years				50 years			
Location 30 miles	Layer 2	Layer 4	Layer 5	Layer 7	Layer 2	Layer 4	Layer 5	Layer 7
Run 00	8.3	4.9	4.7	1.8	10.1	6.8	6.6	2.7
Run 01	10.3	5.9	5.6	2.1	11.2	7.6	7.5	3.1
Run 02	3.7	3.5	3.4	1.3	6.4	5.2	5.2	2.1
Run 03	8.8	4.7	4.4	1.7	10.6	6.5	6.3	2.6
Run 04	8.1	5.0	4.8	1.8	9.9	6.9	6.8	2.8
Run 05	5.2	6.0	5.9	2.4	7.7	8.3	8.4	3.6
Run 06	8.2	3.3	3.1	1.1	9.5	4.5	4.3	1.8
Run 07	8.3	4.9	4.7	1.8	10.1	6.8	6.6	2.7
Run 08	8.2	4.9	4.7	1.8	9.9	6.8	6.6	2.7
Run 09	5.7	2.5	2.4	0.9	7.6	3.7	3.6	1.4
Run 10	5.9	2.3	2.1	0.8	7.9	3.4	3.2	1.3
Run 11	9.8	4.1	3.8	1.4	10.6	5.2	5.0	2.1
Run 12	10.3	3.8	3.5	1.3	11.1	4.8	4.6	1.9
Run 13	1.0	4.3	4.4	1.9	2.8	6.5	6.7	3.0
Run 14	1.0	4.0	4.0	1.7	2.8	6.1	6.2	2.7
Run 15	8.0	7.3	7.1	2.8	9.2	9.4	9.5	4.1
Run 16	8.9	7.0	6.8	2.7	10.2	9.2	9.2	3.9

Monitoring	30 years				50 years			
Location 34 miles	Layer 2	Layer 4	Layer 5	Layer 7	Layer 2	Layer 4	Layer 5	Layer 7
Run 00	20.5	8.7	6.2	2.2	23.4	11.0	8.3	3.2
Run 01	23.9	10.1	7.3	2.5	25.5	12.1	9.2	3.6
Run 02	12.4	6.5	4.6	1.6	17.2	8.7	6.6	2.5
Run 03	21.6	8.2	5.8	2.0	24.7	10.4	7.9	3.0
Run 04	20.1	8.8	6.3	2.2	23.0	11.2	8.4	3.3
Run 05	18.4	11.0	7.9	2.9	23.2	13.9	10.6	4.3
Run 06	15.3	5.6	4.0	1.4	16.9	7.0	5.3	2.0
Run 07	20.5	8.7	6.2	2.2	23.4	11.0	8.3	3.2
Run 08	20.5	8.7	6.2	2.2	23.4	11.0	8.3	3.2
Run 09	11.3	4.4	3.1	1.1	13.9	5.9	4.4	1.7
Run 10	11.7	4.0	2.8	0.9	14.4	5.4	4.0	1.5
Run 11	17.2	6.7	4.8	1.7	18.2	8.0	6.1	2.4
Run 12	18.1	6.1	4.4	1.5	19.1	7.4	5.6	2.2
Run 13	7.4	8.4	6.0	2.3	13.1	11.4	8.6	3.5
Run 14	7.8	7.7	5.5	2.1	14.0	10.7	8.0	3.2
Run 15	23.6	12.9	9.4	3.5	25.9	15.6	11.9	4.9
Run 16	26.4	12.4	8.9	3.2	28.8	15.0	11.4	4.6

Monitoring	30 years				50 years			
Location 38 miles	Layer 2	Layer 4	Layer 5	Layer 7	Layer 2	Layer 4	Layer 5	Layer 7
Run 00	33.6	11.2	11.1	2.6	36.9	13.6	13.4	3.8
Run 01	37.3	12.8	12.5	3.1	39.2	14.8	14.5	4.2
Run 02	25.7	8.6	8.6	2.0	30.5	11.1	11.0	3.0
Run 03	35.4	10.5	10.4	2.5	38.8	12.9	12.7	3.5
Run 04	33.0	11.5	11.3	2.7	36.2	13.9	13.6	3.8
Run 05	38.4	14.8	14.7	3.6	42.9	17.9	17.6	5.0
Run 06	21.9	7.0	6.9	1.6	23.7	8.5	8.3	2.4
Run 07	33.6	11.2	11.1	2.6	36.9	13.6	13.4	3.8
Run 08	33.6	11.2	11.1	2.6	36.8	13.6	13.4	3.8
Run 09	17.5	5.7	5.6	1.3	20.2	7.3	7.2	2.0
Run 10	18.1	5.1	5.0	1.2	20.9	6.6	6.5	1.8
Run 11	24.0	8.2	8.0	2.0	25.1	9.6	9.3	2.8
Run 12	25.1	7.5	7.3	1.8	26.2	8.8	8.6	2.5
Run 13	27.0	11.8	11.8	2.8	33.5	15.1	15.0	4.2
Run 14	29.6	10.8	10.8	2.6	36.8	14.0	14.0	3.8
Run 15	42.2	17.1	16.8	4.2	44.8	19.8	19.4	5.7
Run 16	47.4	16.2	15.9	3.9	50.1	18.9	18.5	5.4

Note: NP = Not Present; 0.0 represents a drawdown that is less than 0.1 foot

Table 6-41. Results from a sensitivity analysis of simulated drawdowns caused by pumping 6,000 AFY from the Sparta Aquifer at Well Field #2 located in PPA #1 at five monitoring locations for model layers 2, 4, 5, and 7.

Monitoring	30 years				50 years			
Location 22 miles	Layer 2	Layer 4	Layer 5	Layer 7	Layer 2	Layer 4	Layer 5	Layer 7
Run 00	NP	0.0	0.0	0.2	NP	0.1	0.1	0.6
Run 01	NP	0.0	0.0	0.4	NP	0.1	0.1	0.9
Run 02	NP	0.0	0.0	0.1	NP	0.0	0.0	0.3
Run 03	NP	0.0	0.0	0.2	NP	0.1	0.1	0.6
Run 04	NP	0.0	0.0	0.2	NP	0.1	0.1	0.6
Run 05	NP	0.0	0.0	0.2	NP	0.1	0.1	0.6
Run 06	NP	0.0	0.0	0.2	NP	0.1	0.1	0.6
Run 07	NP	0.0	0.0	0.2	NP	0.1	0.1	0.6
Run 08	NP	0.0	0.0	0.2	NP	0.1	0.1	0.6
Run 09	NP	0.0	0.0	0.1	NP	0.0	0.0	0.3
Run 10	NP	0.0	0.0	0.1	NP	0.0	0.0	0.3
Run 11	NP	0.1	0.0	0.4	NP	0.2	0.2	0.8
Run 12	NP	0.1	0.0	0.4	NP	0.1	0.2	0.8
Run 13	NP	0.0	0.0	0.1	NP	0.0	0.0	0.4
Run 14	NP	0.0	0.0	0.1	NP	0.0	0.0	0.4
Run 15	NP	0.0	0.0	0.3	NP	0.1	0.1	0.8
Run 16	NP	0.0	0.0	0.3	NP	0.1	0.1	0.8

Monitoring	30 years				50 years			
Location 26 miles	Layer 2	Layer 4	Layer 5	Layer 7	Layer 2	Layer 4	Layer 5	Layer 7
Run 00	0.1	0.2	0.2	0.3	0.3	0.5	0.8	0.7
Run 01	0.3	0.4	0.5	0.5	0.6	0.8	1.2	1.0
Run 02	0.0	0.1	0.1	0.1	0.0	0.2	0.4	0.4
Run 03	0.1	0.2	0.2	0.3	0.3	0.5	0.8	0.7
Run 04	0.1	0.2	0.2	0.3	0.3	0.5	0.8	0.7
Run 05	0.0	0.1	0.2	0.3	0.0	0.4	0.7	0.7
Run 06	0.8	0.3	0.3	0.3	1.6	0.6	0.9	0.7
Run 07	0.1	0.2	0.2	0.3	0.3	0.5	0.8	0.7
Run 08	0.0	0.2	0.2	0.3	0.1	0.5	0.8	0.7
Run 09	0.1	0.1	0.1	0.1	0.4	0.3	0.4	0.4
Run 10	0.1	0.1	0.1	0.1	0.4	0.3	0.4	0.4
Run 11	1.0	0.5	0.6	0.5	1.7	0.9	1.3	0.9
Run 12	1.0	0.4	0.6	0.4	1.7	0.8	1.2	0.9
Run 13	0.0	0.1	0.1	0.2	0.0	0.3	0.4	0.5
Run 14	0.0	0.1	0.1	0.2	0.0	0.3	0.4	0.5
Run 15	0.0	0.2	0.3	0.4	0.1	0.7	1.0	1.0
Run 16	0.0	0.2	0.3	0.4	0.1	0.7	1.0	1.0

Monitoring	30 years				50 years			
Location 30 miles	Layer 2	Layer 4	Layer 5	Layer 7	Layer 2	Layer 4	Layer 5	Layer 7
Run 00	1.0	0.6	0.5	0.4	2.1	1.6	1.3	0.9
Run 01	2.5	1.2	0.9	0.6	3.4	2.3	2.0	1.2
Run 02	0.1	0.2	0.2	0.2	0.4	0.7	0.6	0.5
Run 03	1.0	0.6	0.5	0.3	2.2	1.5	1.3	0.8
Run 04	1.0	0.6	0.5	0.4	2.1	1.6	1.3	0.9
Run 05	0.2	0.4	0.4	0.3	0.7	1.3	1.1	0.9
Run 06	2.5	0.9	0.6	0.4	3.7	1.7	1.4	0.8
Run 07	1.0	0.6	0.5	0.4	2.1	1.6	1.3	0.9
Run 08	1.0	0.6	0.5	0.4	2.1	1.6	1.3	0.9
Run 09	0.7	0.3	0.2	0.2	1.7	0.9	0.7	0.5
Run 10	0.7	0.3	0.2	0.2	1.7	0.9	0.7	0.4
Run 11	4.1	1.4	1.1	0.6	4.8	2.3	1.9	1.1
Run 12	4.3	1.3	1.0	0.6	5.1	2.2	1.8	1.1
Run 13	0.0	0.3	0.2	0.2	0.1	0.8	0.7	0.6
Run 14	0.0	0.3	0.2	0.2	0.1	0.8	0.7	0.6
Run 15	0.9	0.8	0.6	0.5	1.8	1.9	1.7	1.2
Run 16	1.0	0.8	0.6	0.5	1.9	1.9	1.7	1.2

Monitoring	30 years				50 years			
Location 34 miles	Layer 2	Layer 4	Layer 5	Layer 7	Layer 2	Layer 4	Layer 5	Layer 7
Run 00	2.5	1.0	0.9	0.4	4.6	2.3	2.0	0.9
Run 01	5.4	1.8	1.5	0.6	7.0	3.2	2.9	1.3
Run 02	0.3	0.4	0.3	0.2	1.2	1.1	1.0	0.5
Run 03	2.6	1.0	0.8	0.4	4.8	2.2	2.0	0.9
Run 04	2.5	1.0	0.9	0.4	4.6	2.3	2.0	1.0
Run 05	0.6	0.7	0.7	0.4	1.9	1.9	1.8	1.0
Run 06	4.6	1.3	1.1	0.4	6.3	2.4	2.1	0.9
Run 07	2.5	1.0	0.9	0.4	4.6	2.3	2.0	0.9
Run 08	2.5	1.0	0.9	0.4	4.6	2.2	2.0	0.9
Run 09	1.6	0.5	0.5	0.2	3.2	1.3	1.2	0.5
Run 10	1.6	0.5	0.4	0.2	3.2	1.2	1.1	0.5
Run 11	6.8	2.0	1.7	0.7	7.9	3.1	2.8	1.2
Run 12	7.1	1.9	1.6	0.6	8.2	3.0	2.7	1.2
Run 13	0.1	0.4	0.4	0.3	0.3	1.1	1.1	0.7
Run 14	0.1	0.4	0.4	0.3	0.3	1.1	1.1	0.7
Run 15	2.5	1.3	1.1	0.6	4.3	2.8	2.6	1.3
Run 16	2.6	1.3	1.1	0.6	4.4	2.8	2.5	1.3

Monitoring	30 years				50 years			
Location 38 miles	Layer 2	Layer 4	Layer 5	Layer 7	Layer 2	Layer 4	Layer 5	Layer 7
Run 00	3.8	1.8	1.5	0.5	6.3	3.5	3.1	1.0
Run 01	7.2	3.0	2.5	0.7	9.1	4.9	4.2	1.4
Run 02	0.7	0.8	0.6	0.2	2.1	1.8	1.6	0.6
Run 03	3.9	1.8	1.5	0.4	6.5	3.5	3.0	1.0
Run 04	3.8	1.8	1.5	0.5	6.3	3.6	3.1	1.0
Run 05	1.3	1.4	1.2	0.4	3.2	3.1	2.8	1.1
Run 06	5.9	2.1	1.7	0.5	7.9	3.5	3.0	1.0
Run 07	3.8	1.8	1.5	0.5	6.3	3.5	3.1	1.0
Run 08	3.8	1.8	1.5	0.5	6.3	3.5	3.1	1.0
Run 09	2.3	1.0	0.8	0.2	4.2	2.1	1.8	0.6
Run 10	2.4	0.9	0.8	0.2	4.3	2.0	1.7	0.5
Run 11	8.4	3.2	2.6	0.7	9.6	4.5	3.9	1.3
Run 12	8.7	3.0	2.5	0.7	9.9	4.3	3.7	1.2
Run 13	0.2	0.8	0.7	0.3	0.8	1.9	1.7	0.7
Run 14	0.2	0.8	0.7	0.3	0.7	1.9	1.7	0.7
Run 15	3.8	2.3	1.9	0.6	6.0	4.4	3.8	1.4
Run 16	4.0	2.3	1.9	0.6	6.2	4.4	3.8	1.4

Note: NP = Not Present; 0.0 represents a drawdown that is less than 0.1 foot

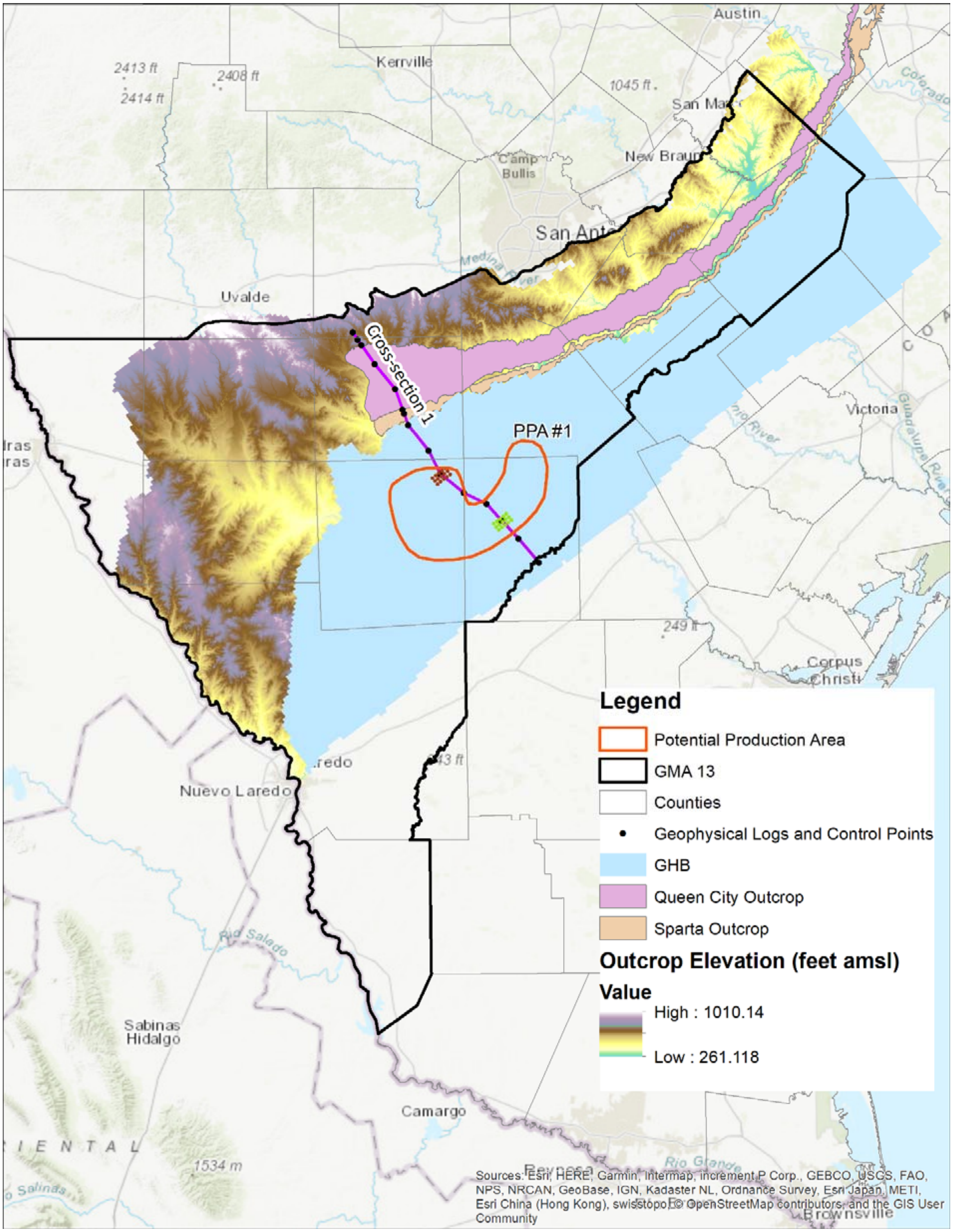


Figure 6-42. Location of cross section through two well fields that were used for developing groundwater models for the potential production areas (PPA). PPA #1 is associated with cross section #1. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.

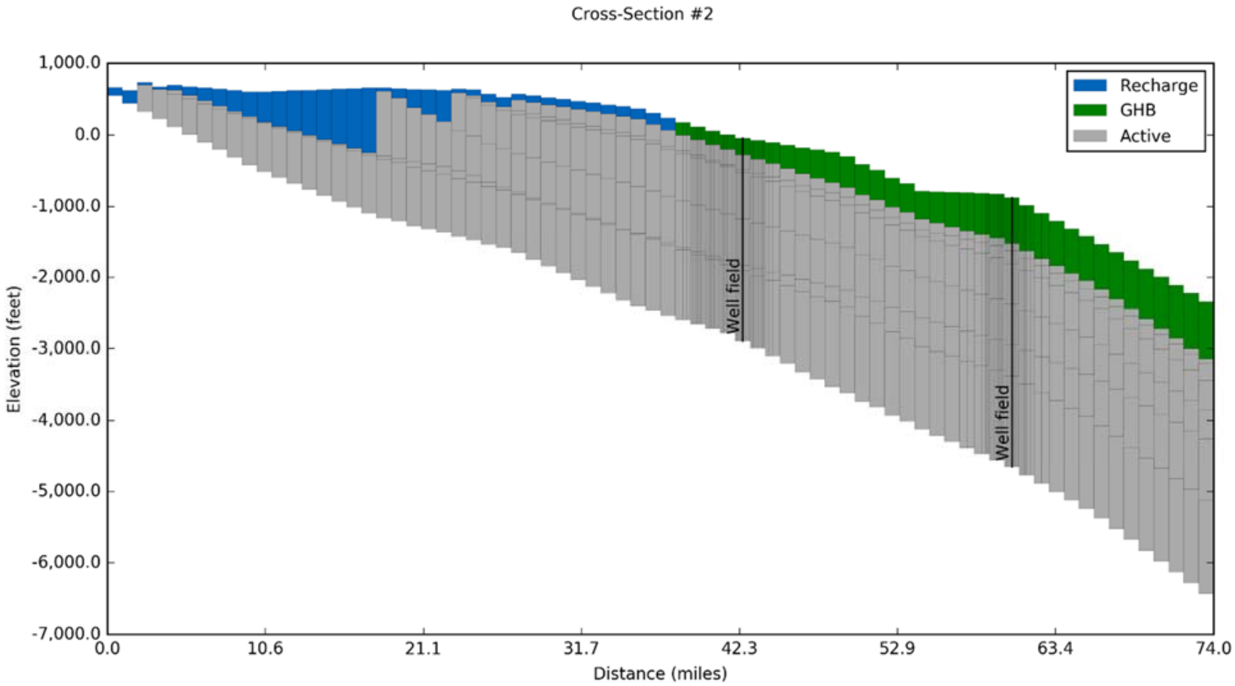


Figure 6-43. Vertical cross section that shows the nine model layers and the hydraulic boundary conditions used in the groundwater model and the position of two well fields and along the cross section that intersects PPA #1. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.

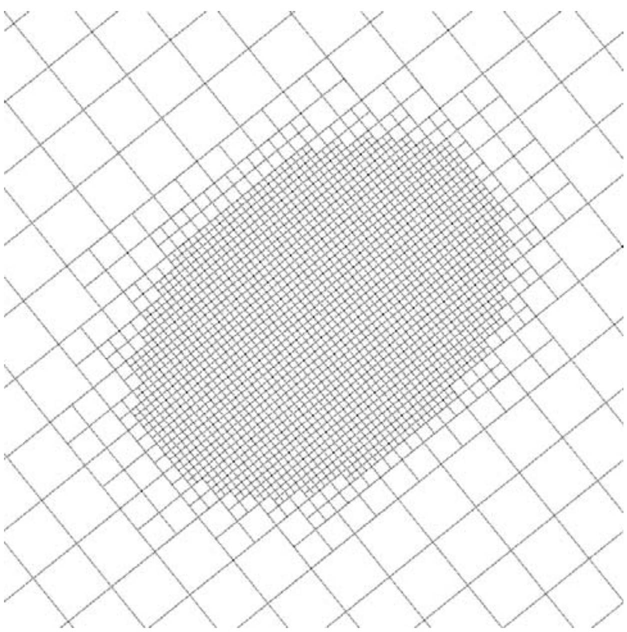


Figure 6-44. Aerial view of the groundwater model for PPA #1 showing the type of grid refinement that occurs in the vicinity of the well fields and faults to reduce from 1-mile by 1-mile grid cells to 1/8-mile by 1/8-mile grid cells. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.

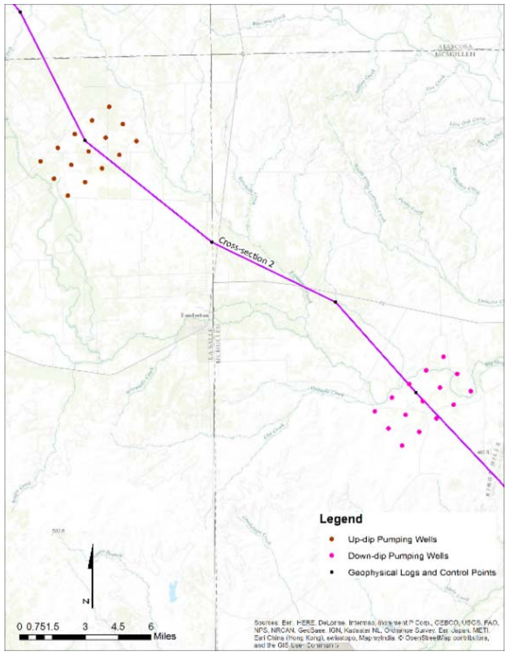


Figure 6-45. **Location the two well fields along cross section #2. Both well fields are illustrated using the 15 well network used to pump 10,000 AFY in the Sparta Aquifer and 20,000 AFY in the Queen City Aquifer.**

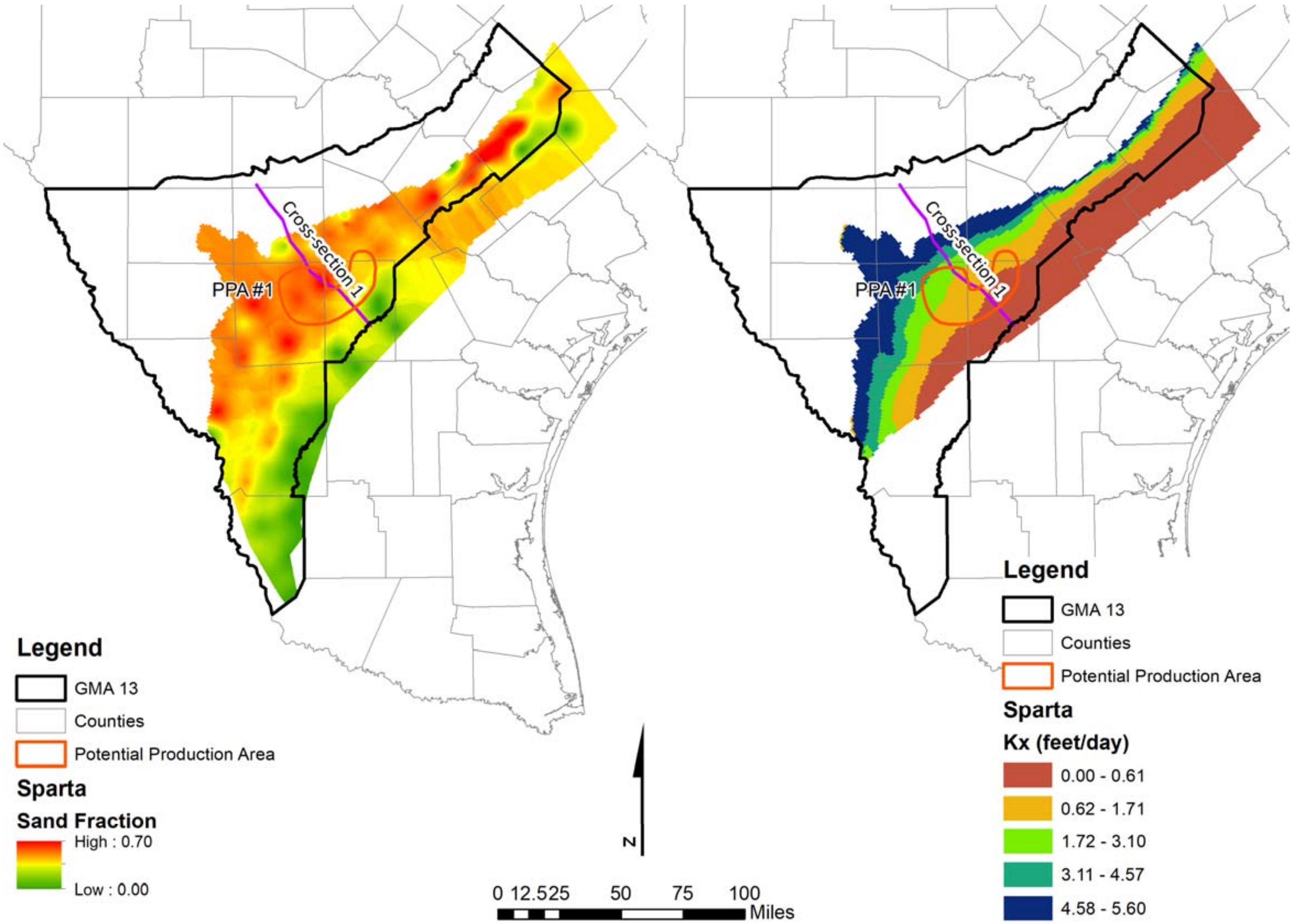


Figure 6-46. Sand fraction map based on the interpolation geophysical logs (a) and horizontal hydraulic conductivity values from the Southern QCSP GAM (Kelly and others, 2004) (b) for the Sparta Aquifer. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.

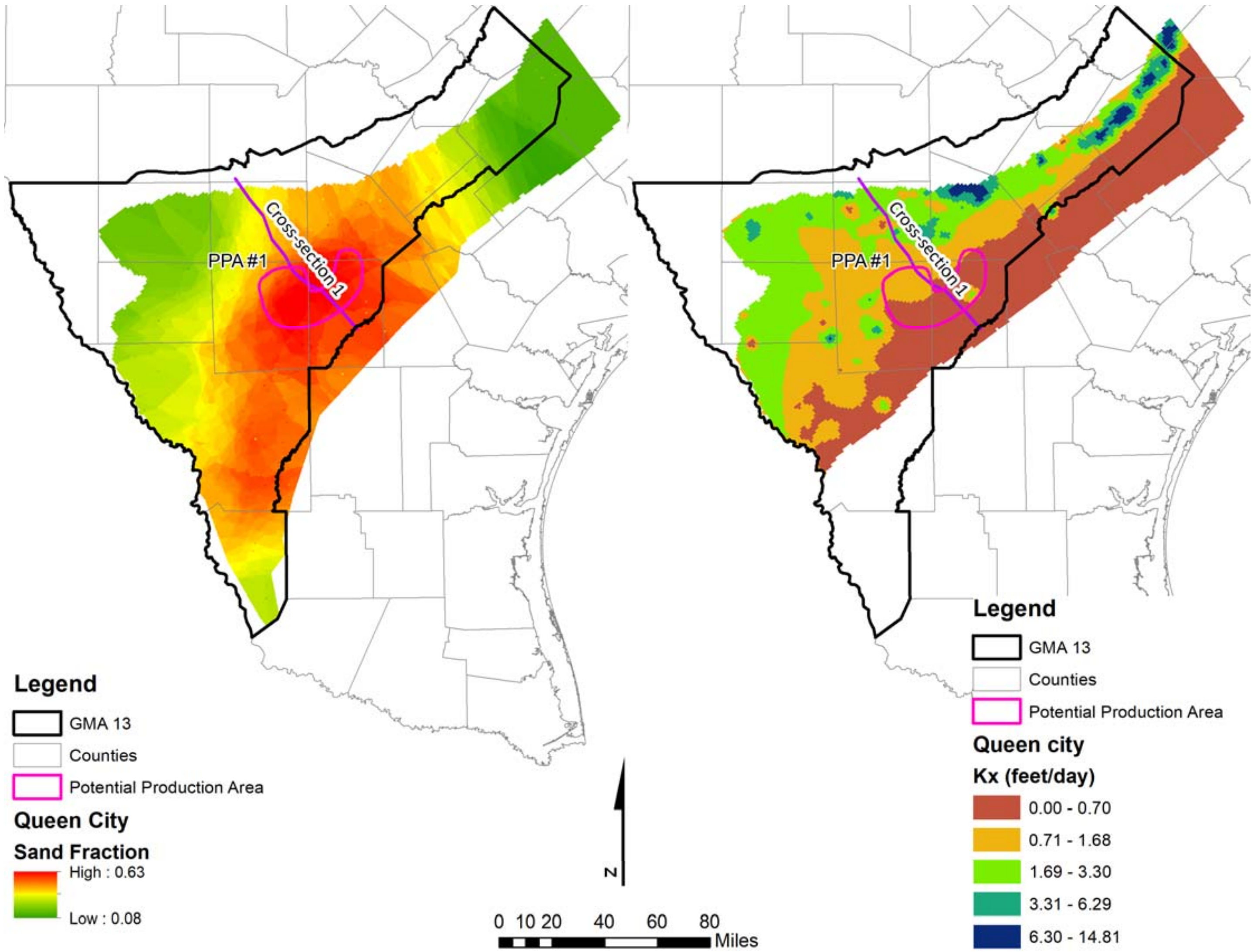


Figure 6-47. Sand fraction map based on the interpolation of geophysical logs (a) and horizontal hydraulic conductivity values from the Southern QCSP GAM (Kelly and others, 2004) (b) for the Queen City Aquifer. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.

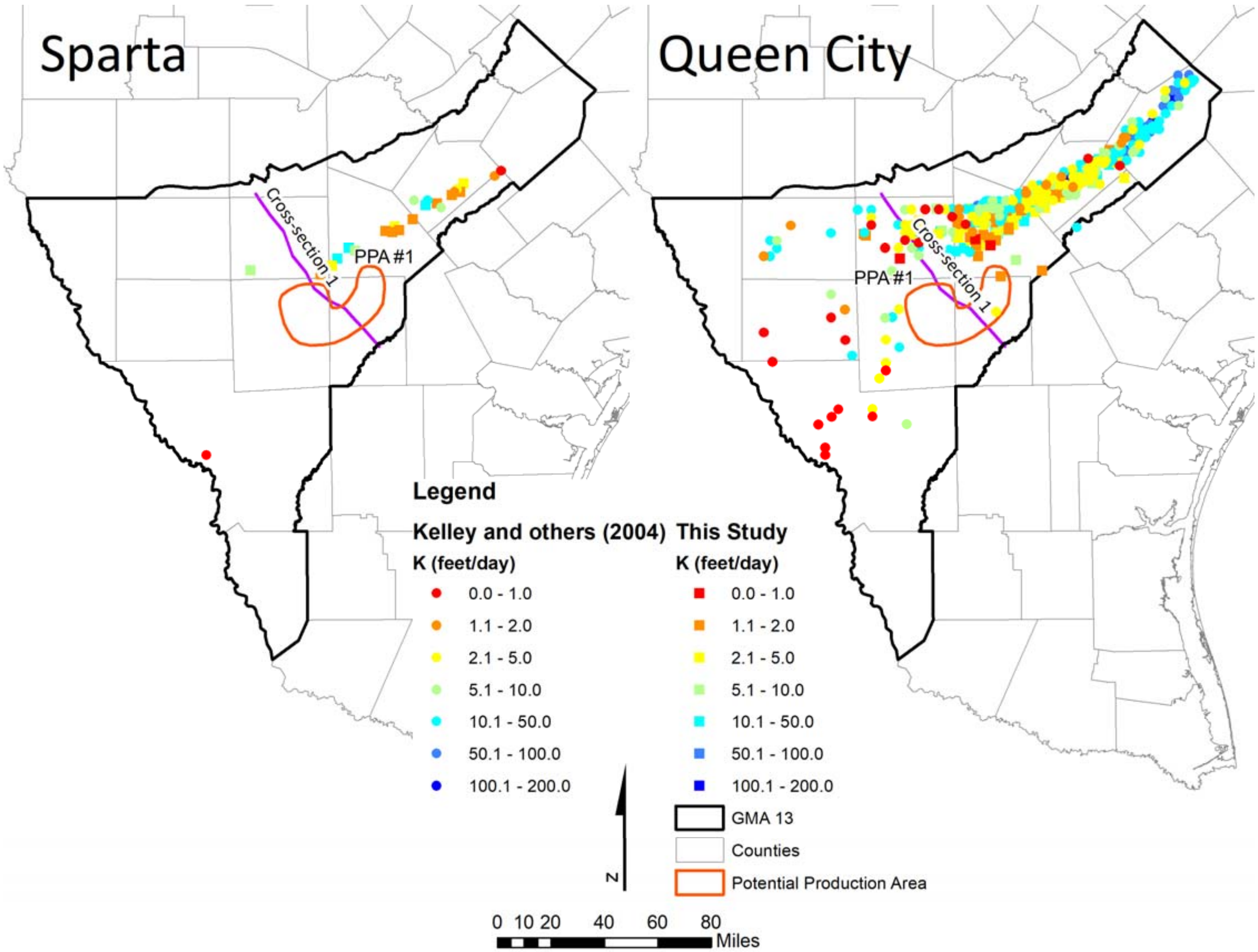
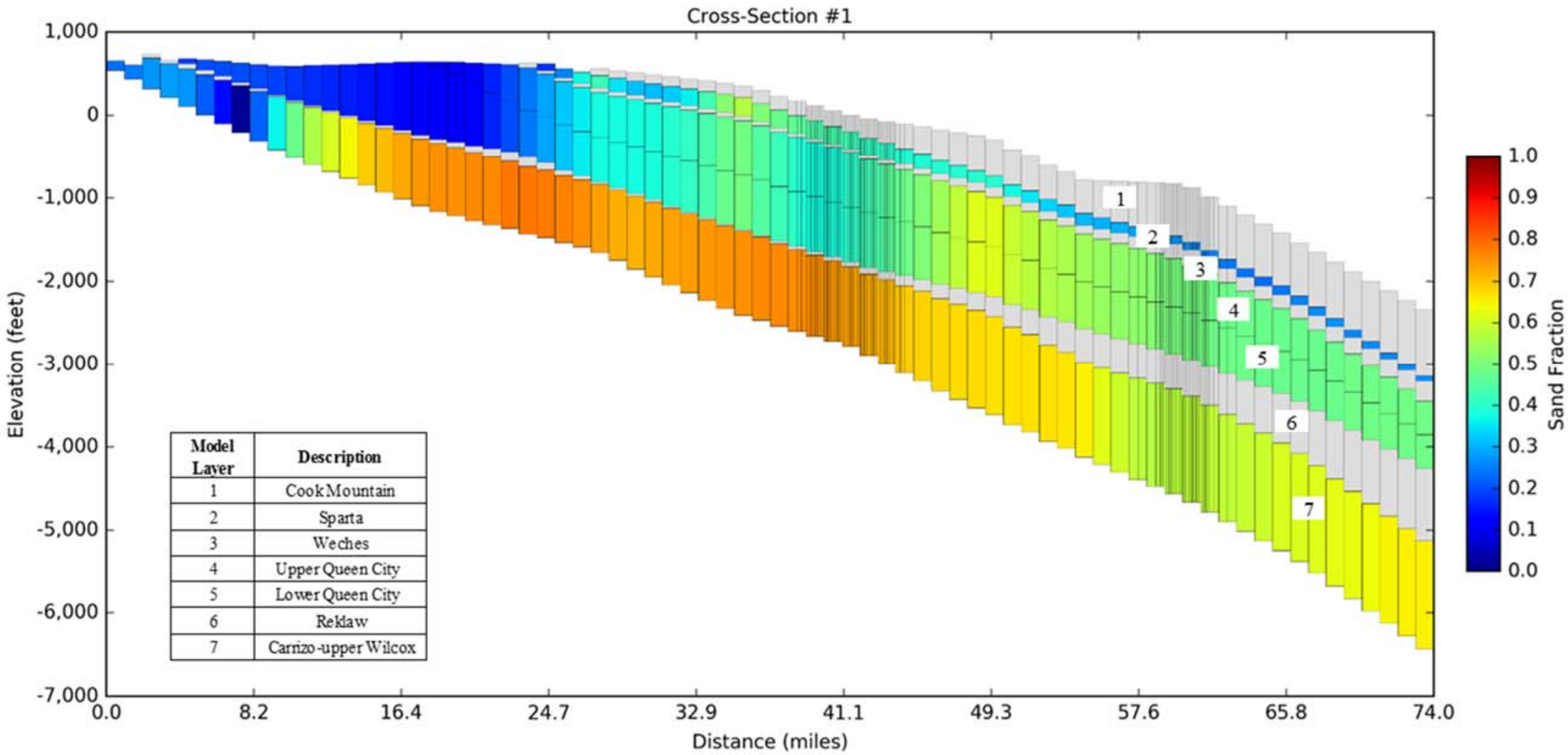


Figure 6-48. Locations in the Sparta and Queen City aquifers where hydraulic conductivity values have been calculated from specific capacity values that were used to help develop relationships of horizontal hydraulic conductivity as a function of sand fraction shown in Figures 6-46 and 6-47. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.



Model Layer	Description
1	Cook Mountain
2	Sparta
3	Weches
4	Upper Queen City
5	Lower Queen City
6	Reklaw
7	Carrizo-upper Wilcox

Figure 6-49. Sand fraction for model layers 2, 4, 5, and 7 for a vertical cross section cut through the three-dimensional model for PPA #1. Model layers 1, 3, and 4 are greyed and represent formations that are characterized as consisting of predominantly clayey deposits. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. The PPA contains fresh groundwater in the Queen City Aquifer, and is also not separated by hydrogeologic barriers sufficient to prevent significant impacts to freshwater resource availability or quality in the Queen City-Sparta or adjacent aquifers.

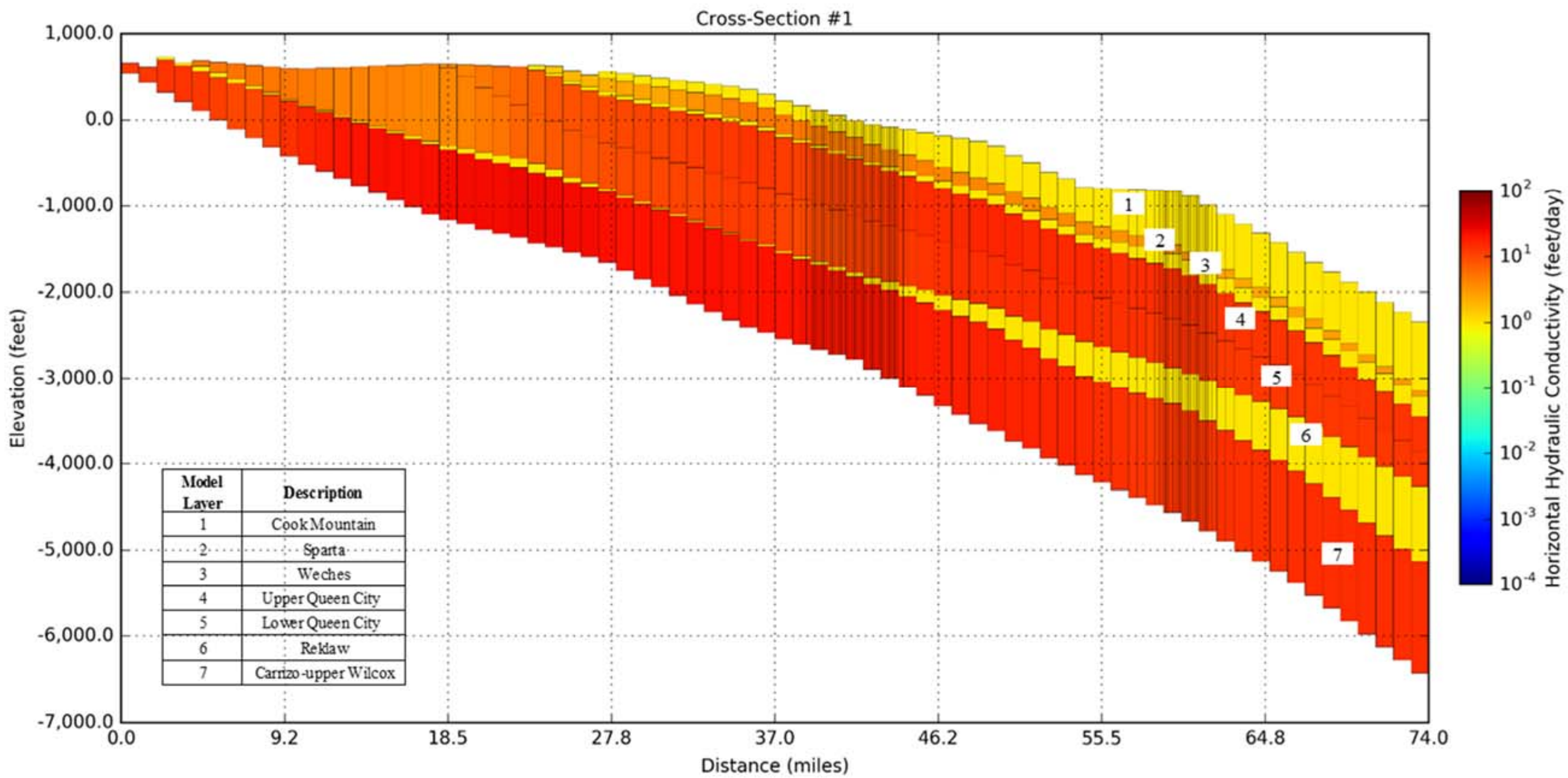


Figure 6-50. Horizontal hydraulic conductivity values in the groundwater model for PPA #1 with properties that are GHSM-based for model layers 2, 4, and 7. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. The PPA contains fresh groundwater in the Queen City Aquifer, and is also not separated by hydrogeologic barriers sufficient to prevent significant impacts to freshwater resource availability or quality in the Queen City-Sparta or adjacent aquifers.

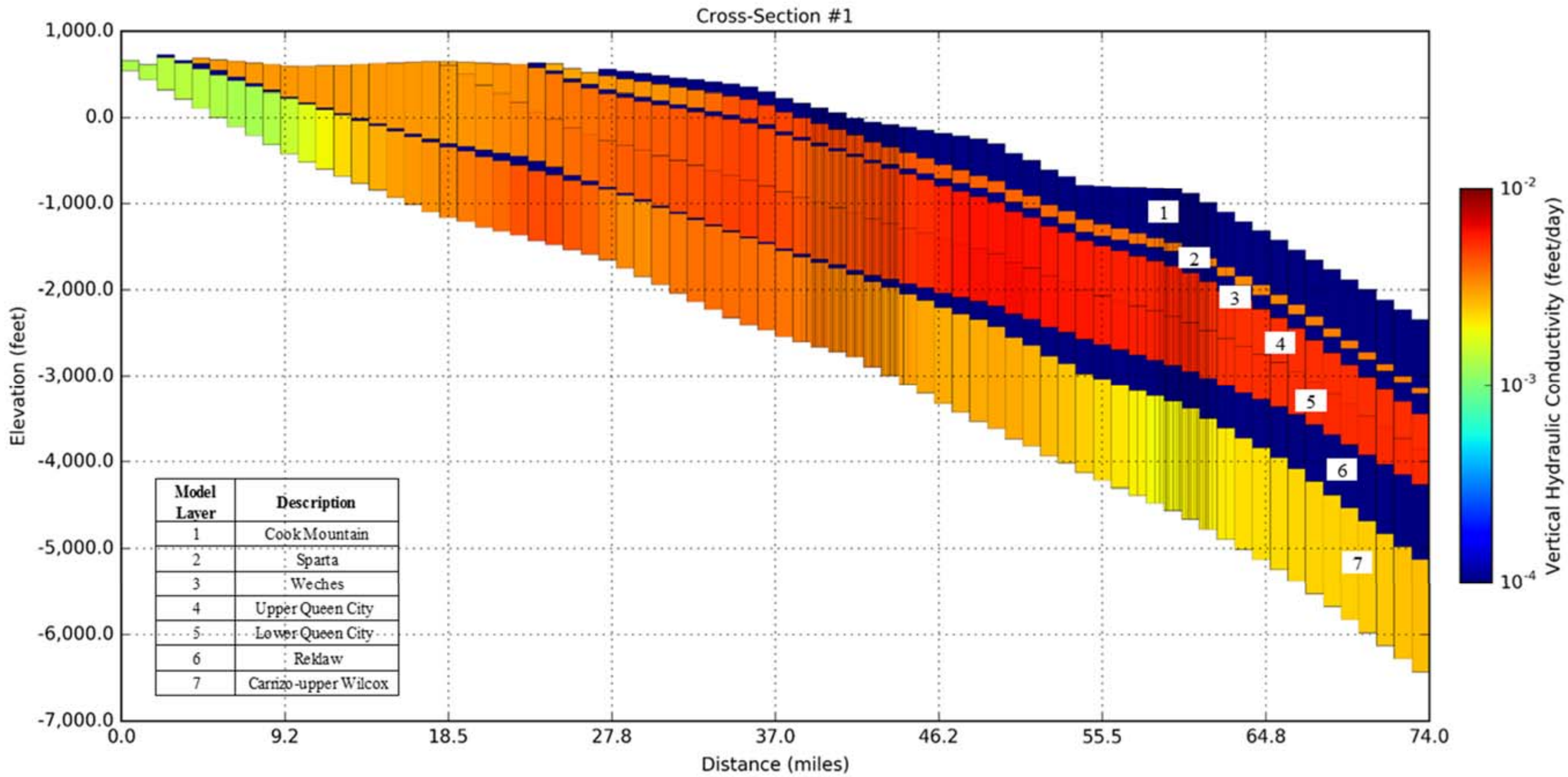


Figure 6-51. **Vertical hydraulic conductivity values in the groundwater model for PPA #1 with properties that are GHSM-based for model layers 2, 4, and 7. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. The PPA contains fresh groundwater in the Queen City Aquifer, and is also not separated by hydrogeologic barriers sufficient to prevent significant impacts to freshwater resource availability or quality in the Queen City-Sparta or adjacent aquifers.**

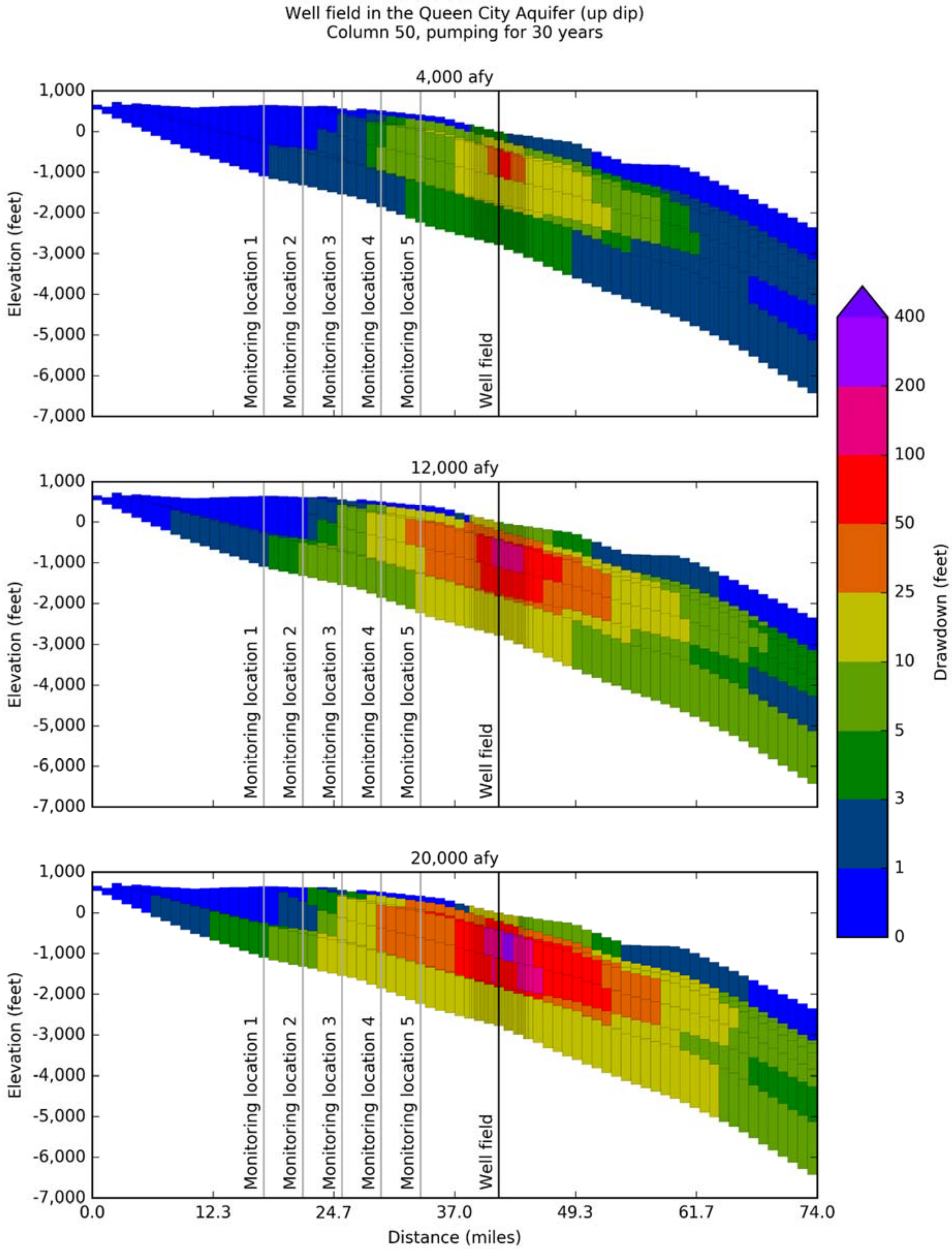


Figure 6-52. **Simulated drawdown at 30 years after pumping the Queen City Aquifer at Well Field #1 in PPA #1 at 4,000, 12,000, and 20,000 AFY. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.**

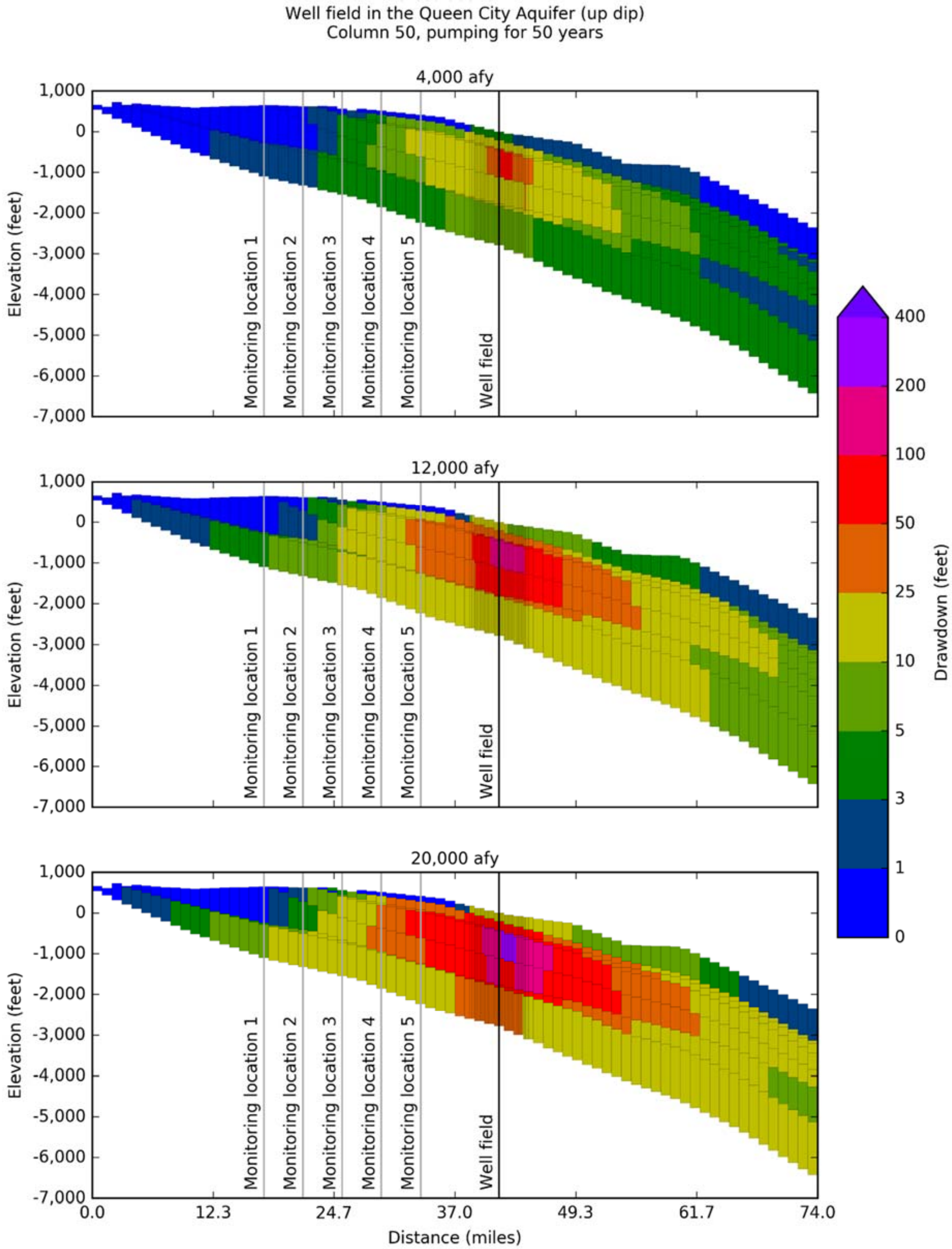


Figure 6-53. **Simulated drawdown at 50 years after pumping the Queen City Aquifer at Well Field #1 in PPA #1 at 4,000, 12,000, and 20,000 AFY. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.**

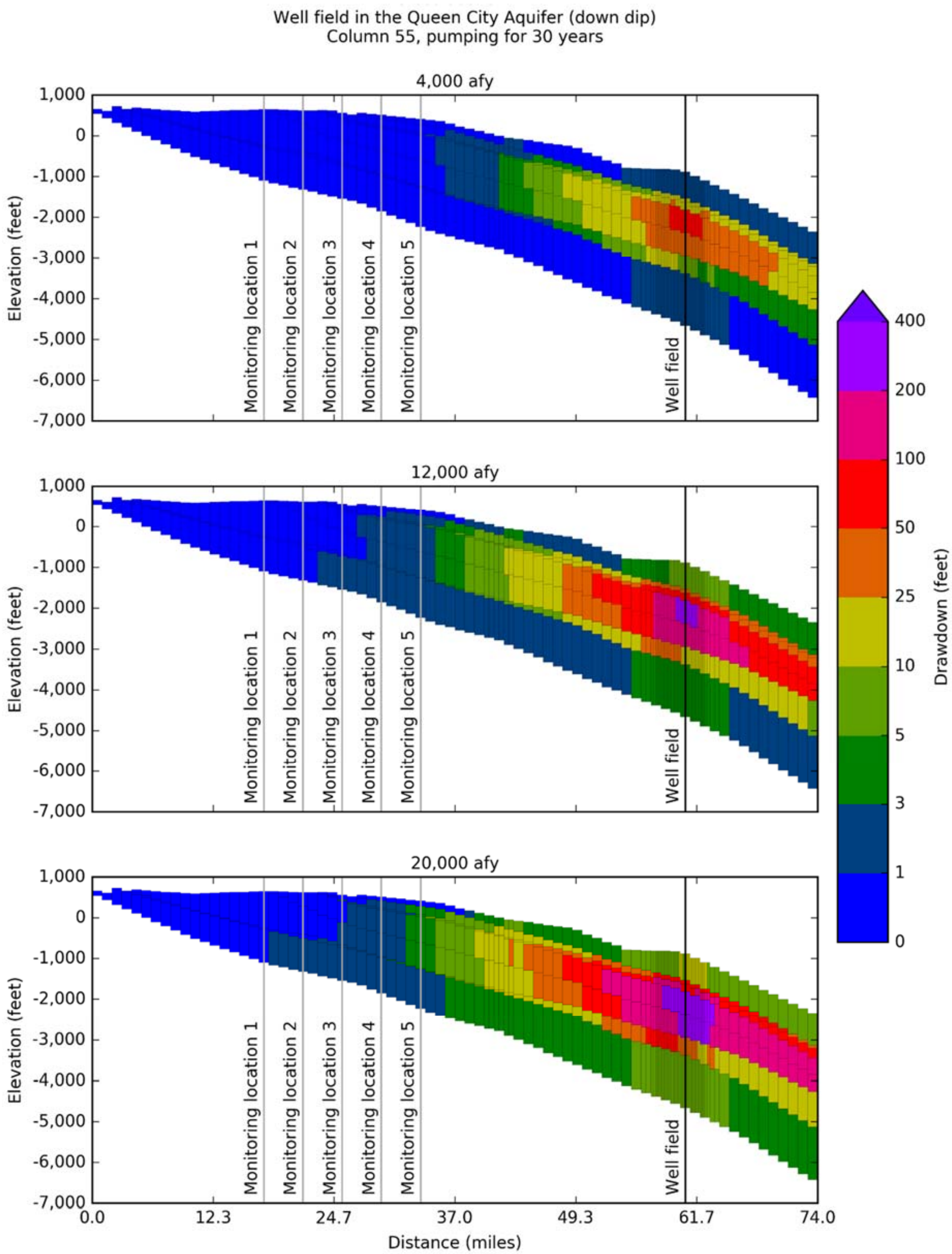


Figure 6-54. **Simulated drawdown at 30 years after pumping the Queen City Aquifer at Well Field #2 in PPA #1at 4,000, 12,000, and 20,000 AFY. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.**

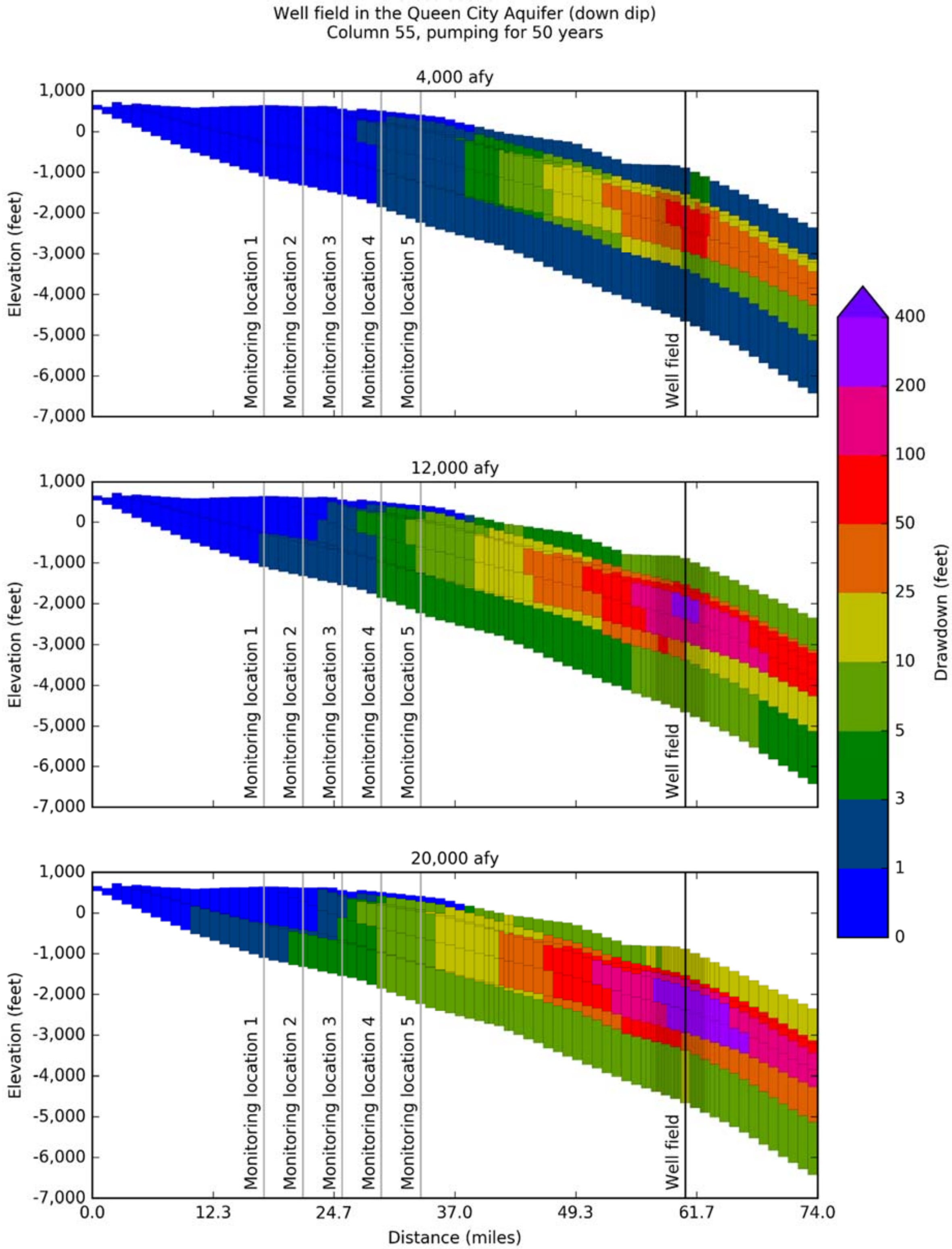


Figure 6-55. Simulated drawdown at 50 years after pumping the Queen City Aquifer at Well Field #2 in PPA #1at 4,000, 12,000, and 20,000 AFY. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.

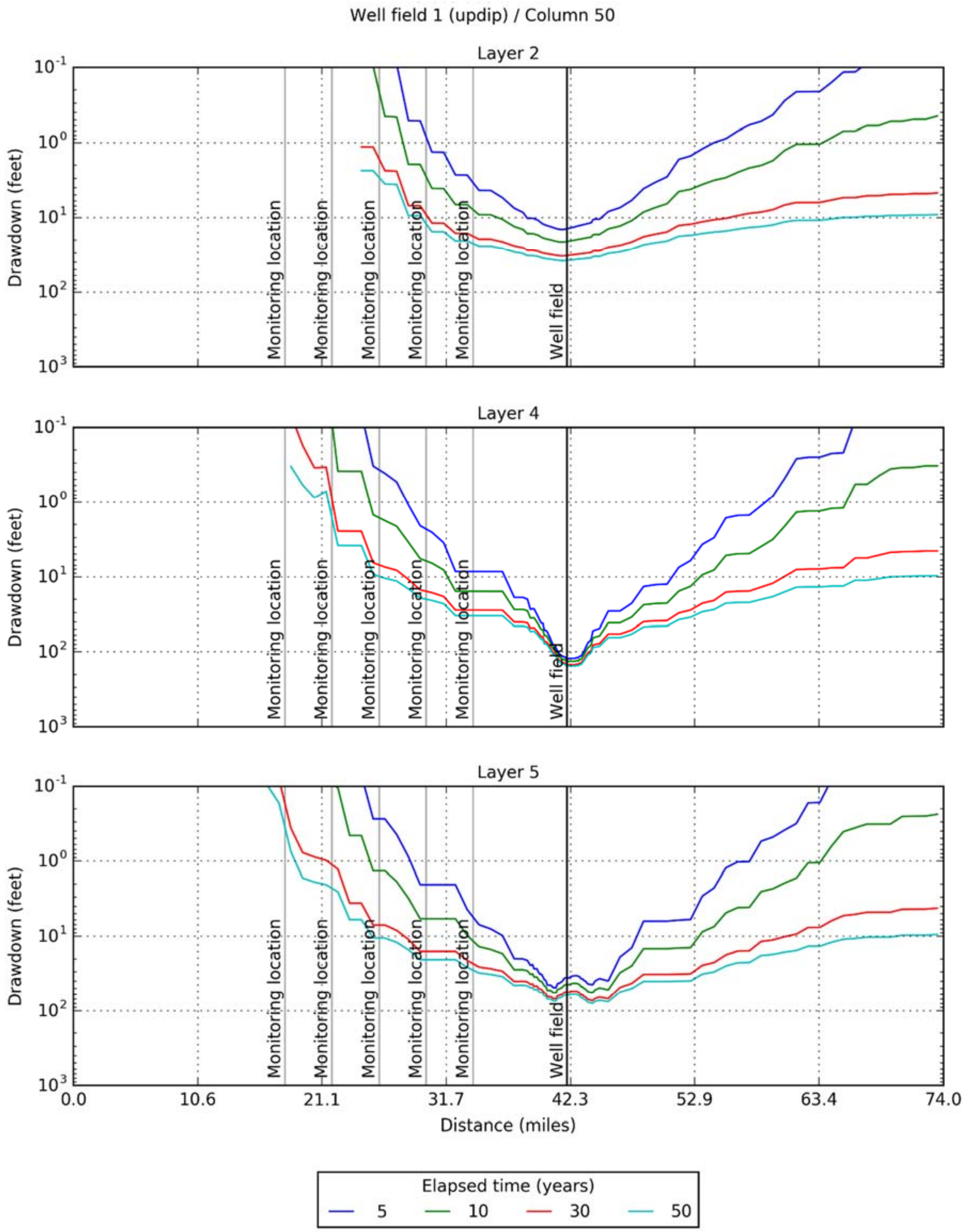


Figure 6-56. Simulated drawdown at 5, 10, 30, and 50 years for model layers 2, 4, and 5 caused by pumping the Queen City Aquifer at Well Field #1 located in PPA #1at 12,000 AFY. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. The PPA contains fresh groundwater in the Queen City Aquifer, and is also not separated by hydrogeologic barriers sufficient to prevent significant impacts to freshwater resource availability or quality in the Queen City-Sparta or adjacent aquifers.

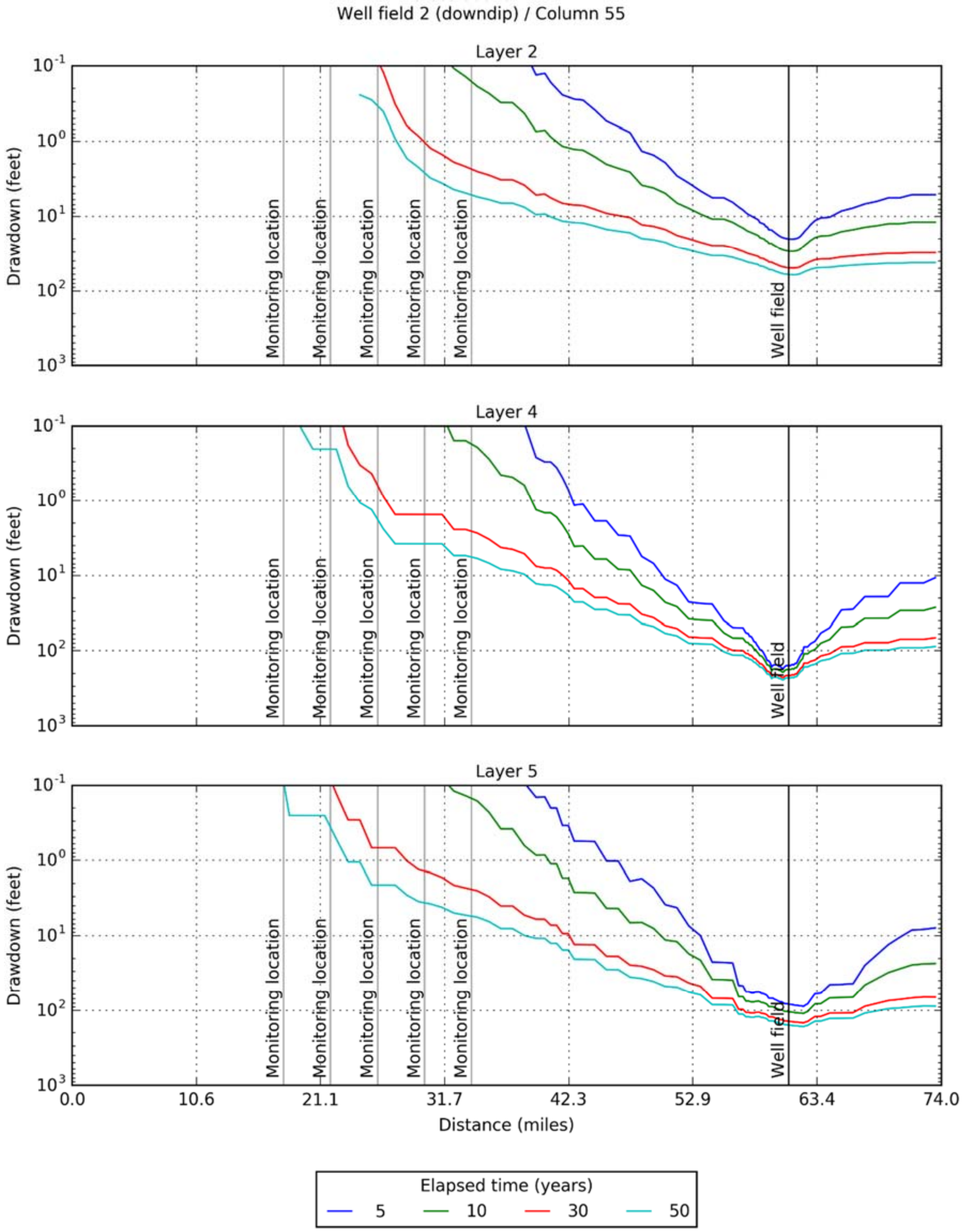


Figure 6-57. **Simulated drawdown at 5, 10, 30, and 50 years for model layers 2, 4, and 5 caused by pumping the Queen City Aquifer at Well Field #2 located in PPA #1at 12,000 AFY. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. The PPA contains fresh groundwater in the Queen City Aquifer, and is also not separated by hydrogeologic barriers sufficient to prevent significant impacts to freshwater resource availability or quality in the Queen City-Sparta or adjacent aquifers.**

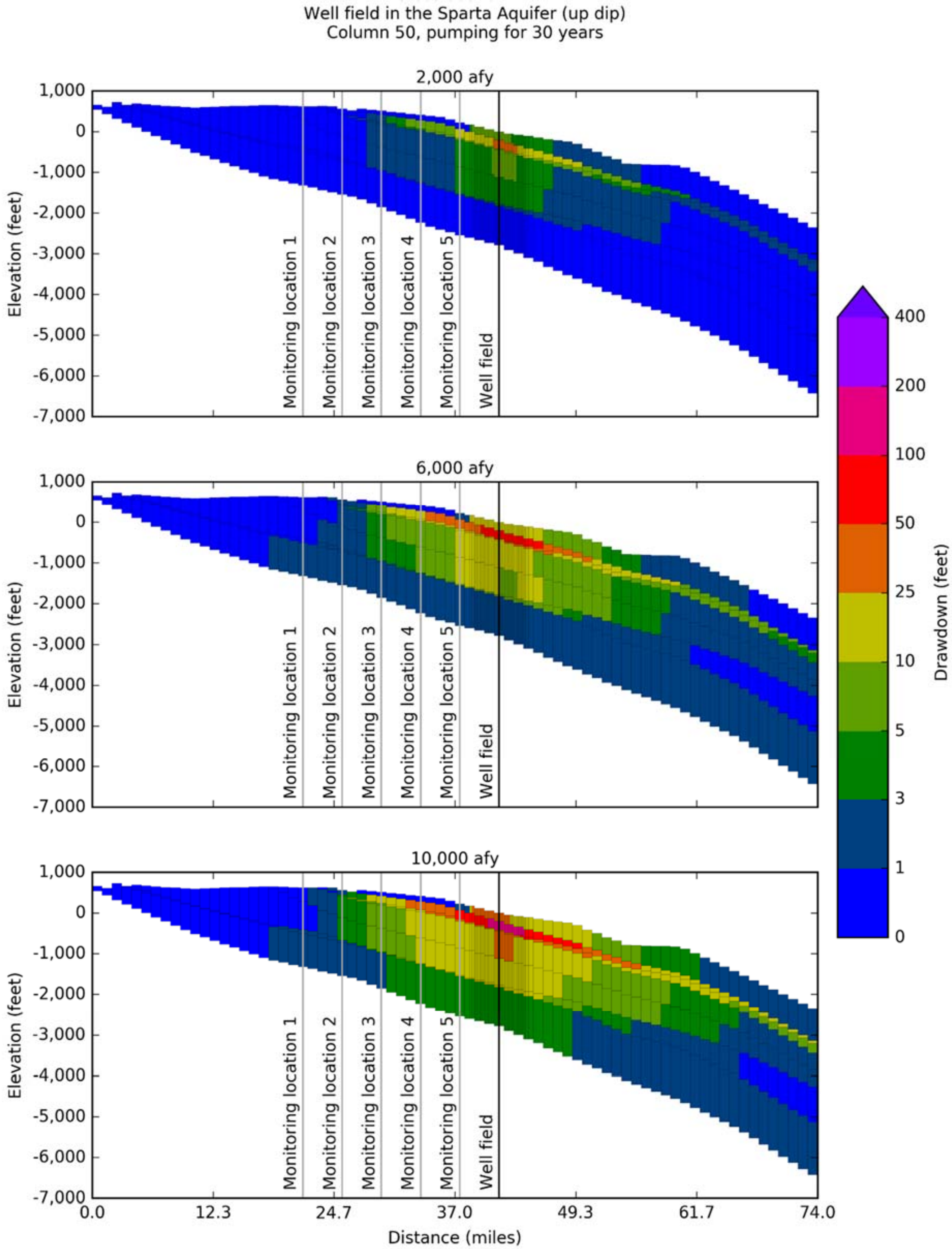


Figure 6-58. **Simulated drawdown at 30 years after pumping the Sparta Aquifer at Well Field #1 in PPA #1 at 2,000, 6,000, and 10,000 AFY. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.**

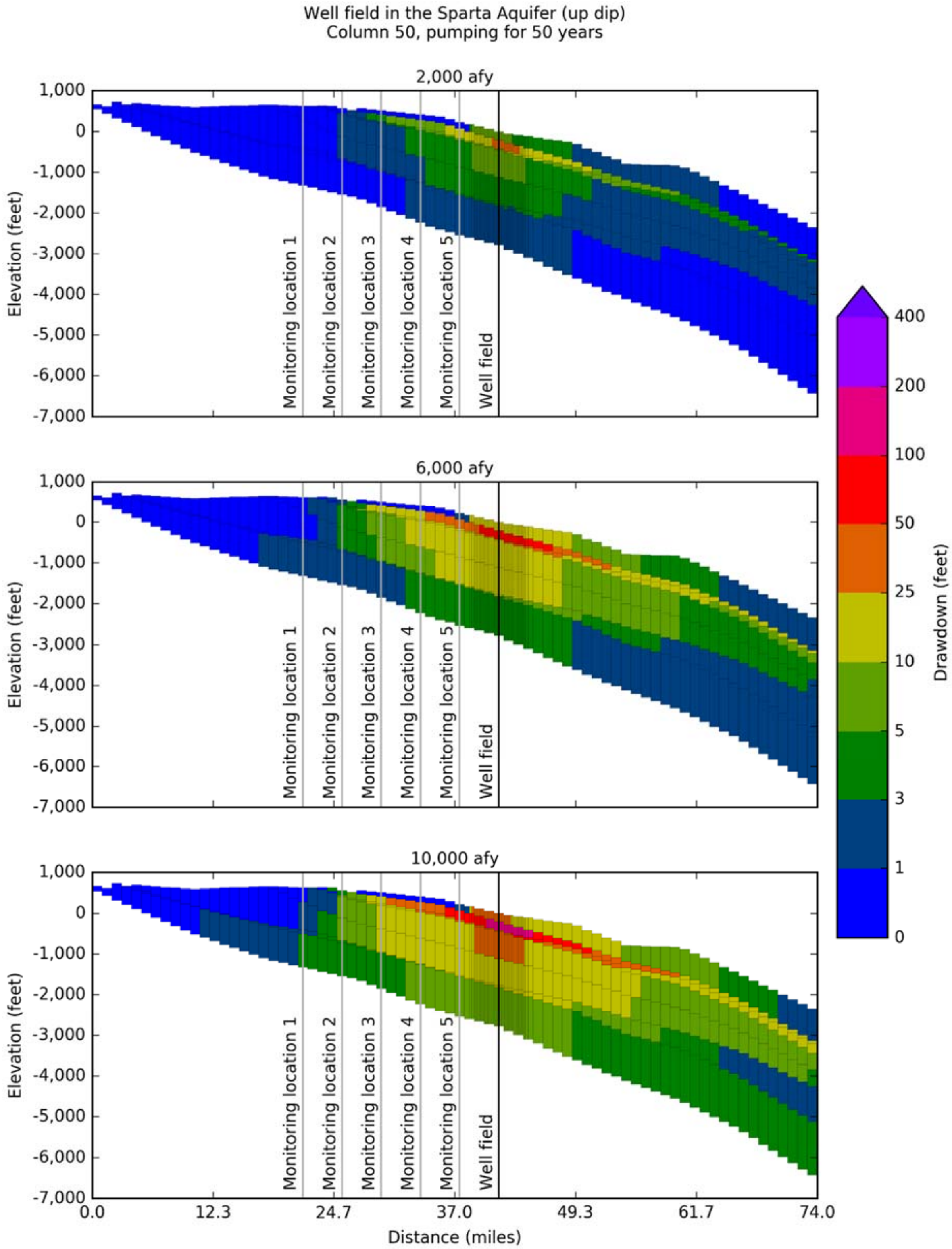


Figure 6-59. **Simulated drawdown at 50 years after pumping the Sparta Aquifer at Well Field #1 in PPA #1 at 2,000, 6,000, and 10,000 AFY. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.**

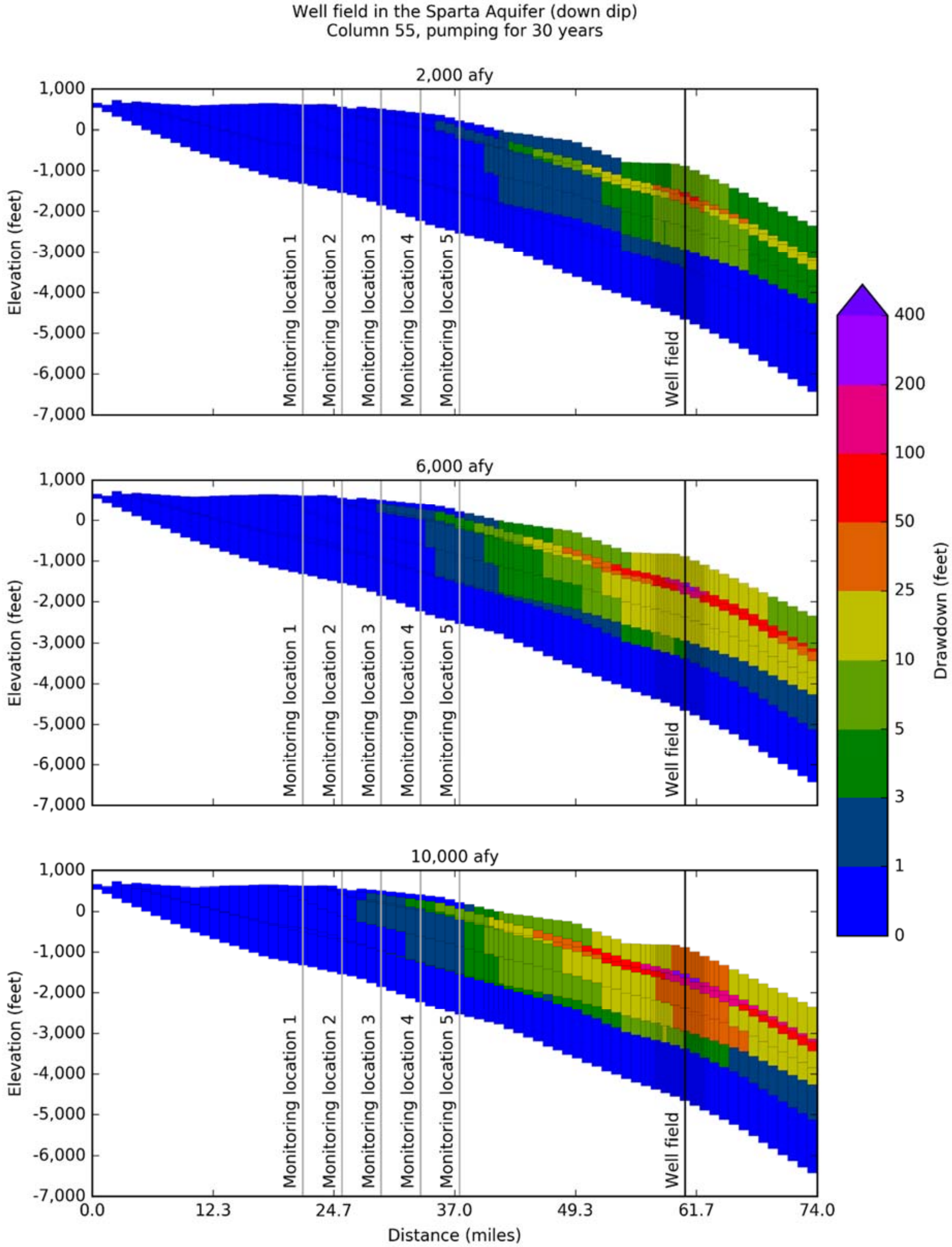


Figure 6-60. **Simulated drawdown at 30 years after pumping the Sparta Aquifer at Well Field #2 in PPA #1 at 2,000, 6,000, and 10,000 AFY. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.**

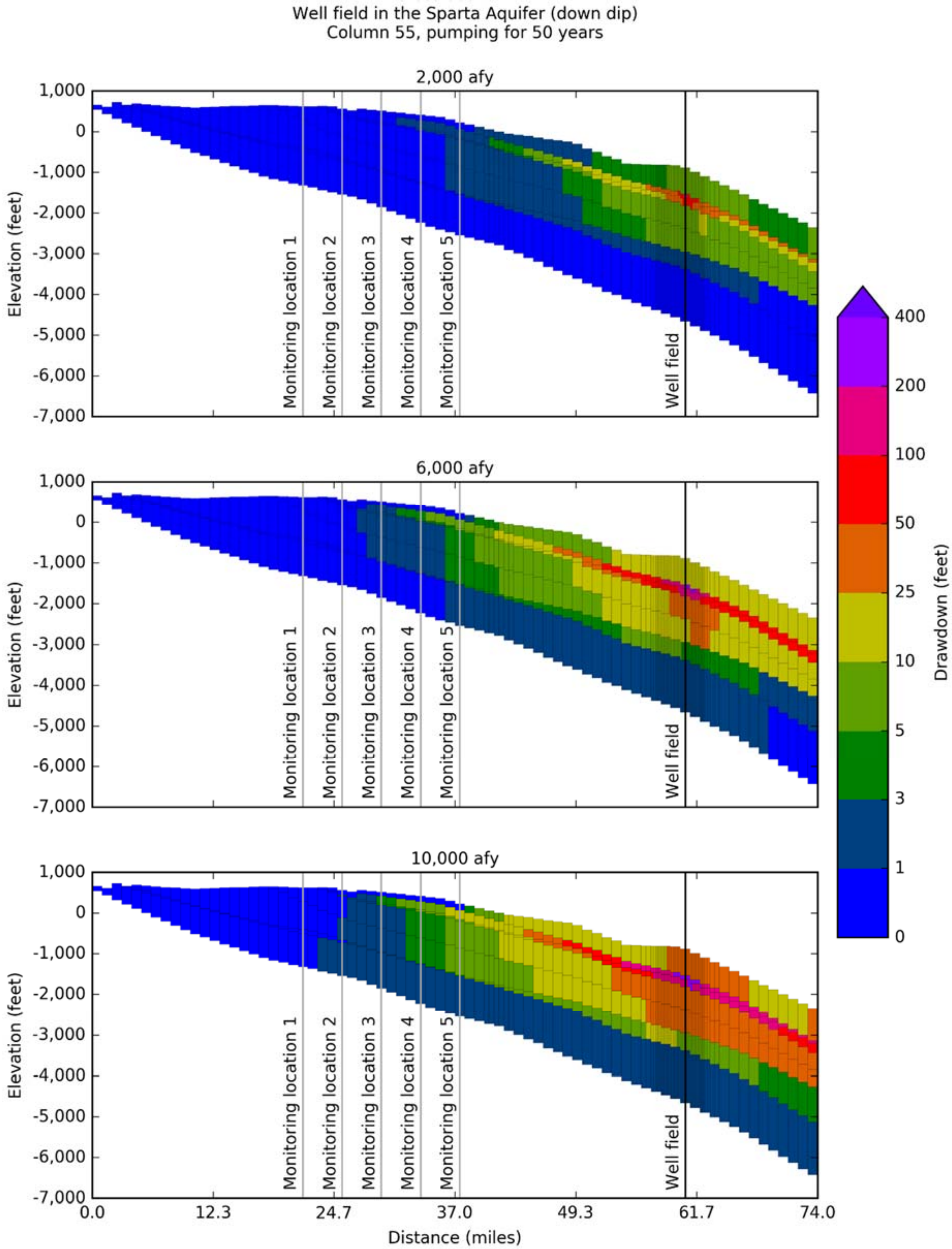


Figure 6-61. **Simulated drawdown at 50 years after pumping the Sparta Aquifer at Well Field #2 in PPA #1 at 2,000, 6,000, and 10,000 AFY. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30.**

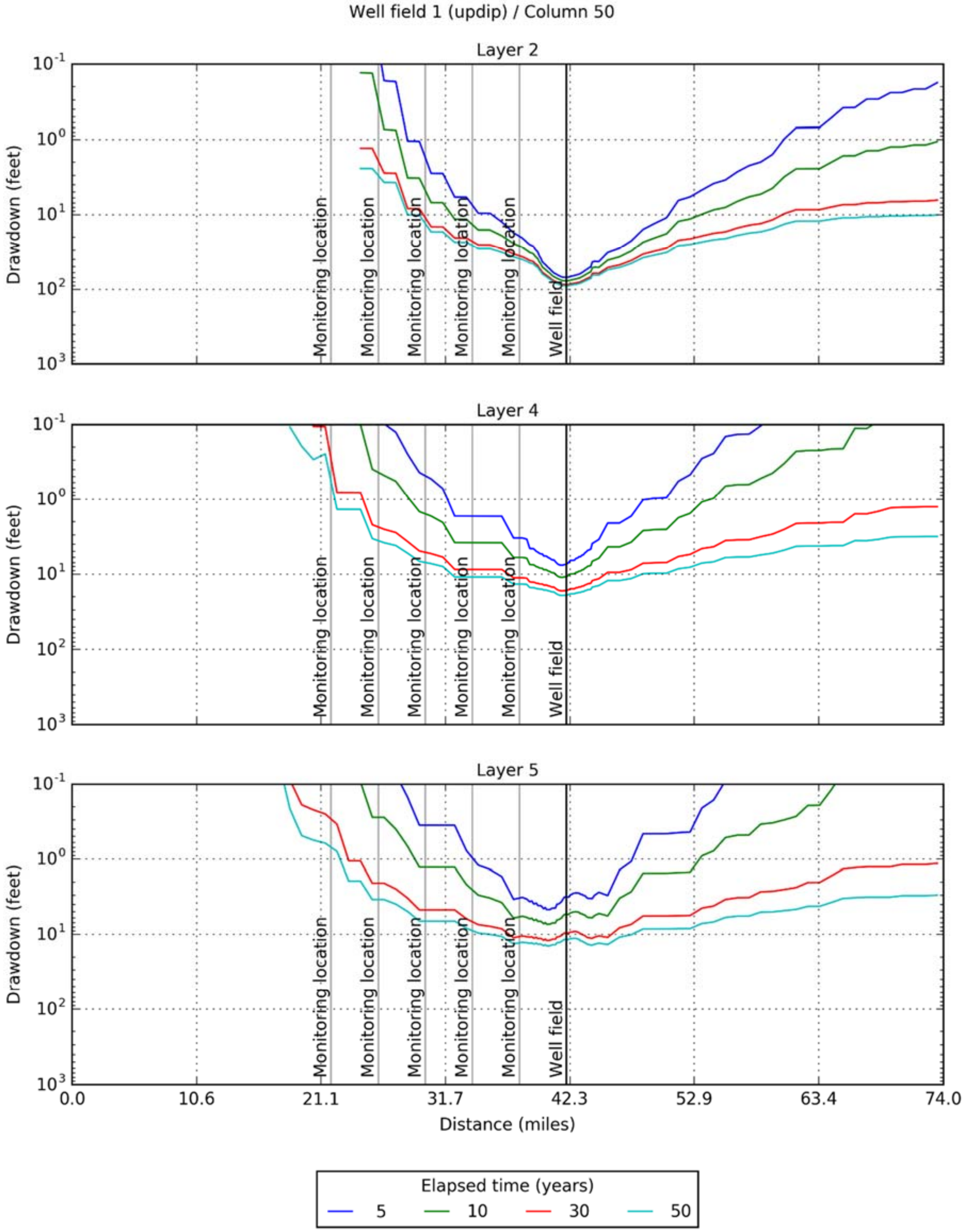


Figure 6-62. **Simulated drawdown at 5, 10, 30, and 50 years for model layers 2, 4, and 5 caused by pumping the Sparta Aquifer at Well Field #1 located in PPA #1at 6,000 AFY. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. The PPA contains fresh groundwater in the Queen City Aquifer, and is also not separated by hydrogeologic barriers sufficient to prevent significant impacts to freshwater resource availability or quality in the Queen City-Sparta or adjacent aquifers.**

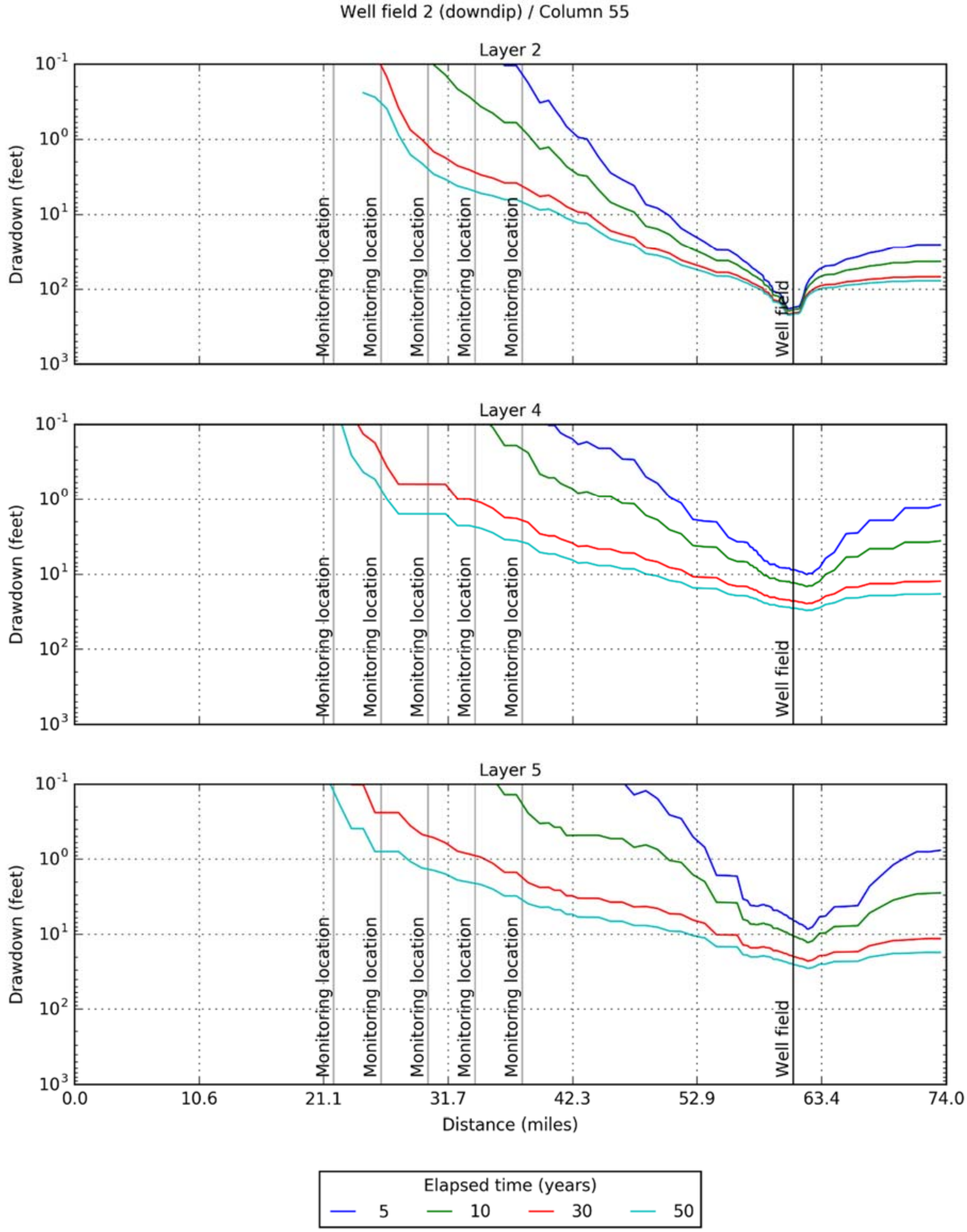


Figure 6-63. **Simulated drawdown at 5, 10, 30, and 50 years for model layers 2, 4, and 5 caused by pumping the Sparta Aquifer at Well Field #1 located in PPA #1at 6,000 AFY. Although this PPA was evaluated, geoscientific analyses indicated that it did not meet all required criteria of a PPA per House Bill 30. The PPA contains fresh groundwater in the Queen City Aquifer, and is also not separated by hydrogeologic barriers sufficient to prevent significant impacts to freshwater resource availability or quality in the Queen City-Sparta or adjacent aquifers.**

7 GIS-based Tools to Calculate Groundwater Volumes and Visualize Water Quality Data

In this section, we present several GIS-based tools that are designed to help facilitate the analysis and visualization of geophysical log information. For each tool, a general description of the tool's capability is provided along with a summary of the tool's input and output files. These tools calculate groundwater volumes and visualize water quality data along cross-sections.

7.1 GIS-based Tool to Calculate Volumes of Fresh, Brackish, and Saline Groundwater

In order to produce the groundwater volume estimates for aquifer units by water quality type and sand distribution (Tables 5-3 through 5-7), we created a tool in ArcGIS that facilitates the groundwater volume calculation process. This tool is named "Volume Calculator" and is provided in the Electronic Deliverable as part of the "GMA 13 Tools" ArcGIS toolbox. Further documentation for this tool, including installation instructions and step-by-step instructions, is included in Section 8.

Notable features of the Volume Calculator Tool are that it:

- Is compatible with ESRI ArcGIS 10.2 and 10.3;
- Incorporates aquifer properties and model layers (i.e., formation or aquifer) surfaces from the Southern Queen City/Sparta GAM (Southern QCSP GAM) by reading shape files created by Groundwater Vistas (Rumbaugh and Rumbaugh, 2010);
- Is consistent with the procedure and algorithms that the TWDB used to calculate TERS for GMA 13 (Wade and Bradley, 2013);
- Provides options to calculate a drainage volume using different assumptions and approaches besides the specific yield, S_y;
- Provides options to partition groundwater volume into fresh, slightly saline, moderately saline and saline water quality categories; and
- Provides the option to export the spatial data for sand thicknesses, porosities, and groundwater volumes (by water quality category) to files that can be read and visualized by Groundwater Vistas.

The Volume Calculator tool was used to calculate the volumes of fresh, slightly saline, moderately saline, and very saline in Tables 5-3, 5-4, 5-5, and 5-6. These tables partition the groundwater by water quality category, by aquifer, by county, and by groundwater conservation areas. The tool provides the ability to calculate groundwater volumes associated with the unconfined and confined portions of the aquifer based on Equations 5-1a, 5-1b, 5-1c, 5-2, 5-3, 5-4a, and 5-4b that are described in Section 5.1.

Figure 7-1 is a schematic of the information flow through the Volume Calculator Tool. The sections below provide a general description of the input and output files identified in Figure 7-1 Further documentation is provided in Section 8.

7.1.1 Data Input Files

The input files used with the Volume Calculator Tool to calculate the groundwater volumes presented in Section 5 are included as part of the Electronic Deliverable. The user can edit these input files, if necessary, as new data become available.

The input files include a shapefile of the model grid for the Groundwater Availability Model for the Queen City and Sparta Aquifers (Kelley and others, 2004) and a table of land surface elevations for the model grid cells. These two input files provide information about the aquifer structure, the water level, and the hydraulic properties of the aquifers, all of which is necessary for performing the volume calculation.

The Volume Calculator tool calculates groundwater volumes by first partitioning the data into model layers and then using two-dimensional interpolation methods to calculate volumes associated with grid cells in each model. Groundwater data that lies outside of the domain of the model grid will be ignored by the Volume Calculator Tool because the tool does not have the information necessary to assign the data to a specific model layer. Therefore, the areal extent over which the Volume Calculator calculates volumes is limited to the extent of the model grid provided by user. If it is necessary to calculate volumes outside of the Southern QCSP GAM model grid, then the user would need to update this input file with an expanded model grid that covers the desired extent. Similarly, if TWDB develops a new GAM for these aquifers, the user would need to update these input files. Calculating volumes by user-specified zones would also require updating the model grid input file since, by default, it only includes state-specified zones such as counties and groundwater conservation districts.

The input files also include two tables that contain the results of the geophysical log analyses. One table contains the geophysical log locations and the second contains all the water quality and sand picks made on the geophysical logs. These two input files provide information about the water quality and sand percentage that is required to create the subdivisions of groundwater volume by water quality type and sand distribution in each aquifer unit. If additional geophysical log analyses are conducted, the user would need to update these input files.

The tool supports the option of using water quality information from water wells. This option is useful to help fill data gaps in the water quality data coverage provided by the geophysical logs. In our application, this option was used to provide water quality data in the up-dip regions of the aquifers where geophysical well coverage was sparse. For our application, the input file for entering the water well data is a shapefile containing water quality (average TDS) information from the TWDB groundwater well database as well as two tables that contain information about wells from the TWDB Submitted Driller Reports. One table contains the submitted driller log locations and the second contains all the sand picks made using the lithological logs provided in those well reports. These input files provide information about the water quality and sand percentage in the outcrop areas where the geophysical logs do not provide adequate spatial coverage. The pairs of TWDB water quality wells and SDR logs used for this study are shown in **Figure 5-4**. If additional Submitted Drillers Reports are desired, the user would need to update these input files.

The tool also supports the option of contouring water quality data in the presence of a fault. To use this option, the user needs a shapefile that contain polylines that define the fault locations and the water quality on both sides of the fault. This input file allows the user to map discontinuities in water quality where fault lines have impacted groundwater flow.

7.1.2 Output Files

The Volume Calculator Tool generates tables containing groundwater volumes by county and by groundwater conservation district. The user has the option to use either porosity or specific yield for calculating the groundwater volume. If the model uses specific yield, then the output files represent total volume calculated using drainable unconfined storage. The groundwater volumes in **Tables 5-3** (top), **5-4**, and **5-6** were generated by using the option for specific yield. If the model uses porosity, then the output files represent total volume calculated using in-place unconfined storage. These output files were used to create **Tables 5-3** (bottom), **5-5**, and **5-7**.

The Volume Calculator Tool also generates the following output files:

- Rasters of sand fraction by water quality type and by aquifer unit. These files are input files for the visualization tools and can be used to generate maps in ArcGIS, as described in Section 7.2. **Figure 7-2** shows maps of groundwater volumes in sands for freshwater, slightly saline, moderately saline, and very saline in the Queen City Aquifer that were generated using these rasters.
- Raster of the sand fraction by water quality type and by aquifer unit. **Figure 7-3** shows maps of the sand fraction for the portion of the Queen City Aquifer that contains freshwater, slightly saline, moderately saline, and very saline groundwater that were generated using these rasters.
- A point shapefile for the water quality and sand picks from the geophysical log analyses. This file is an input file for the visualization tools, as described in Section 7.2, and has limited utility for visualizing the data inputs. This shapefile can be filtered by water quality type, as displayed in Figure 7-2.
- A polygon and point shapefile of the model grid for the QCSP GAM (Kelley and others, 2004) with additional fields to represent the sand fraction by water quality type values for each cell. This shapefile can be filtered by aquifer unit and water quality type, as displayed in Figure 7-2.
- A point shapefile of the additional SDR wells used to fill in data gaps in the outcrop, as shown in **Figure 5-4**.

The Volume Calculator Tool also generates binary files of porosity, sand percent, and groundwater volumes by groundwater quality type that can be loaded into Groundwater Vistas (Rumbaugh and Rumbaugh, 2010). Section 8 describes how to import these files into Groundwater Vistas. The binary format follows the MODFLOW HEAD SAVE single precision specification. Figure 7-4 shows two example Figures generated by Groundwater Vistas. Figure 7-4a shows a map of sand fraction for the Queen City, and Figure 7-4b shows a map of the volume of moderately saline Queen City.

Figure 7-5 illustrates the capability of the tool to map a discontinuity in groundwater quality caused by a fault. The water quality map on the left shows the fault location but the fault shape file does not contain any data regarding the water quality on the up dip and down dip areas of the fault. As a result, there is no change in water quality across the fault. The water quality map on the right was product with the fault shape file containing data regarding the water quality on the up dip and down dip areas of the fault. As a result, there is a significant change in water quality that occurs across the fault.

7.2 GIS-based Tools to Visualize Groundwater Quality

In order to help visualize the data and output files generated by the Volume Calculator Tool, we created several GIS-based visualization tools. The names and functions of these three tools are:

1) Plot XS Profile Tool- Visualization of Well Logs Along Cross-Sections in GMA 13
2) Plot 2D Sand Fractions by Layer Tool - Visualization of Sand Fractions by Aquifer Layer
3) Brackish Estimator Tool - Estimation and Visualization of Brackish Sands by Depth

These tools are provided in the Electronic Deliverable as part of the “GMA 13 Tools” ArcGIS toolbox.

7.2.1 Plot XS Profile Tool - Visualization of Well Logs Along Cross-Sections

The Plot XS Profile Tool creates a Figure that shows vertical profiles of geophysical logs along a cross-section created from a user-designated transect. For each geophysical log, the sand intervals are color-coded based on water quality type. If the cross-section lies within the domain of the model grid used in the Volume Calculator Tool, then the Figure will display the locations and water quality picks for geophysical well logs in relation to model layers.

Figure 7-6 is a schematic of the information flow through the Plot XS Profile Tool. The sections below provide a general description of the input and output files identified in Figure 7-6. Further documentation and instructions are provided in **Section 8**.

Data Input Files

Before the tool can be used, the Volume Calculator Tool needs to be run in order to generate several required input files. The necessary input files generated by the Volume Calculator Tool include rasters of sand percentages by water quality type and by aquifer unit and a shapefile that contains the sand intervals associated with each geophysical log. The input files used with the Plot XS Profile Tool to generate the Figures in this report are included as part of the Electronic Deliverable. The user can edit these input files, if necessary, by re-running the Volume Calculator Tool.

The Plot XS Profile Tool provides the user with the option of creating a cross-section or using an existing cross-section for showing the geophysical log information. As part of the Electronic Deliverable, we include several cross-section shapefiles that can be selected by the user. The tool also supports the option of displaying all geophysical logs within a maximum search distance of the cross-section (as set by an input variable) or of only displaying logs that are manually selecting along a cross-section.

Output Files

The Plot XS Profile Tool produces images of the cross-section with geophysical logs posted at their proper distance along the cross-section. The images are created as portable network graphics and labeled with a “png” extension. A “png” image is a raster graphic that supports lossless data compression. The user can decide whether or not to display or hide sand percent information. If the “Include sand fraction” option is toggled on (default option), the tool generates a Figure similar to **Figure 7-7a.** If the “Include sand fraction” option is toggled off, the tool generates a Figure similar to **Figure 7-6b.** For every cross-section Figure generated, the tool also produces a second png image that provides a color-coded key to the aquifer surfaces displayed in the cross-section figure. This second Figure is similar to **Figure 7-8.**

7.2.2 Plot 2D Sand Fractions by Layer Tool - Visualization of Sand Fractions by Aquifer Layer

The Plot 2D Sand Fractions by Layer Tool produces publication-ready Figures displaying the sand fraction rasters by water quality type for each of the six aquifers of interest (Sparta, Queen City, Carrizo, Upper Wilcox, Middle Wilcox, Lower Wilcox). **Figure 7-9** is a schematic of the information flow through the Plot 2D Sand Fractions by Layer Tool. The sections below provide a general description of the input and output files identified in Figure 7-9. Further documentation and instructions are provided in Section 8.

Data Input Files

Before the tool can be used, the Volume Calculator Tool needs to be run in order to generate several required input files. The necessary input files generated by the Volume Calculator Tool include rasters of sand percentages by water quality type and by aquifer unit. For this application, these rasters were cropped by the active extent of each aquifer unit. The input files used with the Plot 2D Sand Fractions by Layer Tool to generate the Figures in this report are included as part of the Electronic Deliverable. The user can edit these input files, if necessary, by re-running the Volume Calculator Tool. Note that the user would need to crop the new rasters before using them as input files for the Plot 2D Sand Fractions by Layer Tool.

Output Files

The Plot 2D Sand Fractions by Layer Tool produces images of maps that display the rasters of sand percentages by water quality type and by aquifer unit over the area of interest. The images are created as portable network graphics and labeled with a “png” extension. For each run, the tool automatically generates 4 maps, or one for each water quality type (fresh, slightly saline, moderately saline, and very saline). Figures displaying the Carrizo-Wilcox aquifer units (Carrizo, upper Wilcox, middle Wilcox, and lower Wilcox) are generated separately from Figures displaying the Queen City and Sparta aquifer units. **Figure 7-10** shows a sample map that the tool generated for the freshwater sand fraction of Carrizo-Wilcox aquifer units and **Figure 7-11** shows a sample map generated for the Queen City and Sparta aquifer units.

7.2.3 Brackish Estimator Tool - Estimation and Visualization of Brackish Sands by Depth

The Brackish Estimator Tool interpolates sand fraction rasters by water quality type at user-designated depth intervals based on geophysical well log water quality picks. The tool also produces publication-ready Figures displaying both the rasters and the points used to create the rasters. The user can designate the interpolation method used to create the rasters (Kriging, Spline or Inverse Distance Weighting) as well as define the interpolation parameters. **Figure 7-12** is a schematic of the information flow through the Brackish Estimator Tool. The sections below provide a general description of the input and output files identified in Figure 7-12. Further documentation and instructions are provided in Section 8.

Data Input Files

Before the tool can be used, the Volume Calculator Tool needs to be run in order to generate the required input file. The necessary input file generated by the Volume Calculator Tool is a shapefile that contains the sand intervals associated with each geophysical log. This provides the point water quality percentage values required to perform the interpolation. The input file we used to produce the Figures presented in this report are included as part of the Electronic Deliverable. The user can edit this input file if necessary, by re-running the Volume Calculator tool.

Output Files

The Brackish Estimator Tool generates rasters of sand fraction by water quality type at user-designated depth intervals. It also produces ArcGIS map documents that display these rasters over the area of interest and are saved with an “mxd” extension. Images of these maps are also created as portable network graphics and labeled with a “png” extension. For each run, the tool automatically generates 4 maps, or one for each water quality type (fresh, slightly saline, moderately saline, and very saline). **Figure 7-13** shows an example map generated by the tool that displays very saline sand fraction by depth interval. This map was created using the Kriging interpolation option at the following user-designated depth intervals: 0 to 2,000 ft, 2,000 to 4,000 ft, 4,000 to 6,000 ft and 6,000 to 15,000 ft.

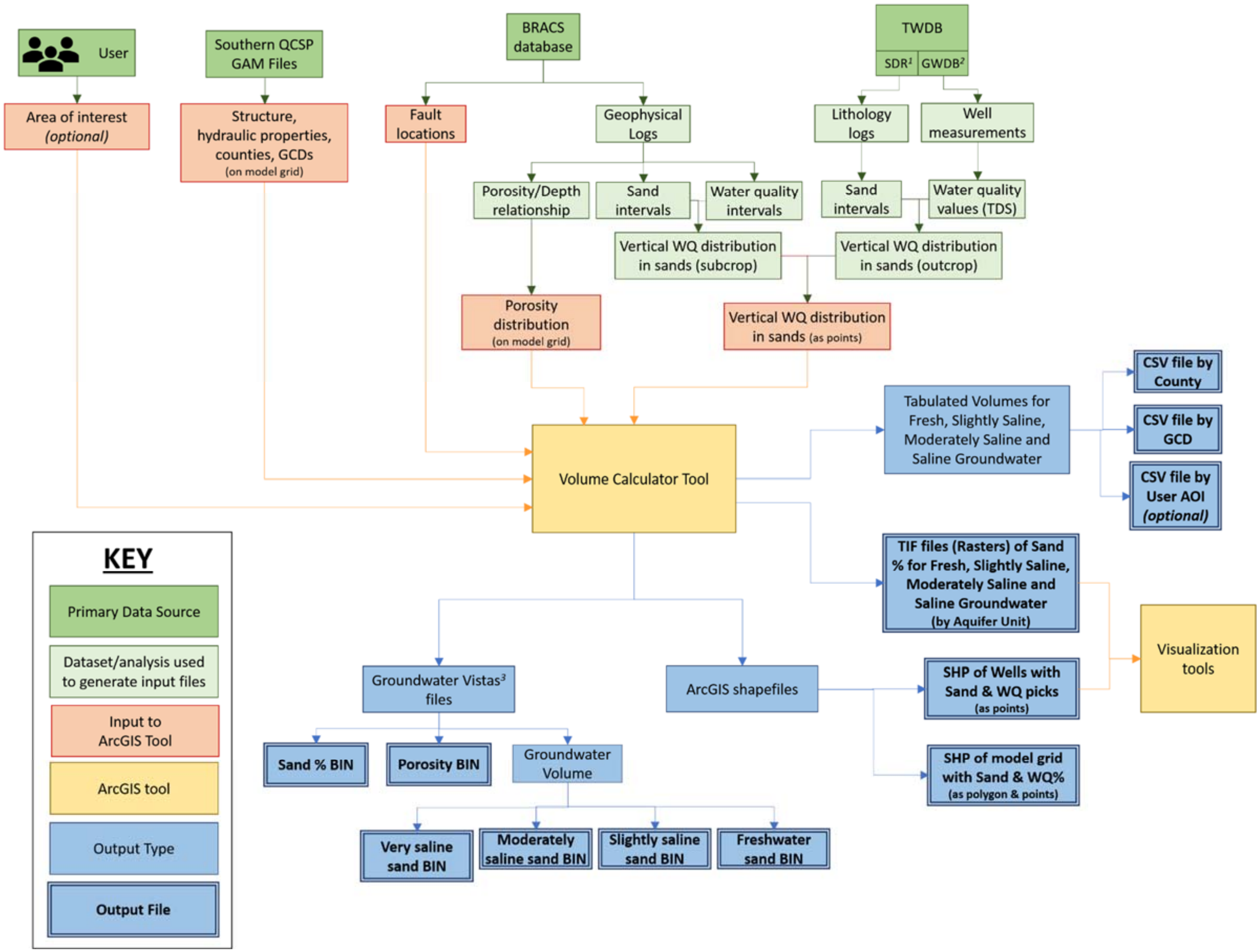


Figure 7-1. Schematic flow chart for the Volume Calculator Tool, including inputs and outputs.

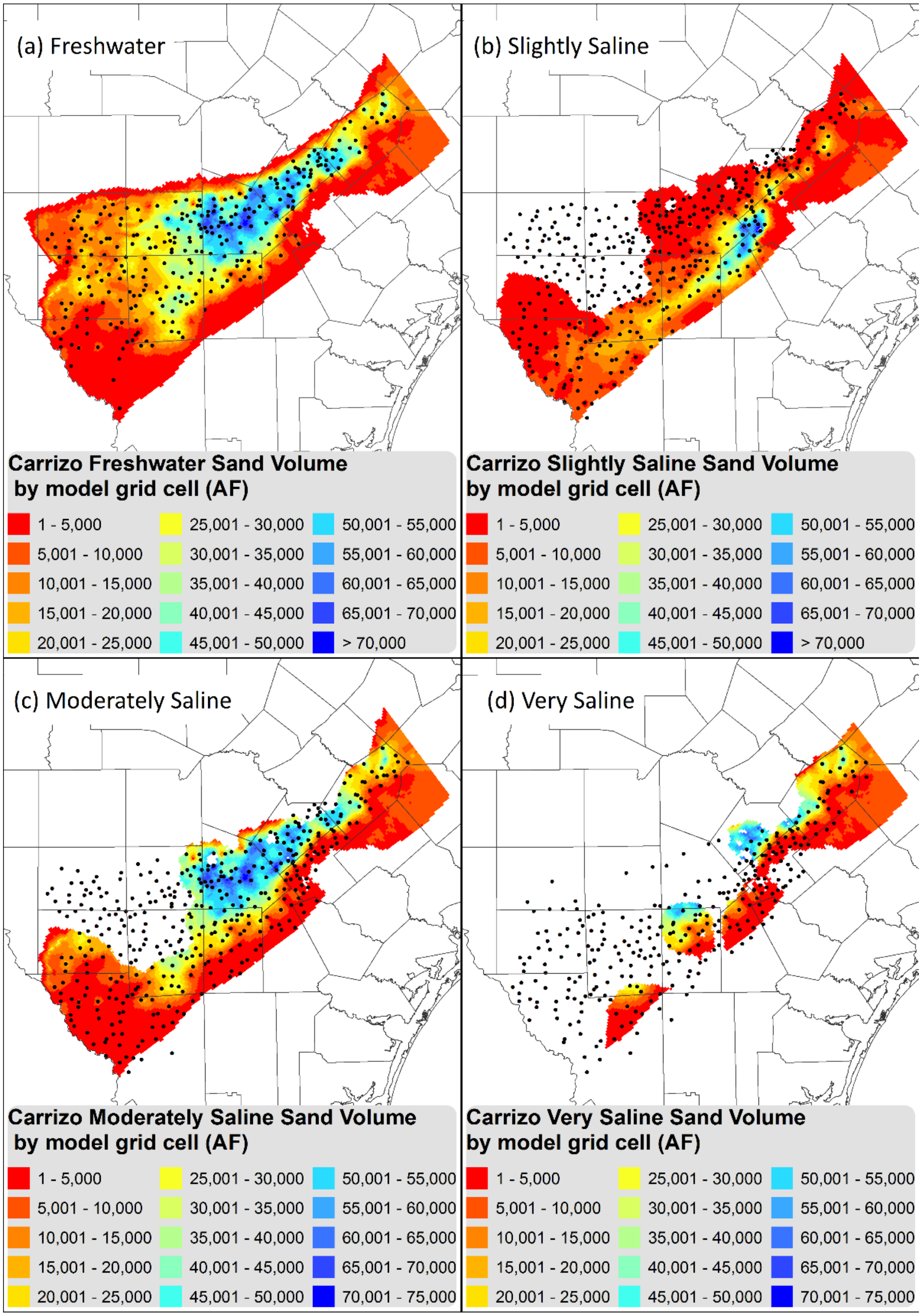


Figure 7-2. Examples of the shapefiles generated by the Volume Calculator tool. These maps show the volume of fresh, slightly saline, moderately saline, and very saline groundwater in sands in the Carrizo Aquifer.

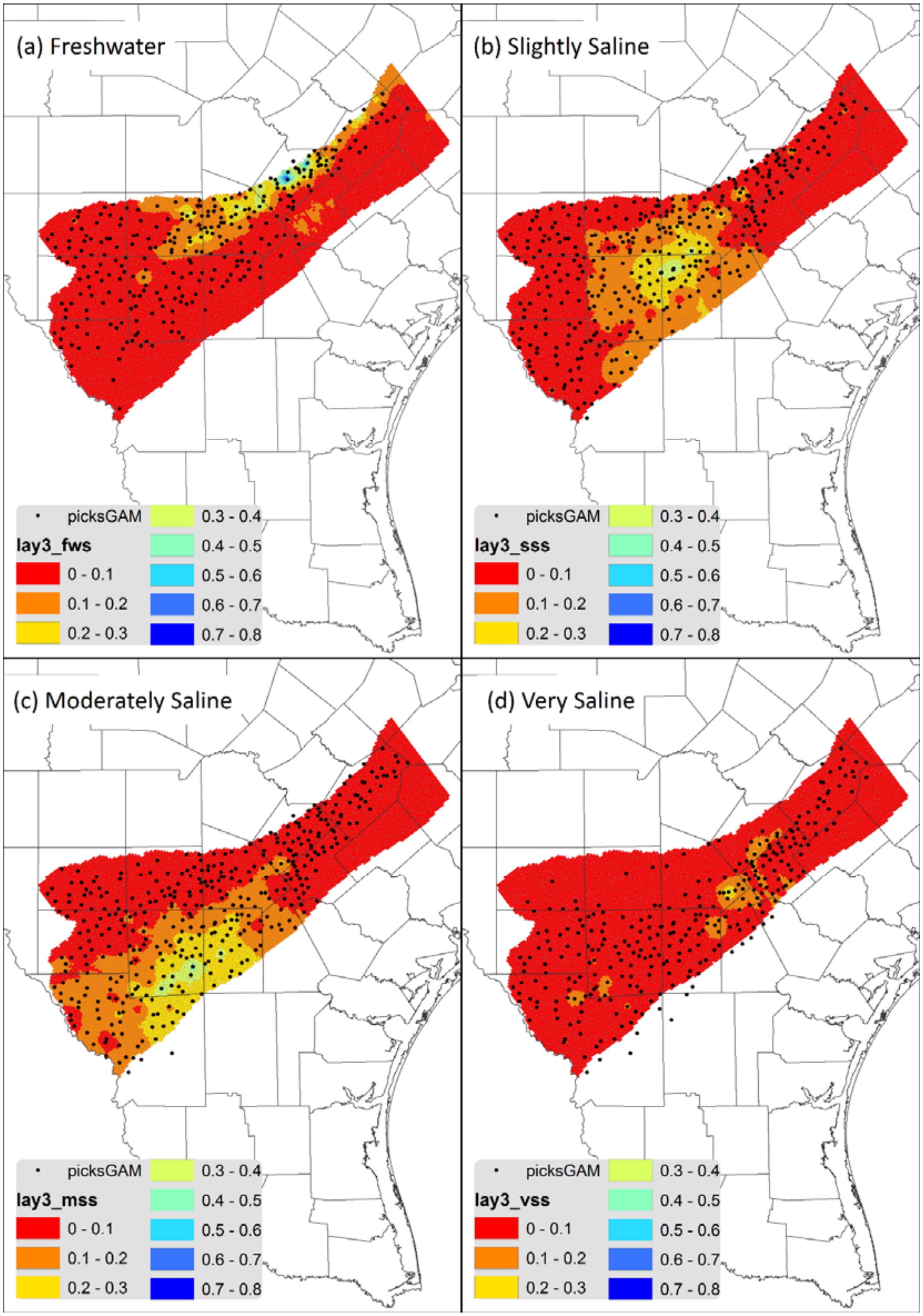


Figure 7-3. **Examples of the shapefiles generated by the Volume Calculator tool. These maps show the output grid shapefile filtered to show the Queen City sand fraction and the output points shapefile used to create these sand fraction values.**

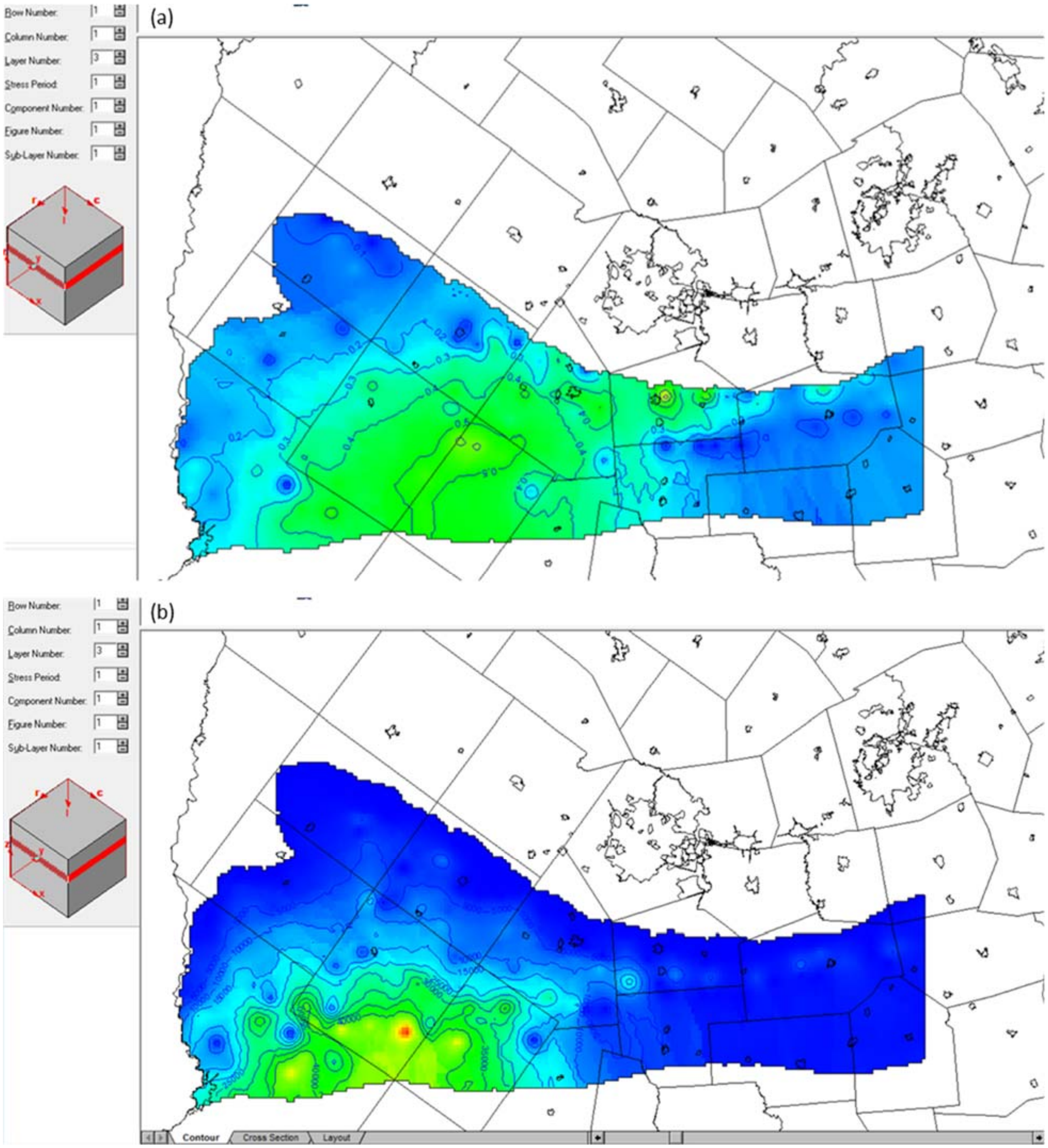


Figure 7-4. **Examples of the Groundwater Vistas files generated by the Volume Calculator tool. These examples show the total Queen City sand fraction (a) and the moderately saline Queen City sand fraction (b).**

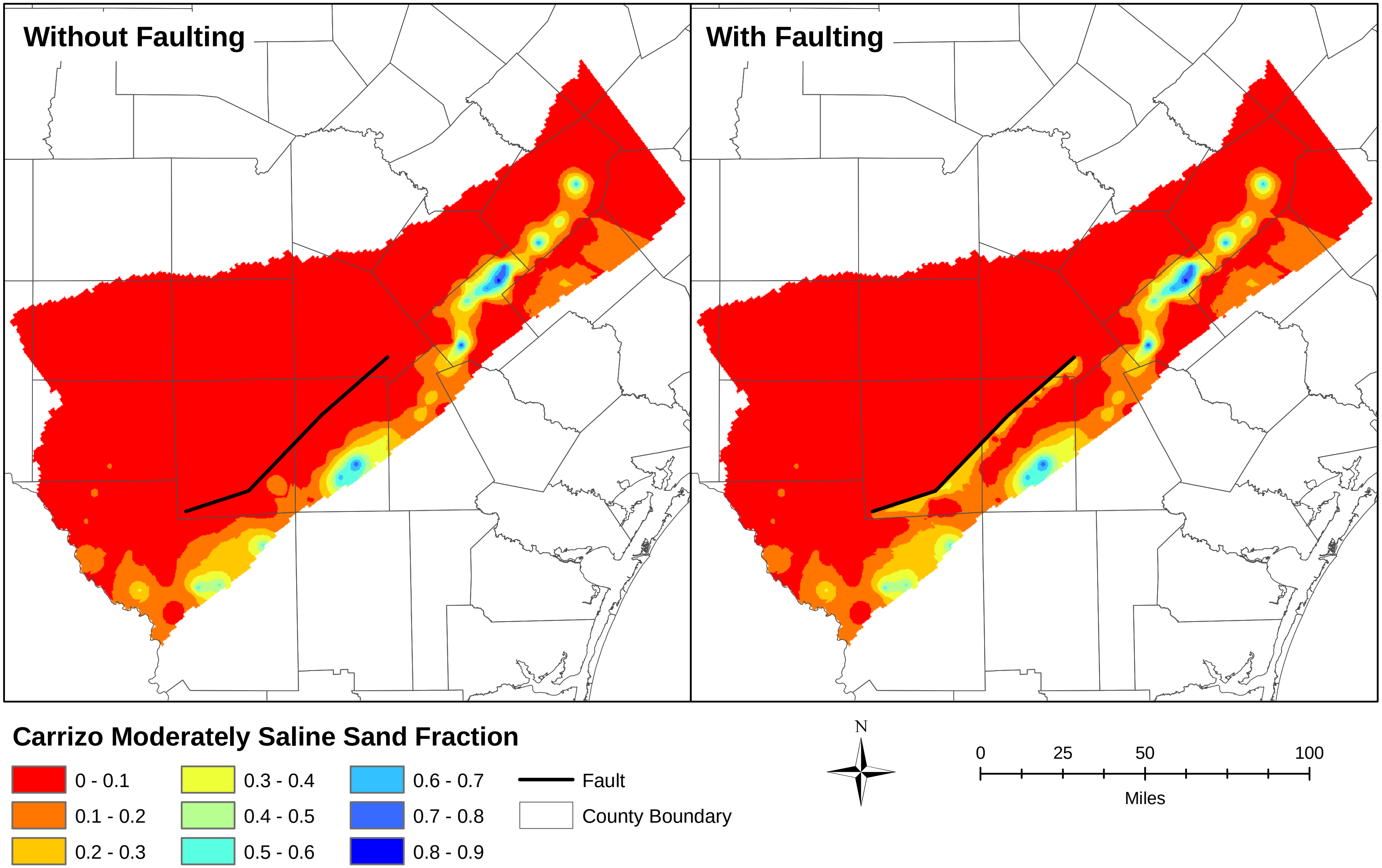


Figure 7-5. **Examples of rasters produced by the Volume Calculator tool when the faulting option is turned off (left) and turned on (right)**

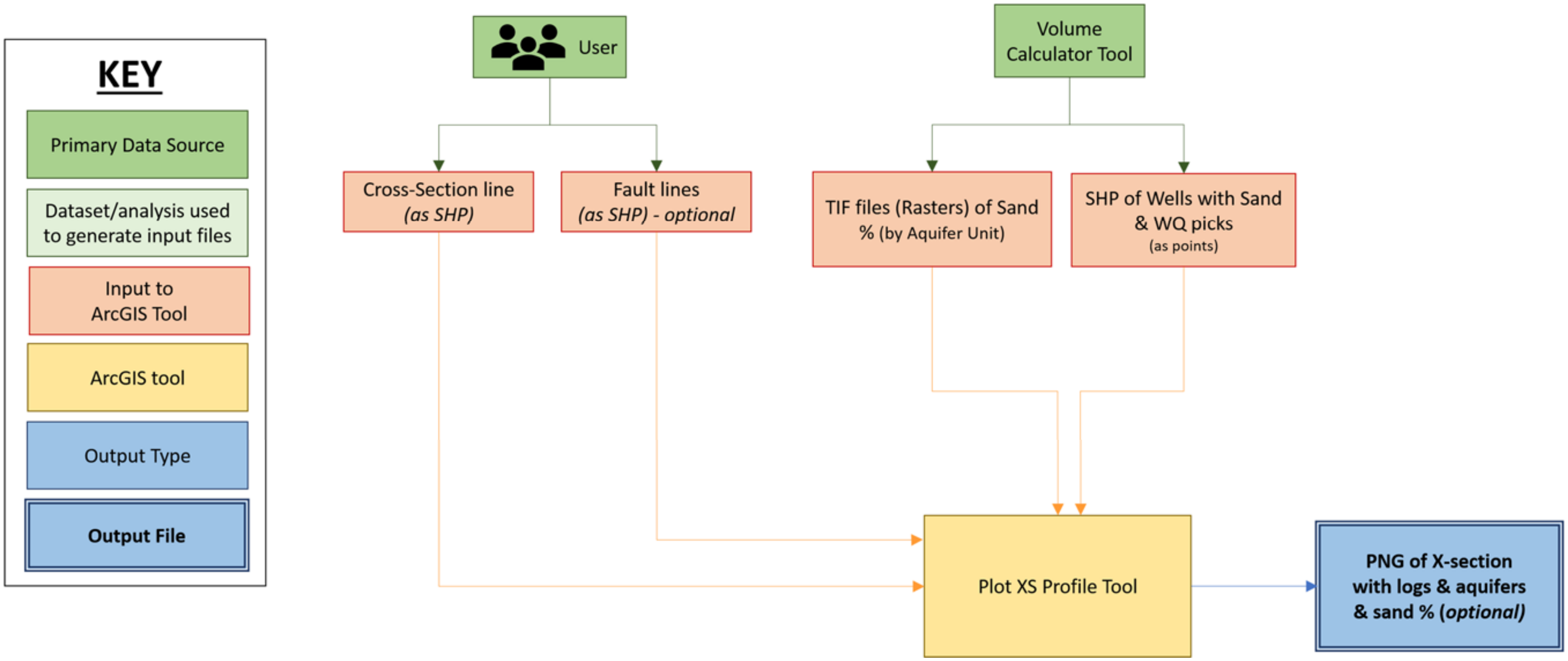


Figure 7-6. Schematic flow chart for the Plot XS Profile Tool, including inputs and outputs.

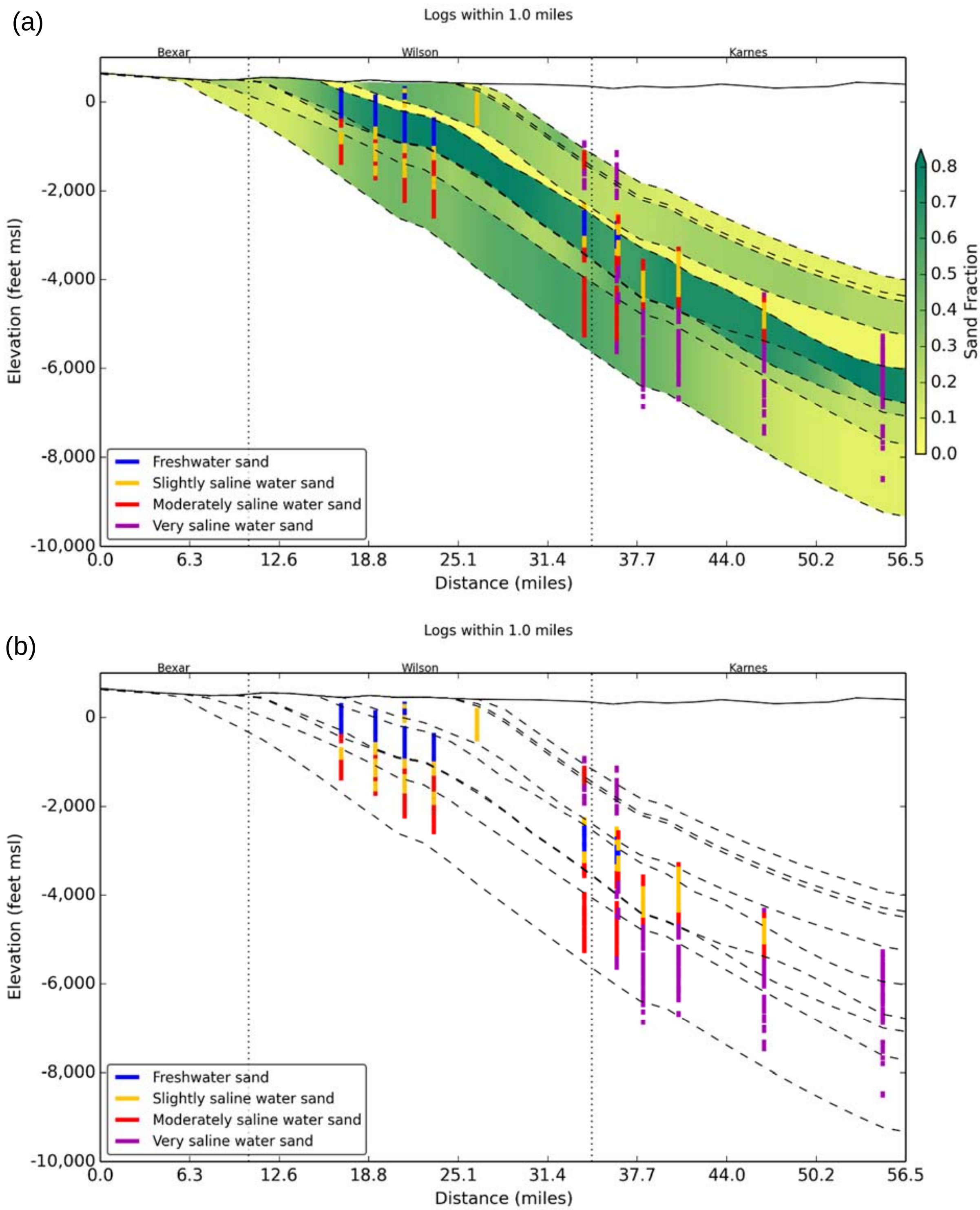


Figure 7-7. Examples of cross section figures generated by the Plot XS Profile Tool, when the sand fraction option is turned on (a) and turned off (b).

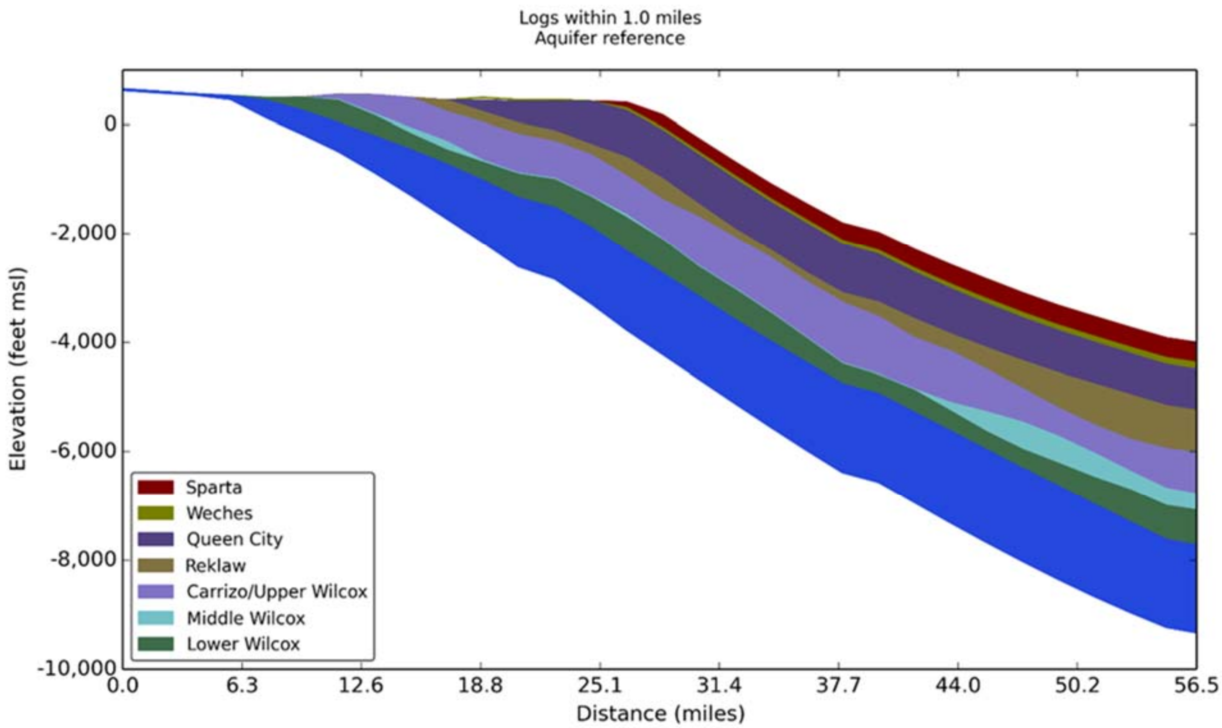


Figure 7-8. Example of color-coded aquifer key generated by the Plot XS Profile Tool

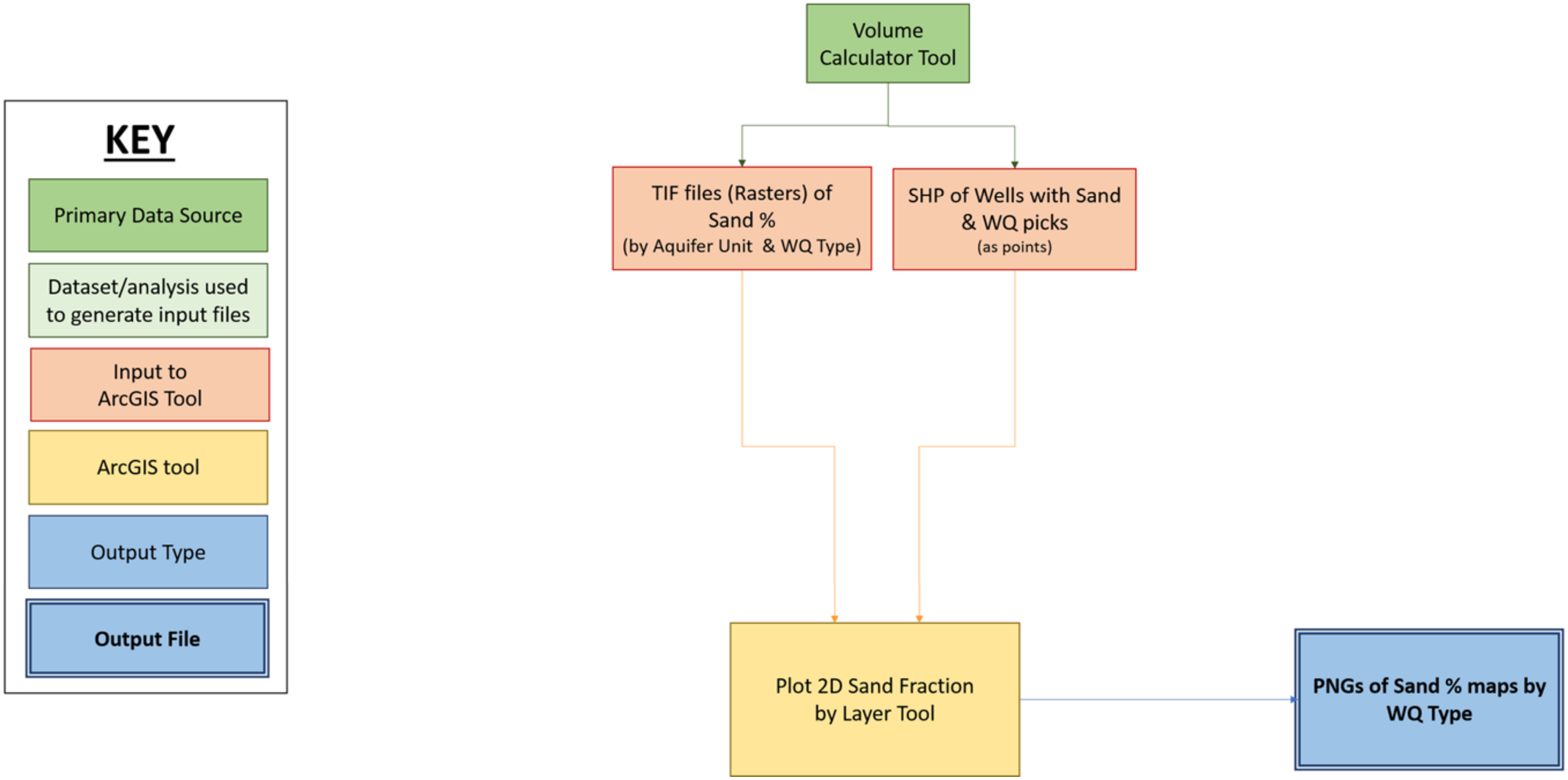


Figure 7-9. Schematic flow chart for the Plot 2D Sand Fractions by Layer Tool, including inputs and outputs.

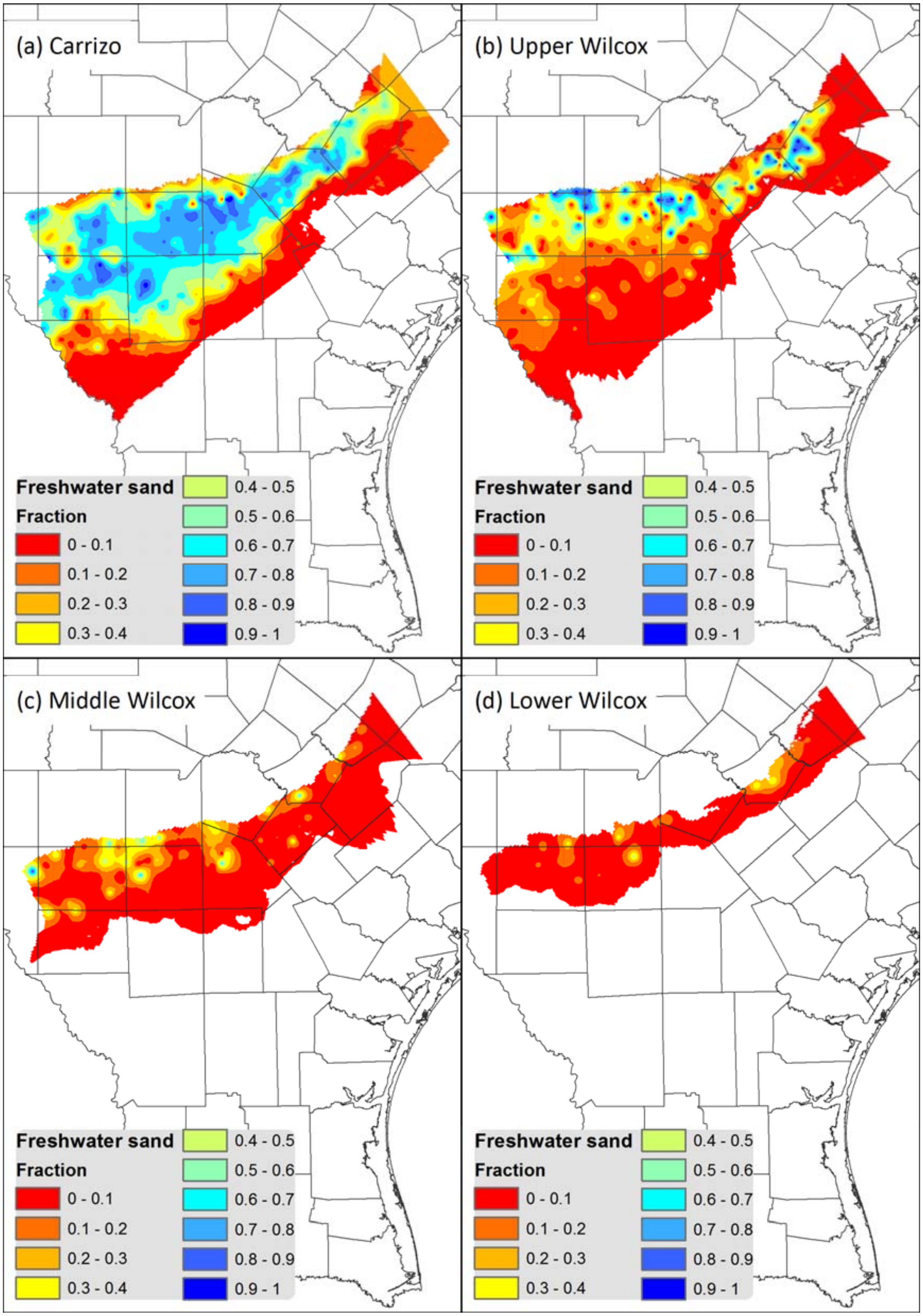


Figure 7-10. Example of map figure generated by the Plot 2D Sand Fractions by Layer Tool for the Carrizo-Wilcox aquifer units, displaying freshwater sand fractions.

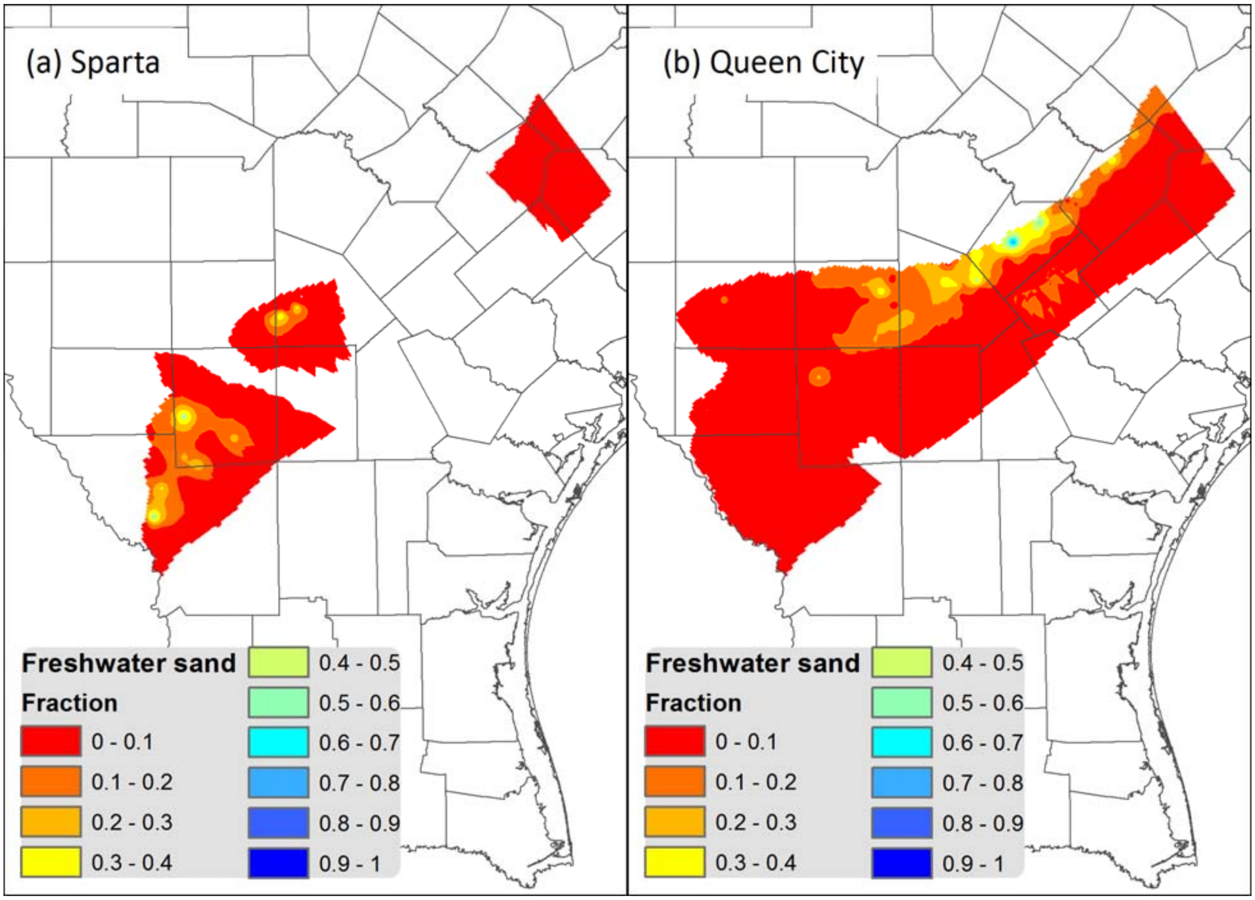


Figure 7-11. Example of map figure generated by the Plot 2D Sand Fractions by Layer Tool for the Queen City – Sparta aquifer units, displaying freshwater sand fractions.

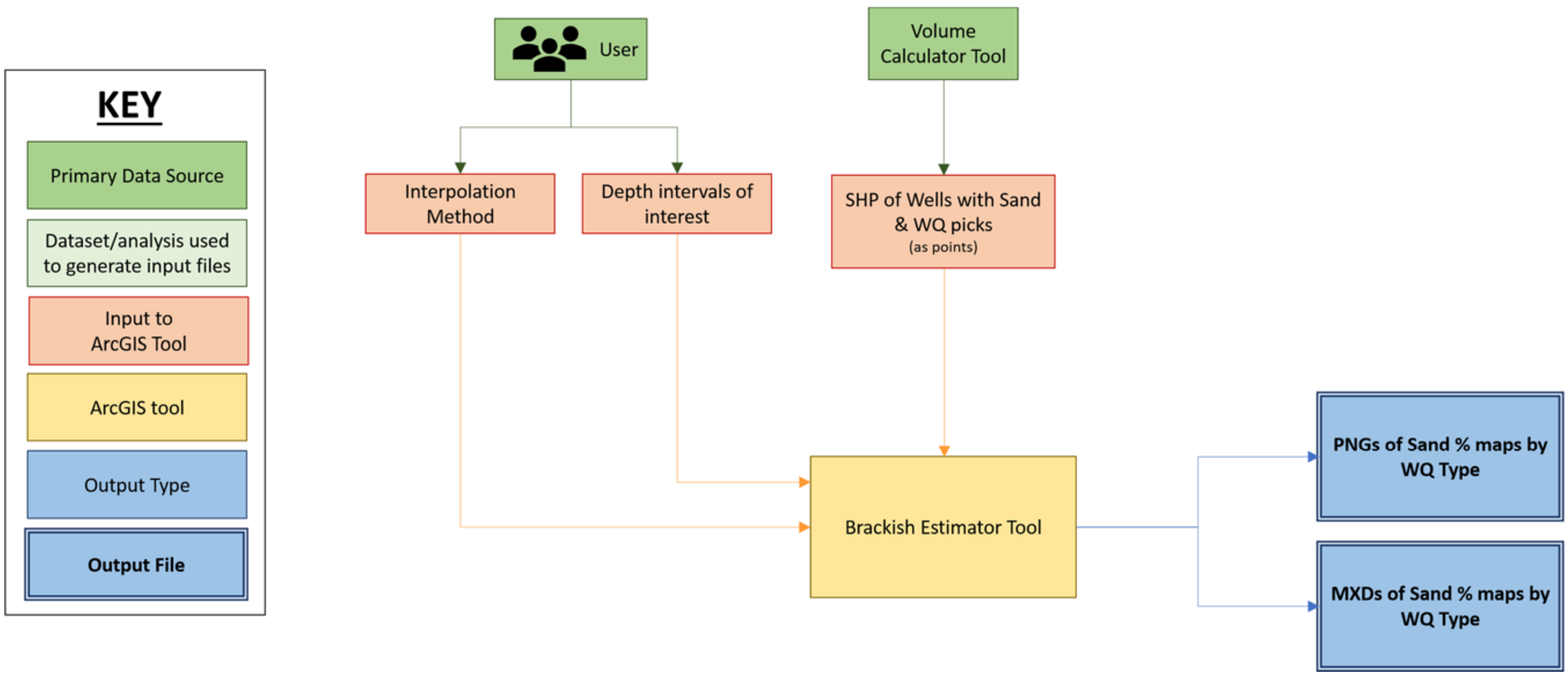


Figure 7-12. Schematic flow chart for the Brackish Estimator Tool, including inputs and outputs.

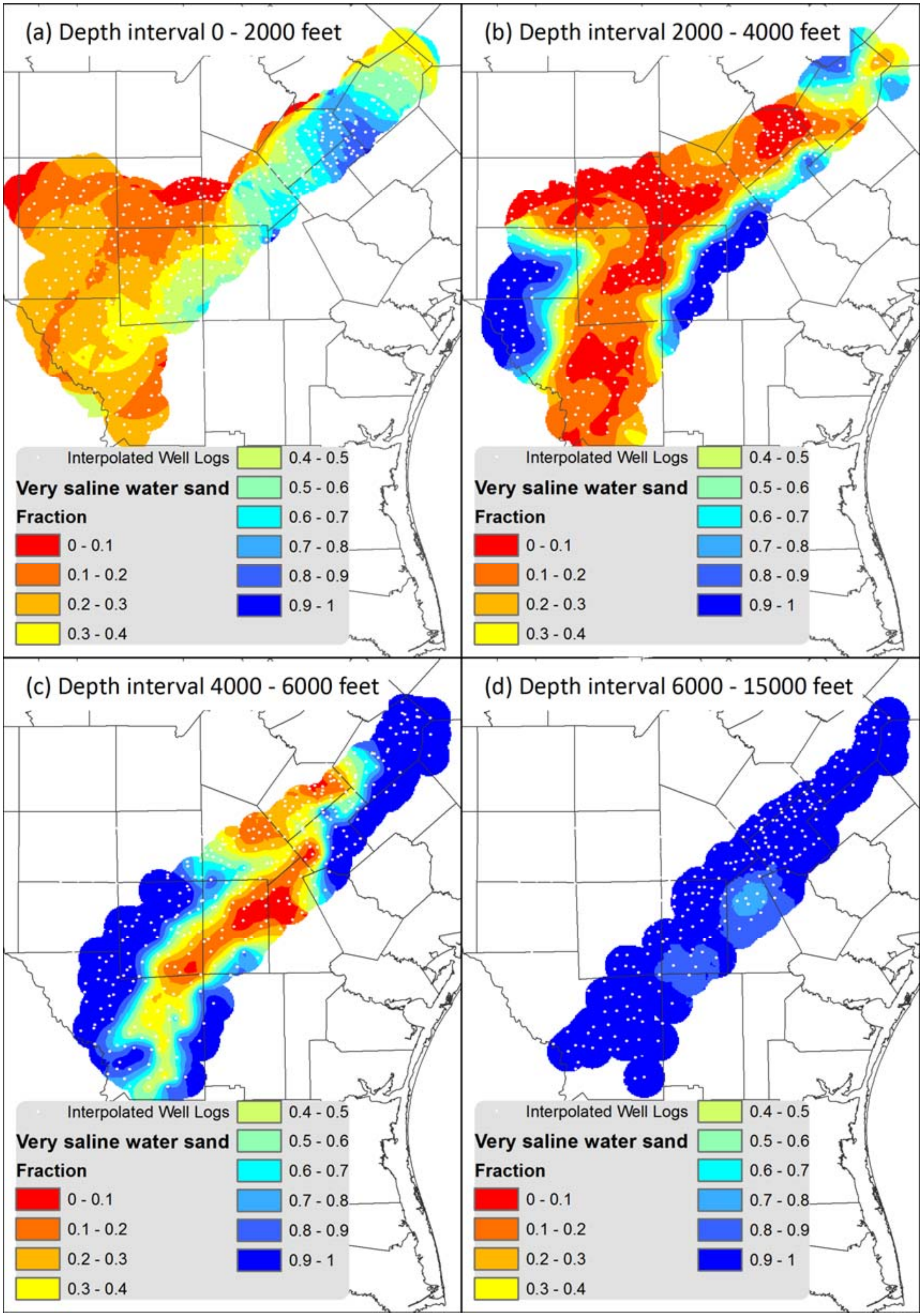


Figure 7-13. **Example of map figure generated by Brackish Estimator Tool, showing the very saline sand fraction for the depth intervals noted and the wells used in the interpolation.**

8 "GMA 13 Tools" ArcGIS Toolbox

These tools were developed in ArcGIS version 10.2.2. The tools have also been tested with ArcGIS version 10.3.1. For best results, we recommend using these ArcGIS versions as we have not tested the toolbox on other versions of ArcGIS.

8.1 Before Installation

1. Install "ArcGIS for Desktop Background Processing (64-bit)" if not already installed on your computer. ArcGIS uses 32-bit processing by default, but 64-bit processing is necessary for this project due to the large extent of the model and the vertical discretization of the aquifers. The 64-bit processing provides the large amounts of memory needed to efficiently process the data. The appropriate setup file is highlighted in the ArcGIS Quick Start Guide screenshot below (Figure 8-1).

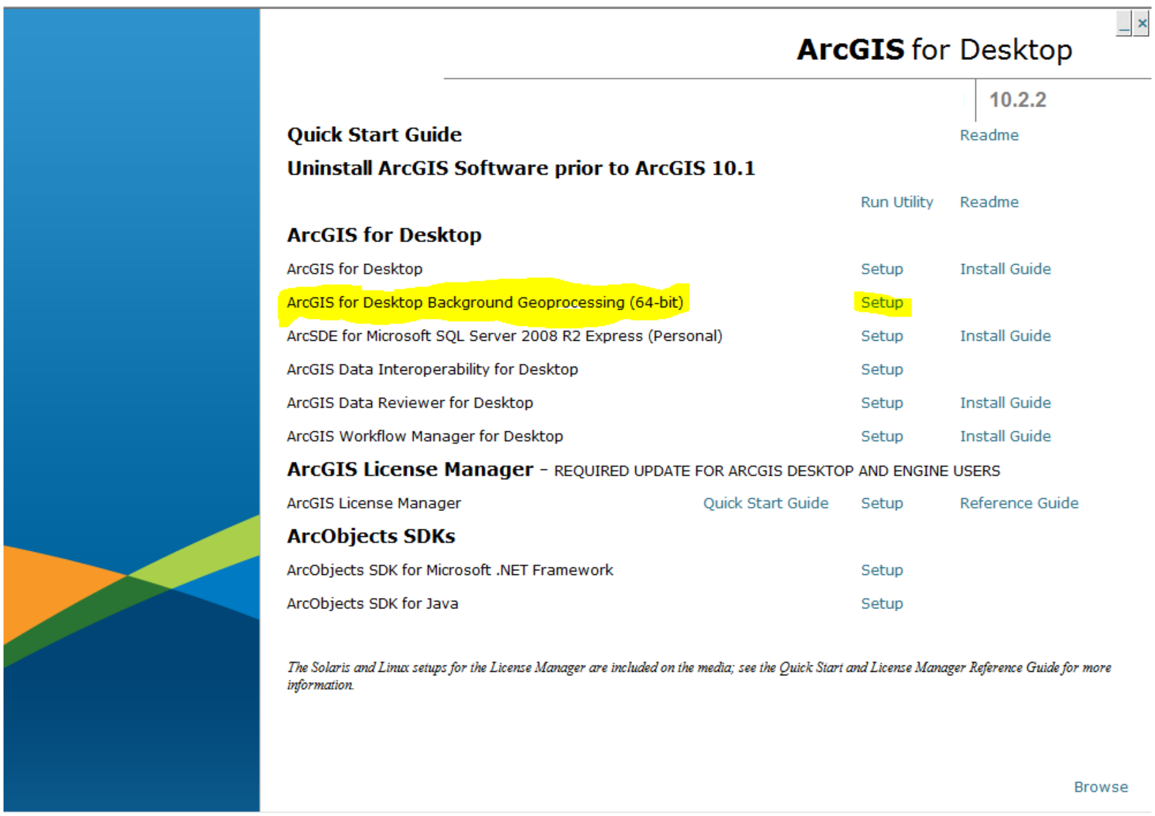


Figure 8-1. Screenshot of ArcGIS Quick Start Guide

Note: You can also run this setup executable directly from the ArcGIS Desktop disk (ArcGIS_BackgroundGP_for_Desktop_1031 _145711.exe)

2. After Step 1 is complete, enable the "Background Processing" option in ArcMap. To do this, open ArcMap and navigate in the menu to **Geoprocessing → Geoprocessing Options**. In the pop-up window, check (or toggle on) the "Enable" checkbox in the "Background Processing" section, as shown in Figure 8-2 below.

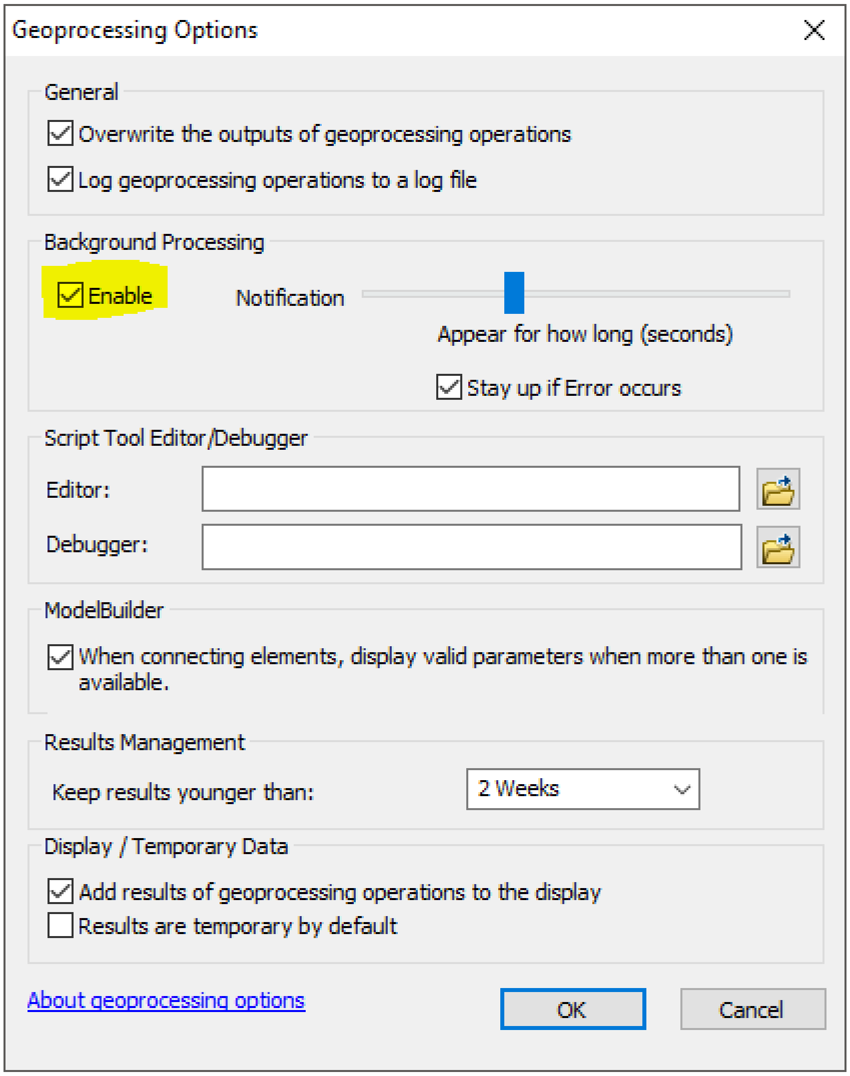


Figure 8-2. Screenshot of Geoprocessing Options window in ArcMap.

3. Install *pyinterval*, a non-standard Python library that provides interval operations and is necessary for running the toolbox scripts. To install *pyinterval*:
   i. Open a command prompt and execute the Python script called "get-pip.py" that is included in the Electronic Deliverable. This script allows the installation of a Python package manager. The command should follow the format:
   <*Path to your Python 64-bit installation*>\Python27\ArcGISx6410.2\python.exe <*Path to the unzipped Electronic Deliverable*>\get-pip.py

   See the screenshot in Figure 8-3 below for an example:

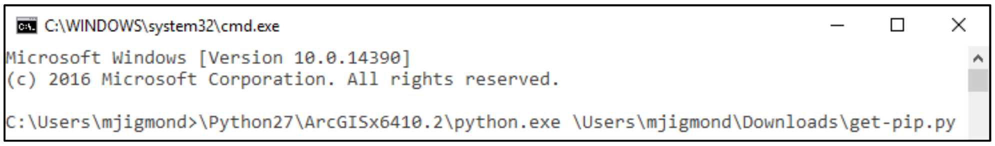


Figure 8-3. Screenshot of *pip* installation.

Helpful tip: Assuming you are running ArcGIS 10.2.x, the default location for Python 64-bit is C:\Python27\ArcGISx6410.2

ii. After Step 3.i. is completed, use the command prompt to install *pyinterval* using the *pip* Python package manager. The command should follow the format: <*Path to your Python 64-bit installation*>\Python27\ArcGISx6410.2\Scripts\pip.exe install pyinterval

See the screenshot in Figure 8-4 below for an example:

Figure 8-4. Screenshot of *pyinterval* installation.

Note: The *pyinterval* library and its documentation is available at https://pypi.python.org/pypi/pyinterval.

4. Ensure that you have access to the Spatial Analyst extension in ArcGIS. To do this, open an empty .mxd in ArcMap. Navigate to Customize > Extensions as shown in the screenshot in Figure 8-5 below. In the pop-up window, toggle on the "Spatial Analyst" option. If you are unable to toggle it on, you will need to get access from your ArcGIS license administrator. Once you have access, the tools in the "GMA 13 Tools" toolbox will be able to automatically enable the extension when running.

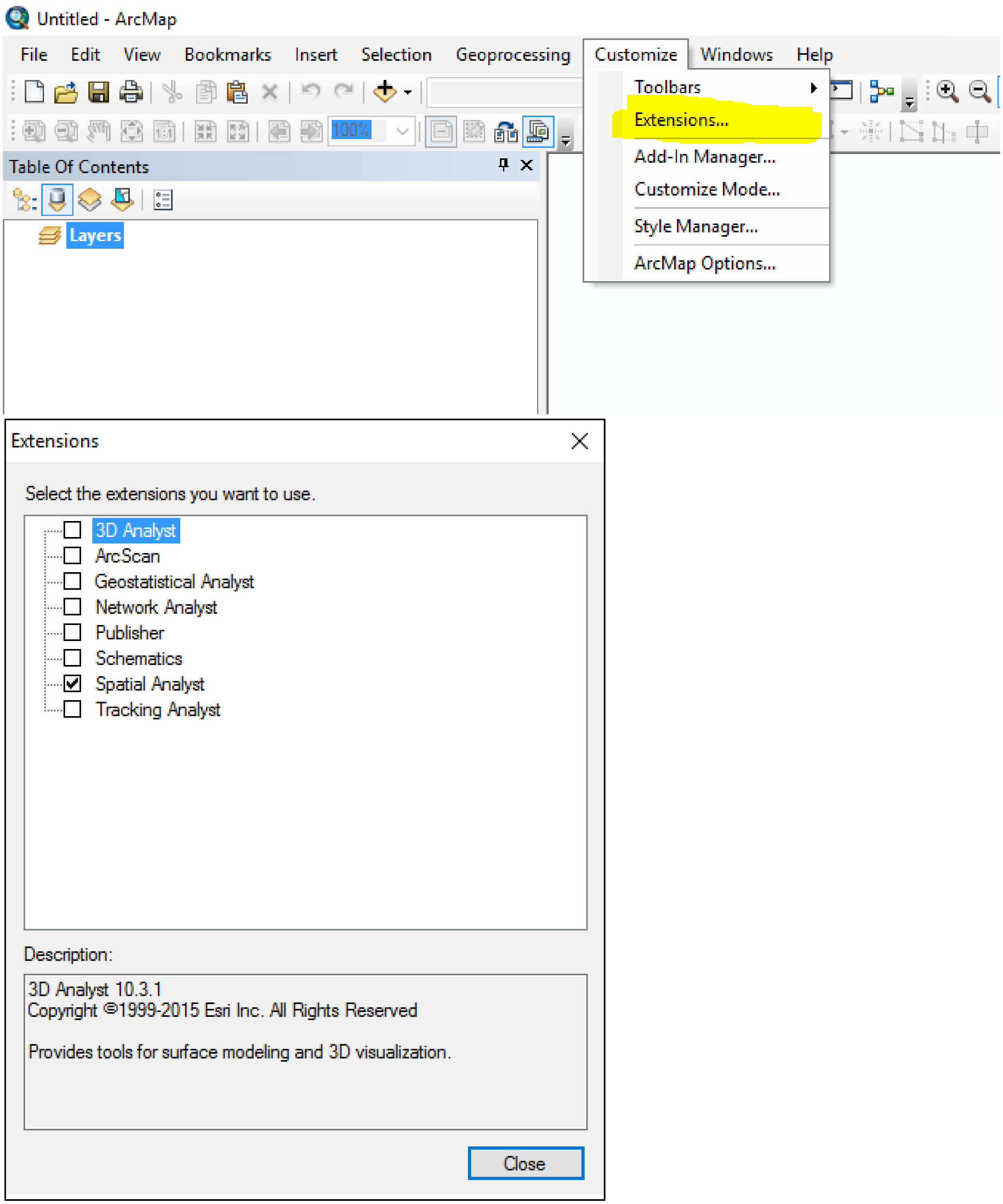


Figure 8-5. Screenshot of Spatial Analyst extension.

8.2 Installation

You will need to add the "GMA 13 Tools" toolbox to your ArcToolbox menu in ArcMap. To do this:

1. Open the "VolumeCalculator.mxd" ArcMap document included in the Electronic Deliverable.
2. Open the ArcToolbox window. If not already visible, you can open the ArcToolbox window by clicking on the highlighted button in the screenshot in Figure 8-6 below:

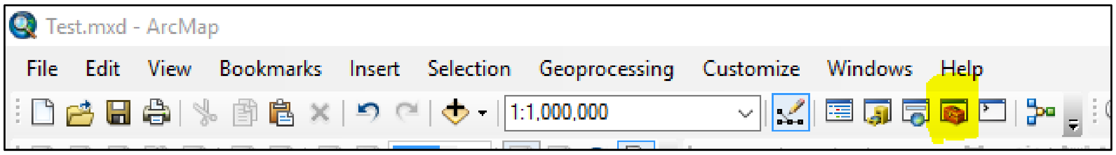


Figure 8-6. Screenshot of ArcToolbox.

3. Right-click on ArcToolbox and select the "Add Toolbox" option as shown in Figure 8-7. Navigate to the Electronic Deliverable folder and select the file called "GMA 13 Tools.tbx."

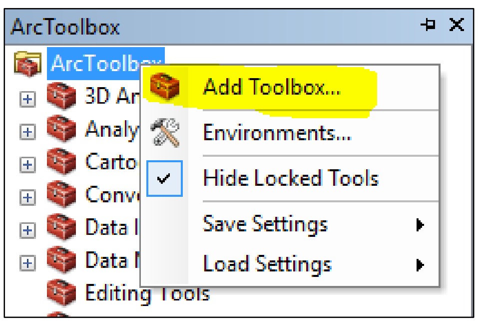


Figure 8-7. Screenshot of Add Toolbox option in ArcToolbox.

4. When installed properly, the "GMA 13 Tools" toolbox and all four tools should show up as an option in your ArcToolbox window, as shown in Figure 8-8 below:

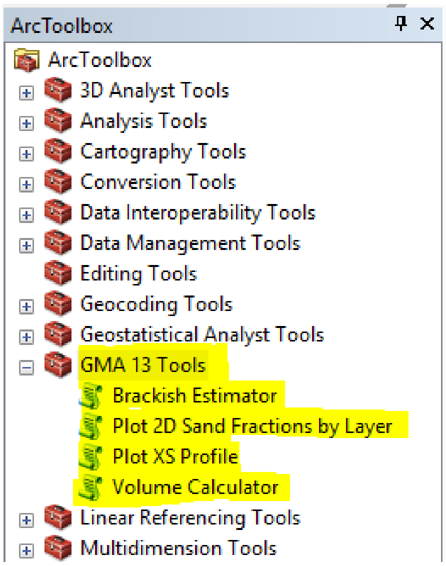


Figure 8-8. Screenshot of properly installed GMA 13 Tools toolbox.

8.3 Using the Toolbox

8.3.1 Volume Calculator Tool

The "Volume Calculator" tool automates the groundwater volume calculation process and performs TERS-like calculations for aquifer units by water quality type. These calculations are described in detail in Chapter 5. The tool provides options to perform these calculations based on specific storage rather than storage coefficient, or based on porosity rather than specific yield. There is also an option to incorporate faulting into the volume calculation. The user can also change the model discretization parameters, if desired.

To run this tool, open the "VolumeCalculator.mxd" included in the Electronic Deliverable and open the "Volume Calculator" tool through the ArcToolBox window. Note, this tool can be used with any ArcGIS map document, as the input definitions are independent of the working .mxd. However, the example map document is provided for convenience and minimizes the possibility of breaking the input links.

Inputs

The tool interface is shown Figure 8-9 below, with inputs numbered in red:

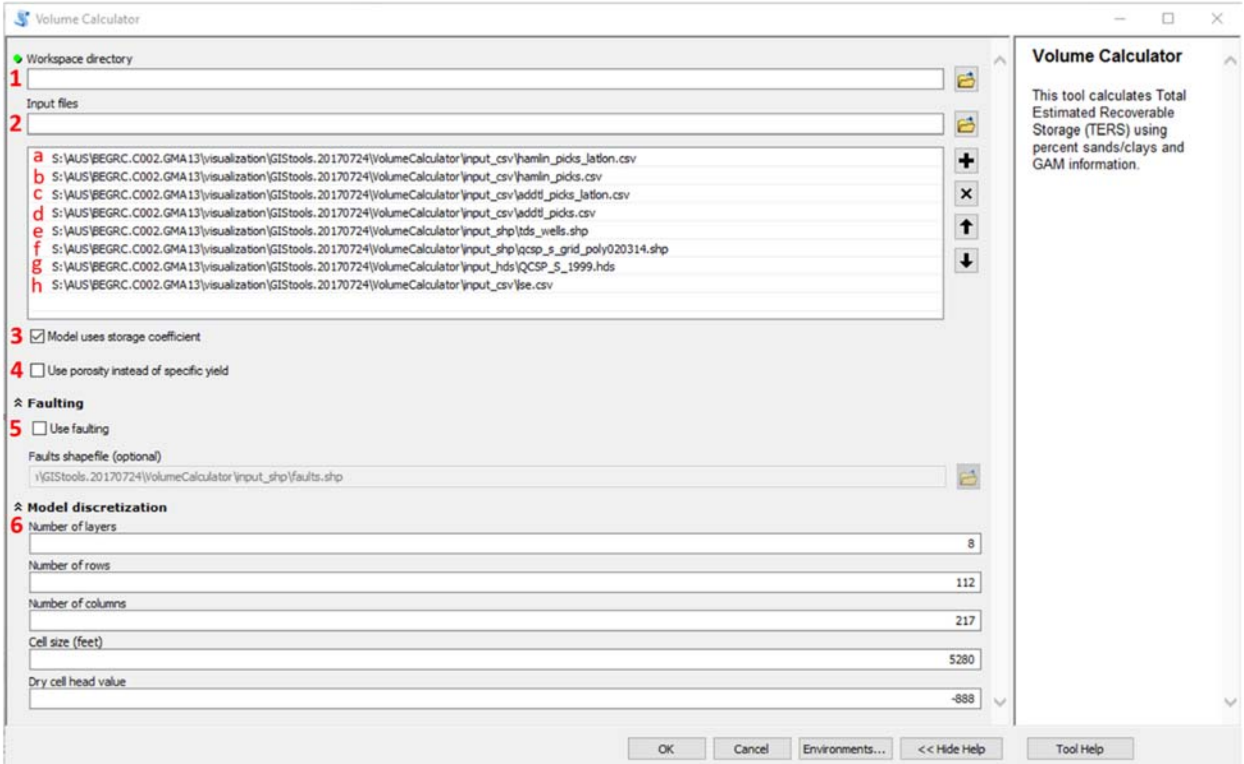


Figure 8-9. Screenshot of interface for Volume Calculator Tool.

Each numbered input in this image is described below:

1. The path to the working (output) directory. All of the tool's outputs will be written to this directory. In the Electronic Deliverable, we have used the folder "*…\VolumeCalculator\output_sy*" for runs using the specific yield calculation option and the folder "*…\VolumeCalculator\output_por*" for runs using the porosity calculation option. The user can specify their own unique folder path.
2. Input files for the volume calculation. By default, these are already populated with paths to input files provided in the Electronic Deliverable. The user can update the file paths if these input files are moved or updated. However, the order of the input files cannot be changed, or the program will not run correctly.
   a. CSV file containing the geophysical log well locations.
   b. CSV file containing the sand and water quality picks made from the geophysical well log analyses.
   c. CSV file containing the driller's log well locations.
   d. CSV file containing the sand picks made from the driller's log records.
   e. SHP file containing TWDB groundwater database wells with average TDS values.
   f. SHP file of the model grid from the Queen City and Sparta Aquifers Groundwater Availability Model (Kelley and others, 2004).
   g. HDS file containing the 1999 water level simulated by the QCSP GAM (Kelley and others, 2004).

h. CSV file containing the land surface elevation for every model grid cell in *the model grid shapefile (Input #2f)*.

***** Note: If you wish to generate aggregated volumes based on user-designated areas (as opposed to counties or districts), you must first modify the model grid shapefile (Input #2f) to include your zoning information. To do this, assign zone values to the "CountyName" column in the shapefile. This can be achieved several ways, including the "Editing" tool or the "Spatial Join" tool in ArcGIS. The resulting zone volumes WILL overwrite the output file*** *ctyVolumeBrack.csv*. ***If you don't want to lose the county-aggregated volumes in that output file, be sure to save a copy elsewhere before re-running the Volume Calculator tool with your new zones.***

3. Option to use storage coefficient rather than specific storage value in the confined volume calculation. Default (toggle on) is to use storage coefficient values.
4. Option to use porosity rather than specific yield value in the unconfined volume calculation. Default (toggle off) is to use specific yield values.
5. Option to use faulting when interpolating water quality distribution. Default (toggle off) is to ignore faulting. If this option is toggled on instead, the user must specify a SHP file containing faults. This is already populated with a default SHP provided in the Electronic Deliverable (*…VolumeCalculator\input_shp\faults.shp*)

   ***** Note: To use this option, you must FIRST run the Volume Calculator tool with the faults option toggled off and then run it again with the faults option toggled on, leaving the workspace directory name (Input #1) unchanged.***

6. Model discretization parameters. By default, these are already populated with the appropriate parameters for the QCSP model grid provided in input **2f**.

Running the Tool

Compared to built-in ArcGIS tools in ArcToolbox, the "Volume Calculator" tool can take a long time (10-30 minutes) to run due to the amount of data and its dependence on the GUI environment. It can be helpful for the user to periodically monitor the progress of the tool to ensure the tool is still running properly. To do this, navigate in the menu to **Geoprocessing ➔ Results** as shown in Figure 8-10.

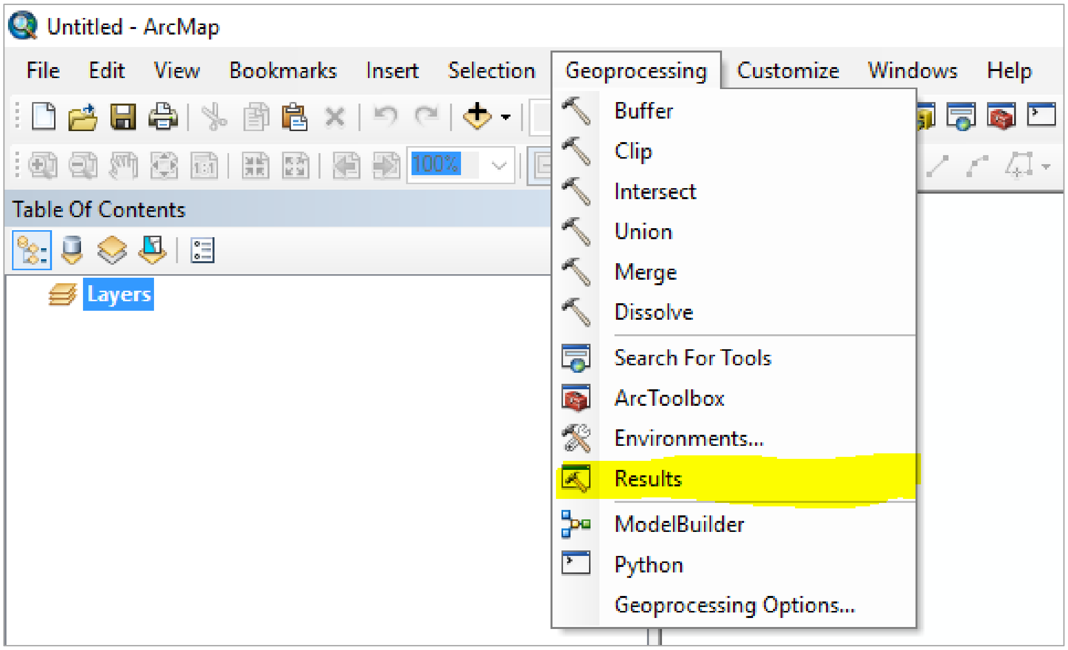


Figure 8-10. Screenshot of Geoprocessing Results option.

This will display a window where messages are printed to a log as the tool progresses. When the tool is running properly, this log should look similar to Figure 8-11 below.

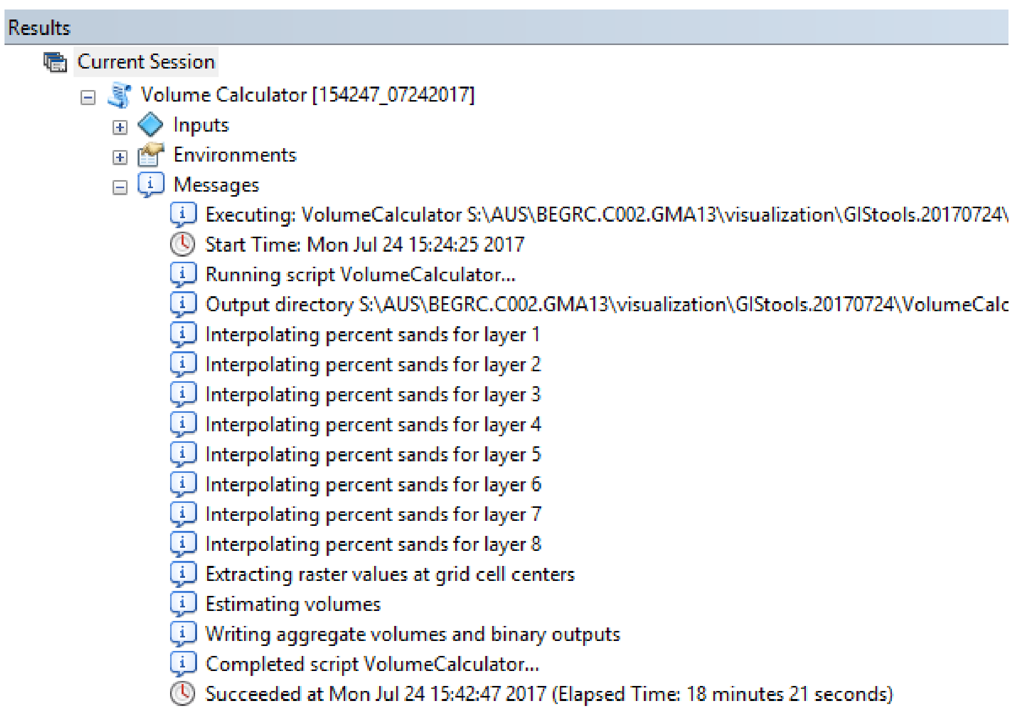


Figure 8-11. Screenshot of Volume Calculator results window.

Output

The "Volume Calculator" tool generates the output files described below. The folders containing these output files are provided in the Electronic Deliverable as "*…\VolumeCalculator\output_sy*" for runs using the specific yield calculation option and as "*…\VolumeCalculator\output_por*" for runs using the porosity calculation option.

a. CSV files with volume estimates by aquifer unit by water quality type aggregated by County (*ctyVolumeBrack.csv*) and GCD (*gcdVolumeBrack.csv*). These can be read and manipulated in Microsoft Excel.
b. TIF files (rasters) of sand percentages by water quality type by aquifer unit (*lay1_fws.tif, etc.*). These files can be used in ArcGIS map documents and are input files for the visualization tools included in the "GMA 13 Tools" ArcGIS toolbox (see following sections). The naming convention for these files follow the format: "lay<*layer number*>_<*water quality abbreviation*>.tif," where

Layer Number	**Aquifer**		**Water Quality Abbreviation**	**Water Quality Type**
1 =	Sparta		fws =	freshwater sand
2 =	Weches		sss =	slightly saline sand
3 =	Queen City		mss =	moderately saline sand
4 =	Reklaw		vss =	very saline sand
5 =	Carrizo		total =	total sand
6 =	Upper Wilcox			
7 =	Middle Wilcox			
8 =	Lower Wilcox			

c. Point SHP file of the locations of geophysical log analyses performed as part of this study in NAD27 coordinate system (*llpntHamlin.shp*) and GAM coordinates (*gampntHamlin.shp*)
d. Point SHP files the water quality and sand picks from the geophysical log analyses performed as part of this study in NAD27 coordinate system (*picks.shp*) and GAM coordinates (*picksGAM.shp*)
e. Point SHP files of the additional driller's log well locations used to fill in data gaps in the outcrop in NAD83 coordinate system (*llpntAdditional.shp*) and GAM coordinates (*gampntAdditional.shp*).
f. Point SHP files of the combined sand and water quality picks from the geophysical log analyses and the submitted driller's logs (*pctHamlin.shp*). These are the points used to create the TIF (raster) files in **b**.

g. Polygon and point SHP files of the model grid for the QCSP GAM (Kelley and others, 2004) with additional fields to represent the sand percentages and water quality percentage values for each cell (*qcsp_s_grid.shp* and *qcsp_s_grid_point.shp*).

h. Point SHP file of the additional driller's log wells with additional fields containing the TWDB groundwater database well pair and its water quality (TDS) information (*tds_join.shp*).

i. Binary files of porosity (*porosity.bin*), sand percent (*pct_sand.bin*), and groundwater volumes by groundwater quality type (*vol_sand_fws.bin*, *vol_sand_sss.bin*, *vol_sand_mss.bin*, *vol_sand_vss.bin*). These files can be loaded into Groundwater Vistas if desired. The binary format follows the MODFLOW HEAD SAVE single precision specification. To display one of these binary files in Groundwater Vistas, import it as if it were a MODFLOW .hds file. To do this, navigate to Plot >Import Model Results in the Groundwater Vistas menu. In the pop-up window shown in Figure 8-12 below, add the path to the BIN file as the Head File path.

*****Note: To display correctly, you must already have an appropriate .gwv file of the Southern QCSP model open in Groundwater Vistas before importing one of these binary files.***

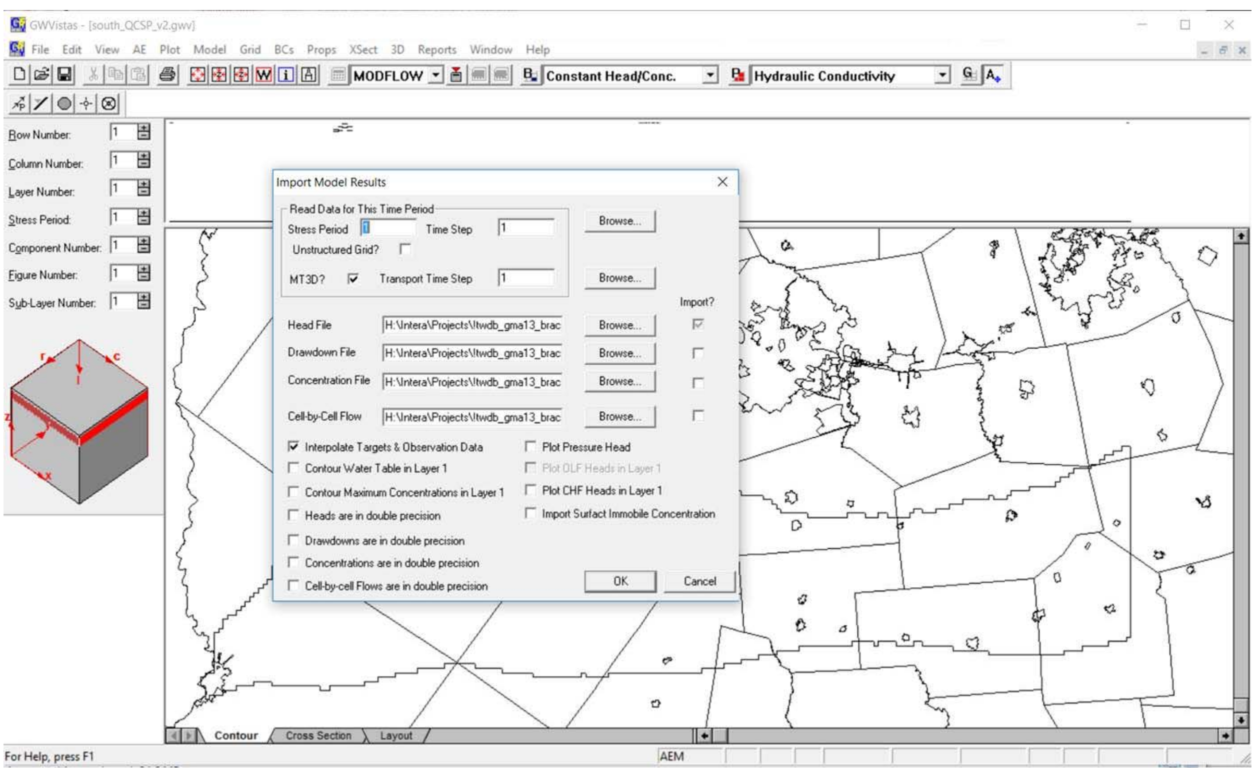


Figure 8-12. Screenshot of import window in Groundwater Vistas.

***** Note: The following visualization tools rely on input files generated by the "Volume Calculator" tool. You can create new input files by re-running the "Volume Calculator" tool with different scenarios.***

However, by default, the visualization tools will display the "Volume Calculator" output files included in the Electronic Deliverable. To visualize other scenarios, you must first manually direct the visualization tools to display your desired input files. You can do this several ways:

- Open the appropriate .mxd for the desired visualization tool and manually replace each layer's data source path to point to your new files.

- Overwrite the input files included in the Electronic Deliverable with your new files, keeping the shapefile or raster names unchanged.

8.3.2 Visualization of Well Logs Along Modeled Cross sections in GMA 13

The "Plot XS Profile" visualization tool produces publication-ready cross section figures at user-designated transects. These figures display the locations and water quality picks for geophysical well logs in relation to aquifer layers. The figures can also optionally display sand percent information by aquifer layer, as derived from the sand fraction surfaces produced by the "Volume Calculator" tool.

To run this tool, open the "plotxs_generalized.mxd" included in the Electronic Deliverable and open the "Plot XS Profile" tool through the ArcToolBox window. **** Note: This tool will NOT work unless opened within this ArcGIS map document.**

Inputs

The tool interface is shown in Figure 8-13 below, with inputs numbered in red:

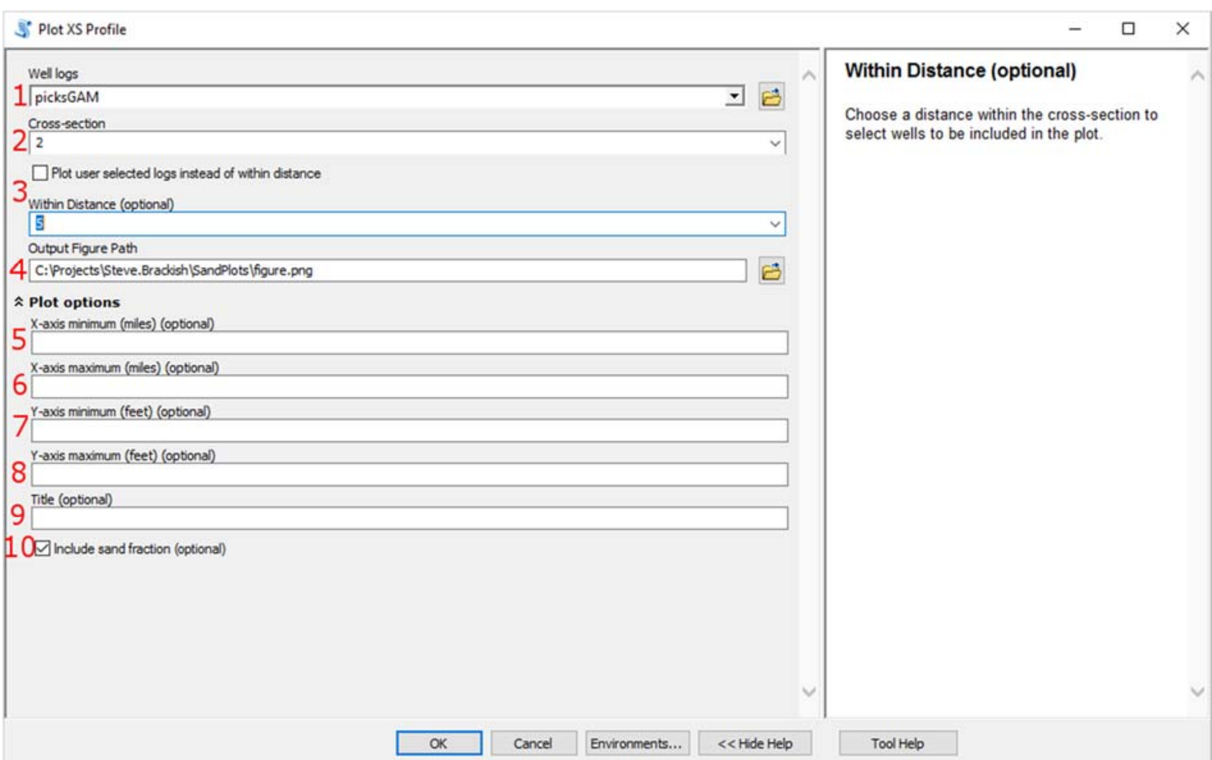


Figure 8-13. Screenshot of interface for Plot XS Profile Tool.

1. Point SHP file of the water quality and sand picks from the geophysical log analyses in GAM coordinates (*picksGAM.shp), as* generated by the Volume Calculator tool.
2. Layer name of user-designated cross section.
   ***** Note: By default, there are 9 cross sections included in the map document as options. If a cross section is required in a location that is not included, the user should create a new shapefile in the desired location and add it to the map document. This cross section location will then show up as an option in the drop-down menu.***
3. Option to only display selected wells along a cross section or to display all wells within a specified distance of a cross section. Default (toggle off) is display all wells within a specified distance of a cross section. The user can choose a predefined distance of 1, 3, 5, or 10 miles from the drop-down menu. If this option is toggled on instead, the user must first manually select the wells of interest using one of the interactive selection methods within ArcMap.
4. The user-specified path for the output location of the figure.
5. The minimum x value to be used in the output figure. Default (empty entry) will use the updip extent of the cross section.
6. The maximum x value to be used in the output figure. Default (empty entry) will use the downdip extent of the cross section.
7. The minimum y value to be used in the output figure. Default (empty entry) will use the topmost elevation of the cross section.
8. The maximum y value to be used in the output figure. Default (empty entry) will use the bottommost elevation of the cross section.
9. Custom title for the figure. Default (empty entry) will produce a generic title such as "Cross section #2 – Logs within 5.0 miles".
10. Option to include or exclude the sand fraction values on the figure. Default (toggle on) is to display sand fraction values**. **Note: By default, the tool uses the sand fraction rasters saved in the folder "…*\SandPlots\inputs\ters_rasters*." If you re-ran the Volume Calculator tool, you will need to replace the rasters in this folder with your new sand fraction rasters. You can generate these new rasters by cropping the output TIFs (rasters) from the Volume Calculator tool to the appropriate active areas by layer.**

Outputs

The "Plot XS Profile" tool generates the output files described below. The folders containing these output files are provided in the Electronic Deliverable as "*…\SandPlots\outputs\XSections*"

1. PNG file of cross section figure displaying locations and water quality picks for geophysical well logs in relation to aquifer layers. The tool has the option of including sand fraction values. If this option is toggled on (default), the resulting figure will look similar to Figure 8-14. If this option is toggled off, the resulting figure will look similar to Figure 8-15.
2. PNG file of aquifer reference figure displaying the stratigraphy at the cross section. The name of this file will be the same as output file #1, except with a "_aq" suffix. This figure will look similar to Figure 8-16.

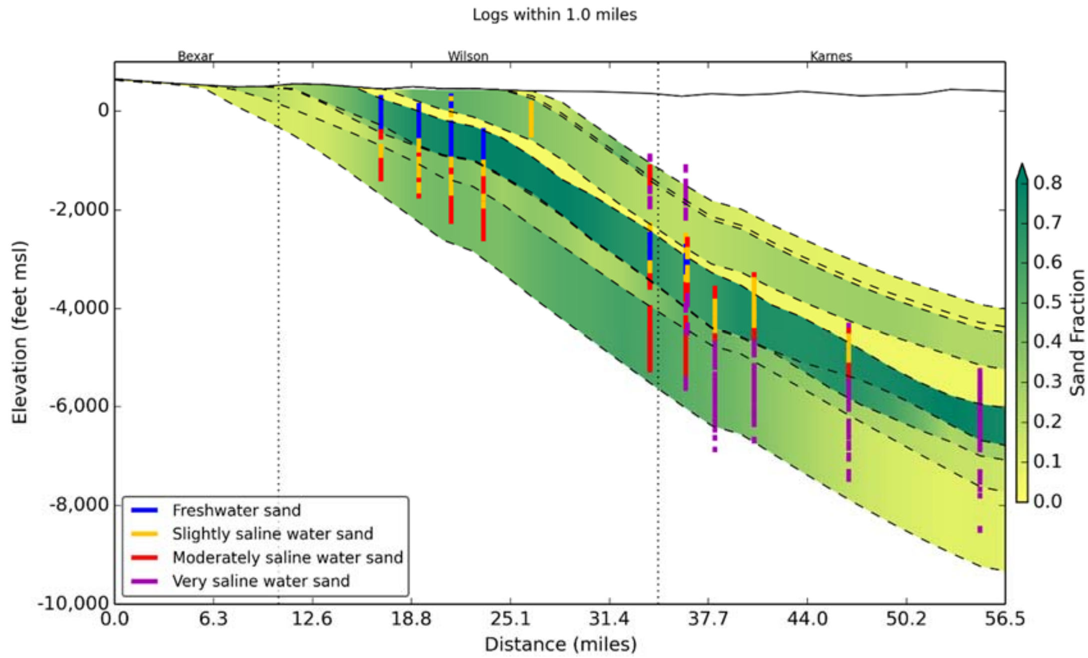


Figure 8-14. **Sample cross section generated by the Plot XS Profile Tool with the "display sand fraction" option toggled on.**

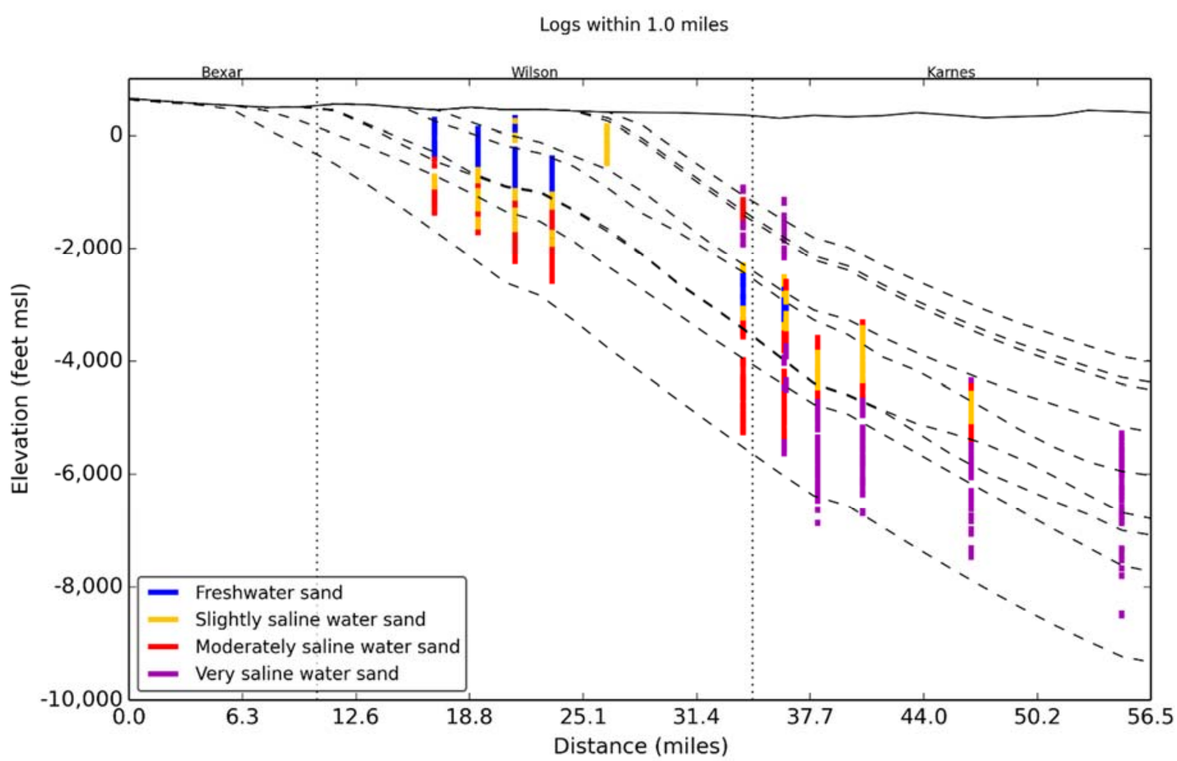


Figure 8-15. **Sample cross section generated by the Plot XS Profile Tool with the "display sand fraction" option toggled off.**

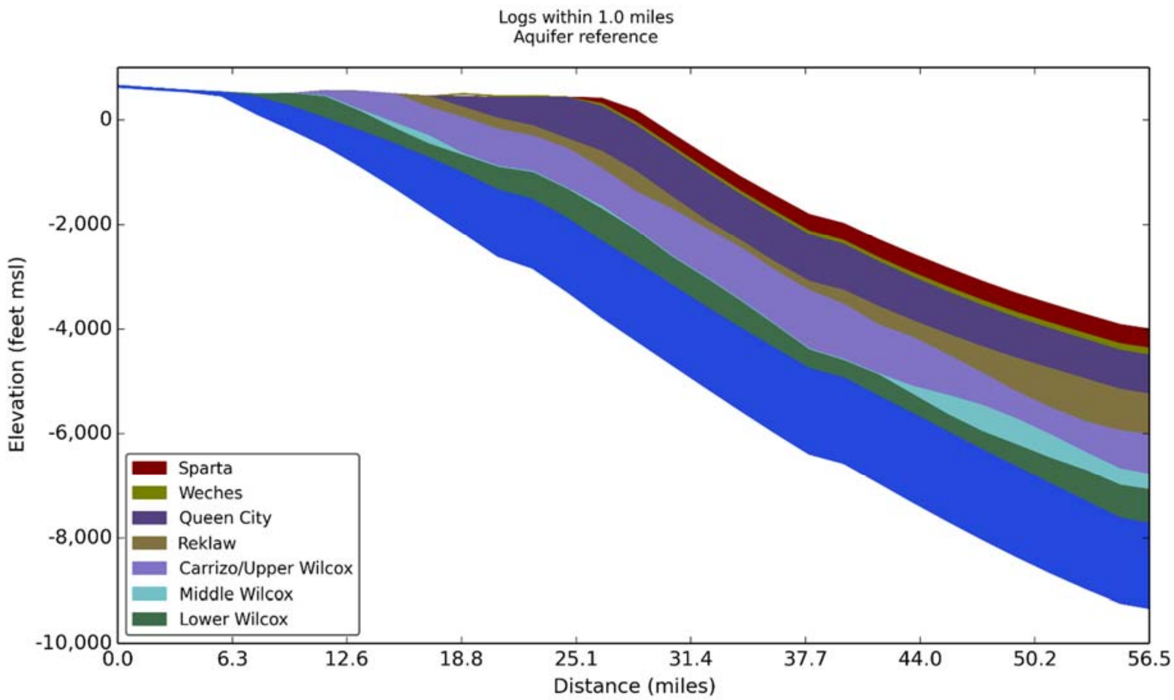


Figure 8-16. Sample cross section generated by the Plot XS Profile Tool that provides a color-coded key to the aquifer structure shown in Figures 8-14 and 8-15.

8.3.3 Estimation and Visualization of Brackish Sands by Depth

The "Brackish Estimator" tool generates sand fraction rasters by water quality type at user-designated depth intervals based on geophysical well log water quality picks. The tool also produces publication-ready figures displaying both the rasters and the points used to create the rasters. The user can designate the interpolation method used to create the rasters (Kriging, Spline or Inverse Distance Weighting) as well as define the interpolation parameters.

To run this tool, open the "brack_estimator.mxd" included in the Electronic Deliverable and open the "Brackish Estimator" tool through the ArcToolBox window. **** Note: This tool will NOT work unless opened within this ArcGIS map document.**

Inputs

The tool interface is shown in Figure 8-17 below, with inputs numbered in red:

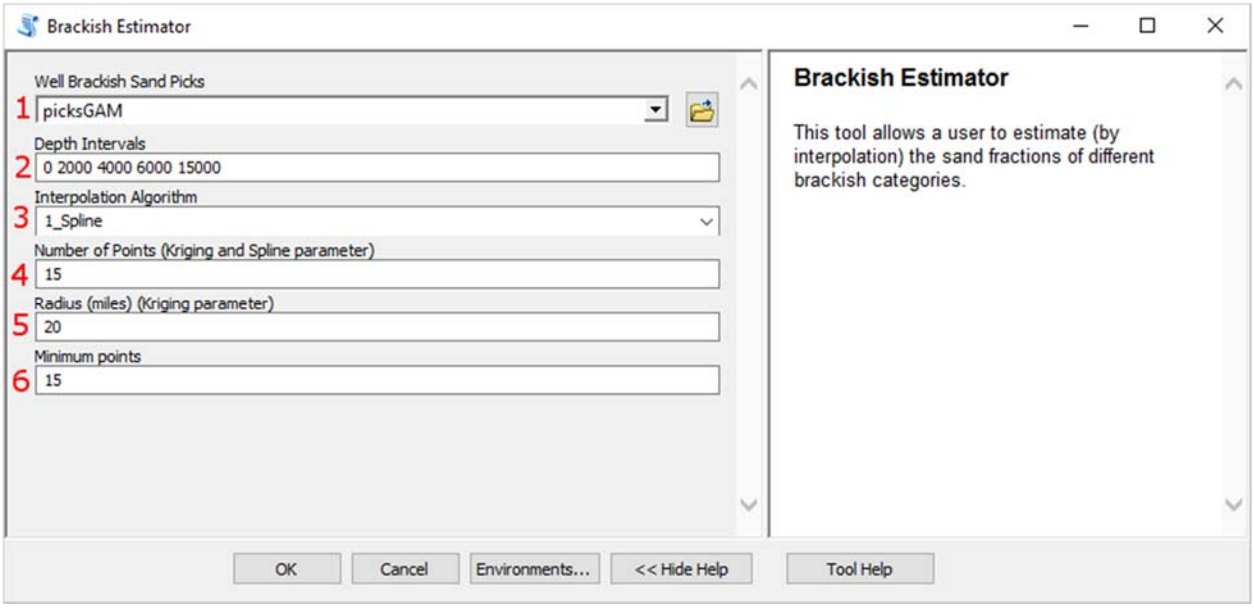


Figure 8-17. Screenshot of interface for Brackish Estimator Tool.

1. Point SHP file of the water quality and sand picks from the geophysical log analyses in GAM coordinates (*picksGAM.shp*), *as* generated by the Volume Calculator tool
2. User-specified depth intervals, entered as five numeric values separated by any number of blank spaces.
   *****Note: Given the pronounced dip orientation of the aquifers in this study, we recommend very large depth intervals so that the interpolation algorithm has a large enough number of points in a somewhat random spatial distribution.***
3. User-specified interpolation algorithm. The user can choose from three built-in ArcGIS interpolation algorithms: Spline, Kriging or Inverse Distance Weighting (IDW)
4. The number of points to be used for local approximation (when using Spline method) or within the search radius (when using Kriging method). This parameter is ignored when using the IDW interpolation method.
5. The search radius to be used (when using Kriging method). This parameter is ignored when using either the Spline or IDW interpolation method.
6. Minimum number of points necessary for creating a raster. For any combination of depth and sand type, if the number of selected points is less than this user-specified threshold, the tool will not perform the interpolation for the respective set of points.

Outputs

The "Brackish Estimator" tool generates the output files described below. The folders containing these output files are provided in the Electronic Deliverable as "*…\SandPlots\outputs\rasters*"

1. TIF files of sand fraction rasters by water quality type at user-designated depth intervals. The naming convention for these files is as follows: "*<interpolation method>_<min depth>_<max depth>_<water quality type>_<time stamp>.tif*"
   Example: "Kriging_0_2000_fws_153659.tif" is the freshwater sand fraction raster for the depth interval 0 to 2000 ft, created at 15:36:59 using the Kriging interpolation method.

2. PNG files of maps that display these sand fraction rasters over the area of interest. **Figure 7-3** shows an example map generated by the tool. This map was created using the Kriging interpolation option at the following user-designated depth intervals: 0 to 2,000 ft, 2,000 to 4,000 ft, 4,000 to 6,000 ft and 6,000 to 15,000 ft. While only the "very saline" map is shown, the tool does automatically generate similar maps for each water quality type.
3. MXD files of ArcMap map documents of the maps created. These allow the user to make manual adjustments if required.

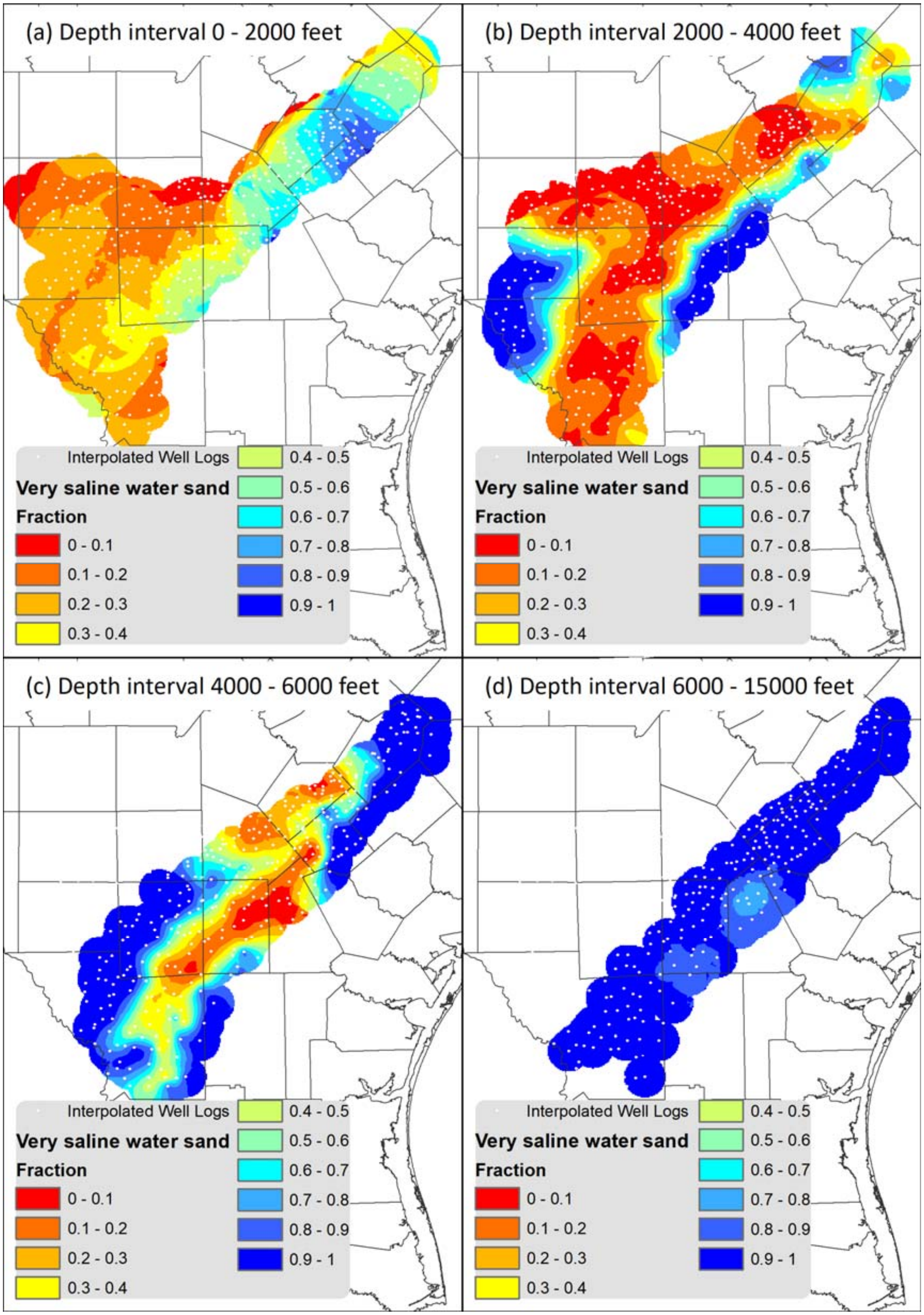


Figure 8-18. Example of map figure generated by Brackish Estimator Tool, showing the very saline sand fraction for the depth intervals noted and the wells used in the interpolation.

8.3.4 Visualization of Sand Fractions by Layer

The "Plot 2D Sand Fractions by Layer" tool produces publication-ready figures displaying the sand fraction rasters by water quality type for each of the 6 aquifers of interest (Sparta, Queen City, Carrizo, Upper Wilcox, Middle Wilcox, and Lower Wilcox).

To run this tool for the Carrizo-Wilcox aquifer units, open the "brack_viz_layers_czwx.mxd" included in the Electronic Deliverable and open the "Plot 2D Sand Fractions by Layer" tool through the ArcToolBox window. To run this tool for the Queen City-Sparta aquifer units, use the "brack_viz_layers_qcsp.mxd" map document instead. ***** Note: This tool will NOT work unless opened within one of these ArcGIS map documents.***

Inputs

The tool interface is shown in Figure 8-19 below, with inputs numbered in red:

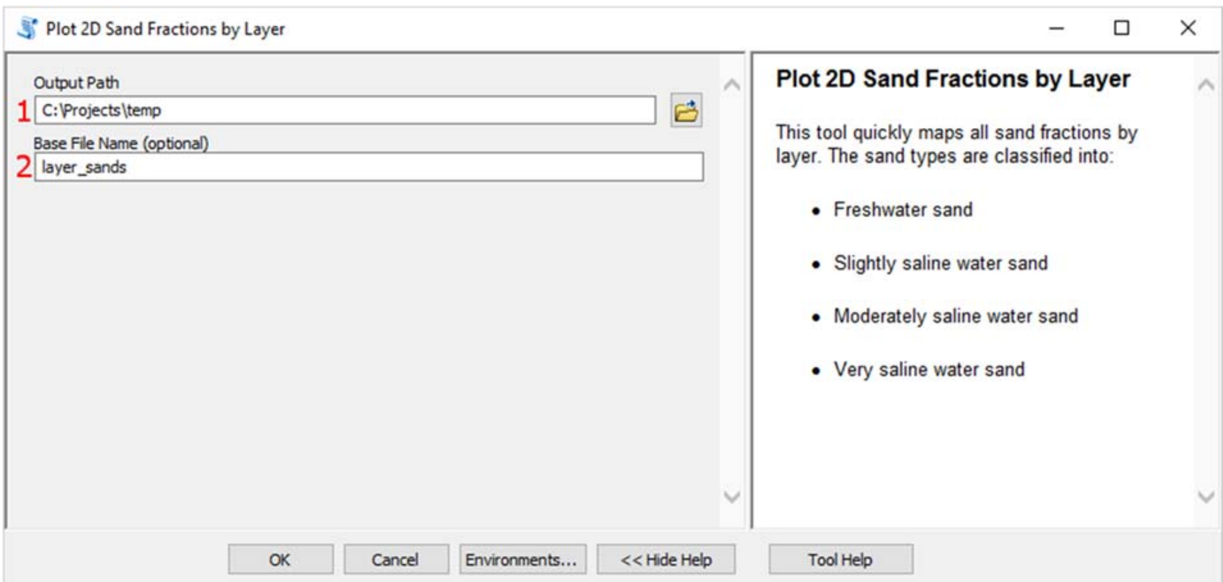


Figure 8-19. Screenshot of interface for Plot 2D Sand Fractions by Layer Tool.

1. The path to the output directory. All of the tool's outputs will be written to this directory.
2. Optional user-specified base file name for the resulting figures. Default (blank) results in generic file names beginning with "*czwx_sand_fractions_by_layer*" for Carrizo-Wilcox aquifer units or "*qcsp_sand_fractions_by_layer*" for Queen City – Sparta aquifer units. These file names will be suffixed with the following acronyms:
    a. fws: freshwater sand
    b. sss: slightly saline water sand
    c. mss: moderately saline water sand
    d. vss: very saline water sanOutputs

****Note: By default, the tool uses the sand fraction rasters saved in the folder "…*\SandPlots\inputs\ters_rasters*." If you re-ran the Volume Calculator tool, you will need to replace the rasters in this folder with your new sand fraction rasters. You can generate these**

new rasters by cropping the output TIFs (rasters) from the Volume Calculator tool to the appropriate active areas by layer.

Outputs

The “Brackish Estimator” tool generates the output files described below. The folders containing these output files are provided in the Electronic Deliverable as In the Electronic Deliverable, we have used the folder “…\SandPlots\outputs\SandPercByAq.”

PNG files of maps that display the rasters of sand percentages by water quality type over the area of interest. The Carrizo-Wilcox aquifer units (Carrizo, Upper Wilcox, Middle Wilcox, and Lower Wilcox) are mapped together and separately from the Queen City and Sparta aquifer units, which are mapped together. Figure 8-20 shows a sample map that the tool generated for the Carrizo-Wilcox aquifer units and Figure 8-21 shows a sample map for the Queen City and Sparta aquifer units. While these figures only show “freshwater sand,” the tool automatically generates maps for all the water quality types.

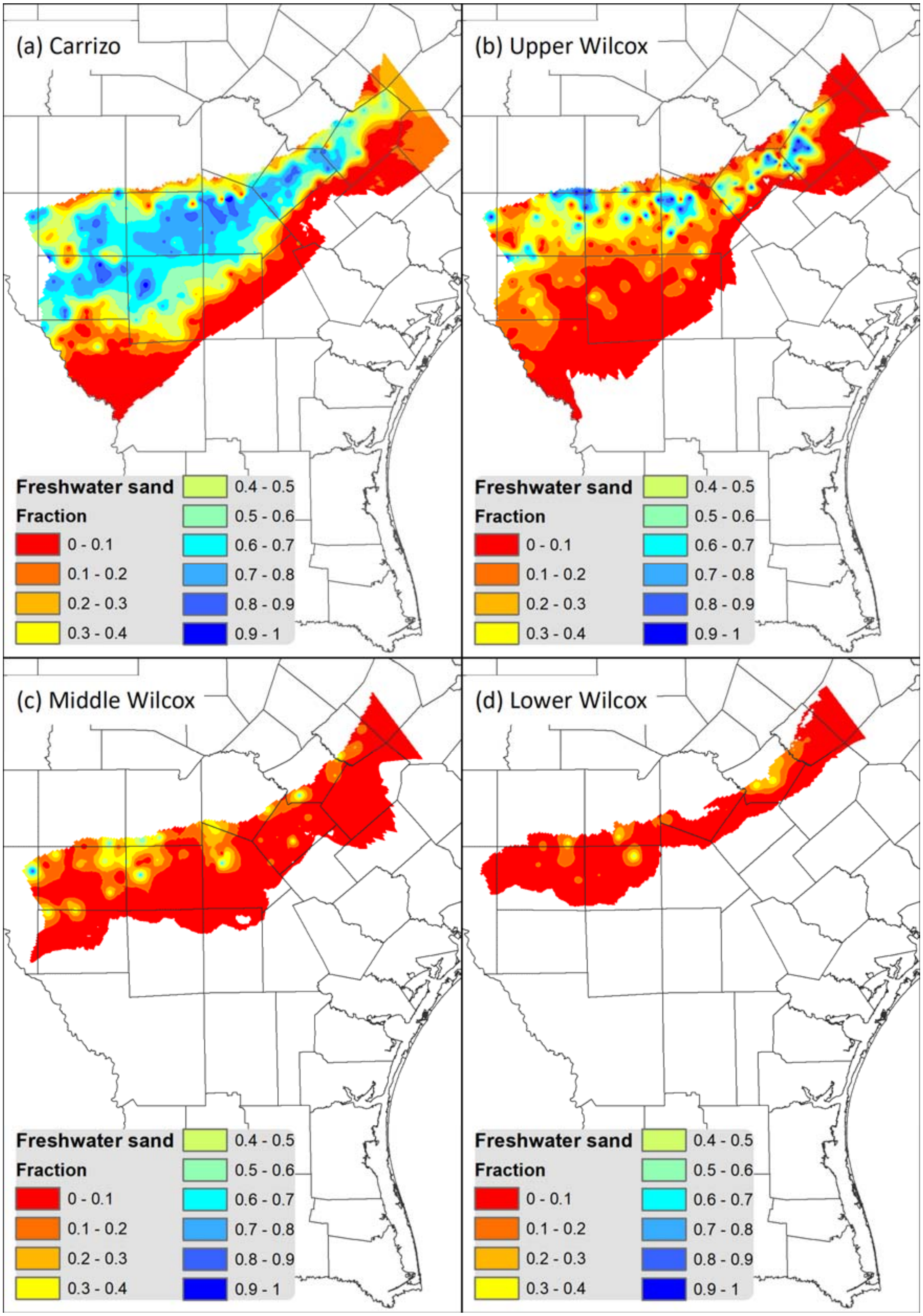


Figure 8-20. Example of map figure generated by the Plot 2D Sand Fractions by Layer Tool for the Carrizo-Wilcox aquifer units, displaying freshwater sand fractions.

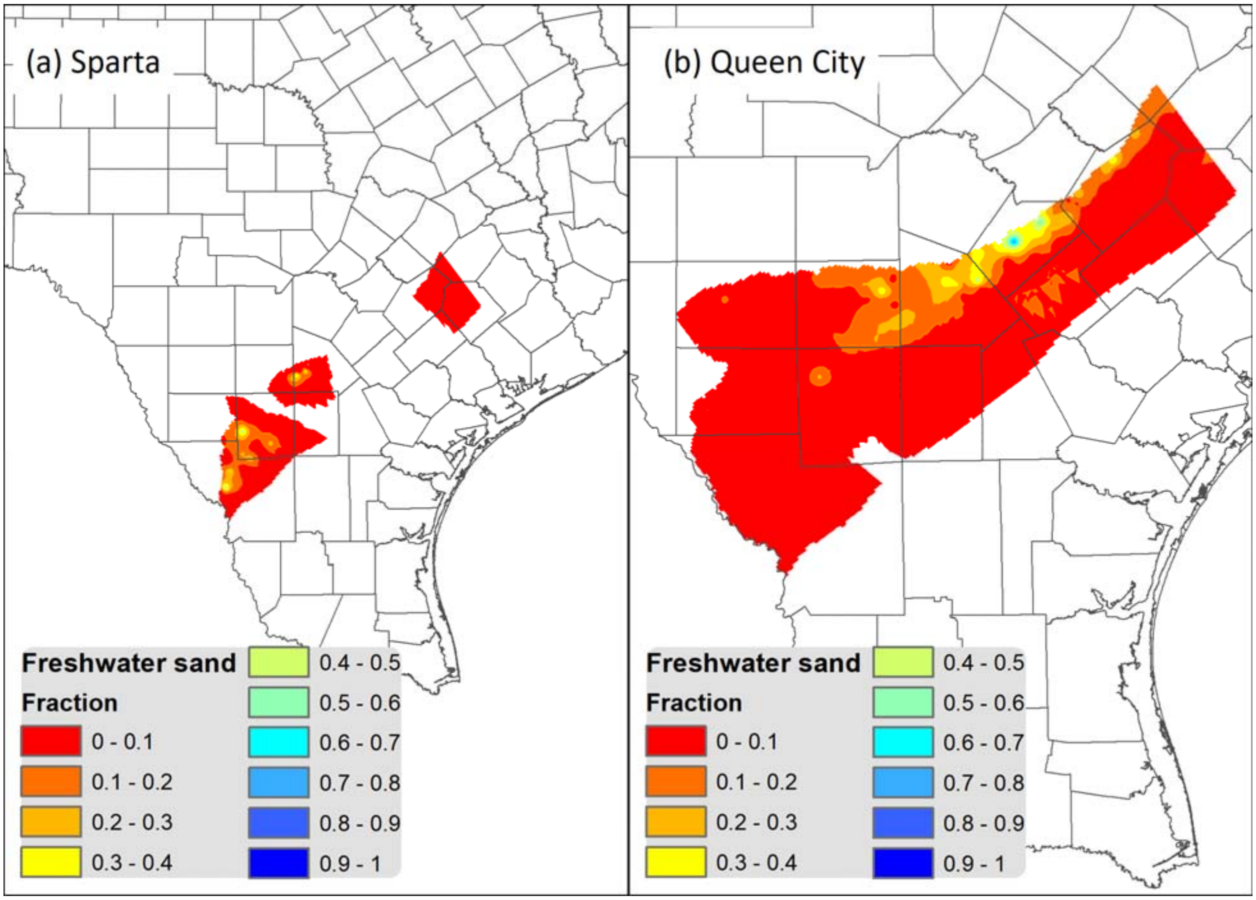


Figure 8-21. Example of map figure generated by the Plot 2D Sand Fractions by Layer Tool for the Queen City - Sparta aquifer units, displaying freshwater sand fractions.

9 Conclusions and Recommendations

Two potential production areas were delineated in the Carrizo-Wilcox Aquifer, and one in the Queen City- Sparta aquifers based on the application of an empirical approach to salinity mapping (total dissolved solids) from geophysical logs, which was in turn rooted in an understanding of the groundwater quality of these aquifers. These three potential production areas were selected based on the criteria listed in House Bill 30, which are as follows:

- These areas are separated by hydrogeologic barriers sufficient to prevent significant impacts to water availability or water quality in any area of the same or other aquifers, subdivisions of aquifers, or geologic strata that have an average total dissolved solids level of 1,000 milligrams per liter or less at the time of designation of the zones.
- Are not located in an area of the Edwards Aquifer subject to the jurisdiction of the Edwards Aquifer Authority, the boundaries of the Barton Springs-Edwards Aquifer Conservation District, the Harris-Galveston Subsidence District, or the Fort Bend Subsidence District.
- Are not located in an aquifer, subdivision of an aquifer, or geologic stratum that has an average total dissolved solids level of more than 1,000 milligrams per liter and is serving as a significant source of water supply for municipal, domestic, or agricultural purposes at the time of designation of the zones, or in an area of a geologic stratum that is designated or used for wastewater injection through the use of injection wells or disposal wells permitted under Chapter 27.

However, our detailed analyses indicated that complete isolation of the potential production areas is not possible because of one or more factors like the presence of freshwater sands in close proximity, the nature of local faults, and the interlayered and interfingered nature of the fresh and brackish groundwater sands in GMA 13. While none of the three delineated areas met all the requirements listed above, potential production area 1 in the Carrizo-Wilcox Aquifer seemed to be more favorable than the other two. This was based on potential production area 1 having better hydrogeologic barriers (such as the local shaly nature of the middle Wilcox), and the lack of associated faults (which, if present, might have increased the possibility of groundwater mixing). In the interest of showing details of our evaluation, and for possible future use of the findings by the TWDB, discussions on all three potential production areas have been included in this report.

Groundwater volumes were estimated for different groundwater quality classifications in the Carrizo-Wilcox, Queen City, and Sparta aquifers. The equations for calculating groundwater volumes require input values of aquifer properties for each aquifer, most of which were obtained from the GMA 13 Groundwater Availability Model for the respective aquifer. The groundwater volumes were calculated for both drainable unconfined storage and in-place unconfined storage – the former based on the specific yield values obtained from the Groundwater Availability Model, and the latter based on porosity values determined as part of this study.

The total Carrizo-Wilcox volume calculated for in-place unconfined storage is 4.9 billion acre-feet, or approximately 2.4 times greater than the total volume calculated using drainable unconfined storage (2.0 billion acre-feet). The total Sparta volume calculated for in-place unconfined storage is 1.5 billion acre-feet, or approximately 2.2 times greater than the total volume calculated using drainable unconfined storage (677 million acre-feet). The total Queen City volume calculated for in-place unconfined storage is 2.2 billion acre-feet, or approximately 2.2 times greater than the total volume calculated using drainable unconfined storage (974 million acre-feet). The sand fraction (groundwater contained in sand) is about 0.38 in the Carrizo-Wilcox Aquifer, 0.23 in the Sparta Aquifer and 0.33 in the Queen City Aquifer. The sand fraction values vary among the Carrizo-Wilcox aquifer units, ranging from 0.63 in the Carrizo Aquifer to 0.27 in the middle Wilcox Aquifer.

The volumes of fresh (TDS <1,000 mg/L), brackish (TDS = 1,000 – 10,000 mg/L), and very saline (TDS = 10,000 – 35,000 mg/L) groundwater in the Carrizo-Wilcox Aquifer calculated for drainable unconfined storage are 466 million acre-feet, 834 million acre-feet, and 744 million acre-feet, respectively. Of the Carrizo-Wilcox Aquifer units, the lower Wilcox Aquifer contains the most groundwater (35%). However, the majority of groundwater (66%) in this aquifer unit is very saline. Only about 23% of the groundwater in the Carrizo-Wilcox Aquifer is fresh water, and the majority of this fresh water occurs in the Carrizo Aquifer (73%). Brackish water (the sum of slightly saline and moderately saline water) makes up the majority of water in both the Sparta Aquifer (56%) and Queen City Aquifer (71%). Freshwater makes up very little of the remaining Sparta groundwater (9%), whereas very saline accounts for 35% of the total groundwater. The Queen City is fresher, with freshwater accounting for slightly more (15%) of the total groundwater than very saline water (14%).

Groundwater models were developed and applied to simulate changes in groundwater levels caused by pumping from two potential production areas in the Carrizo-Wilcox Aquifer, and one in the Queen City and Sparta aquifers. The primary objective for the modeling is to provide the TWDB with sufficient information to determine the amount of brackish groundwater that a potential production area can produce over a 30 and 50-year period without causing a significant impact to water availability. The groundwater models were used to simulate pumping at 5,000, 15,000, and 30,000 acre-feet per year for 50 years at four hypothetical well fields in two potential production areas in the Carrizo-Wilcox Aquifer. For the Queen City Aquifer, groundwater models simulated pumping at 2,000, 6,000, and 10,000 acre-feet per year for 50 years at two hypothetical well fields in one potential production area; the same was simulation was performed for the Sparta Aquifer. For all groundwater model simulations, drawdowns were tabulated after 30 years and 50 years of pumping at hypothetical monitoring wells located in the fresh water zones and/or up dip regions of the pumped aquifer. For most of the monitoring locations, the amount of drawdown is a linear function of the pumping rate at a well field, and once this relationship is established using information provided in the report, it can be used to calculate the pumping rate that would cause a specific drawdown amount at a specific monitoring well location. Besides tabulation of drawdown values, plots of drawdown for elapsed times of 5 years, 10 years, 30 years, and 50 years have been shown.

The primary recommendation is that additional hydraulic data is gathered in the brackish groundwater zones and new groundwater models are developed that are constrained by the measured aquifer properties and calibrated to measured water levels.

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Appendix A: Existing Groundwater Sources in the Potential Production Areas

Three databases were referenced for information regarding existing groundwater wells located in the PPA regions, including the TWDB groundwater database, the Texas Department of Licensing and Regulation (TDLR) Submitted Drillers Reports (SDR) database, and the Texas Commission on Environmental Quality (TCEQ) Public Water Supply (PWS) database. For this analysis, shapefiles of groundwater wells that were available on-line on March 9, 2018 were used respectively of the TWDB groundwater database (http://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp) and the TDLR SDRDB database (http://www.twdb.texas.gov/groundwater/data/drillersdb.asp), while a version of the PWS database provided by the TCEQ in July 2018 was used. Wells in the TWDB and TCEQ databases have aquifer information while the TDLR database does not.

For this analysis, only water wells with municipal, domestic or irrigation uses, or proposed uses in the case of the TDLR database, are included. Further, well status information was available in the TWDB and TCEQ databases and wells that were listed as not currently supplying water, i.e. have been plugged, abandoned, destroyed, etc., are not included in this analysis. Where identifiable, overlap between the TWDB and TCEQ databases is reported here under the TWDB database results. Well data in the TDLR database do not have attributes to indicate if any of those wells are also in either of the other databases so there may be some overlap between this and the other two databases.

Results indicate there are collectively 1,045 groundwater wells among the use categories in interest that are located in the PPA regions. In the Carrizo-Wilcox PPAs there are 625 wells and 336 wells in PPA1 and PPA2, respectively, and in the Queen City-Sparta PPA there are 84 wells (Table 1). Of these, collectively 562 (54%) are from the TDLR database and do not have associated aquifer name information.

In the Carrizo-Wilcox PPA #1, most wells (401, 64%) are domestic wells, followed by irrigation wells (181, 29%) and municipal wells (43, 7%) (Table 1). Of the wells with aquifer data, 174 (69%) are completed in the Carrizo Sand and 66 (26%) are completed in the Queen City or Sparta (Table 2). All municipal wells are completed in the Carrizo Sand or the Queen City, most domestic wells (86%) are completed in the Carrizo Sand, Queen City, or Sparta, and most irrigation wells (84%) are completed in the Carrizo Sand (Table 2).

In the Carrizo-Wilcox PPA #2, most wells (179, 53%) are irrigation wells, followed by domestic wells (147, 44%) and municipal wells (11, 3%) (Table 1). Of the wells with aquifer data, 160 (84%) are completed in the Carrizo Sand and 18 (9%) are completed in the Queen City or Sparta (Table 2). All municipal wells are completed in the Carrizo Sand, most domestic wells (76%) are completed in the Carrizo Sand, Queen City, or Sparta, and most irrigation wells (96%) are completed in the Carrizo Sand (Table 2).

In the Queen City-Sparta PPA, most wells (58, 69%) are domestic wells, followed by irrigation wells (15, 18%) and municipal wells (11, 13%) (Table 1). Of the wells with aquifer data, 21 (72%)

are completed in the Carrizo Sand and 4 (14%) are completed in the Queen City (Table 2). Most municipal wells (90%) are completed in the Carrizo Sand, most domestic wells (79%) are completed in the Carrizo Sand or Queen City, and most irrigation wells (91%) are completed in the Carrizo Sand (Table 2).

Table 1. Numbers of wells in the groundwater well databases by well use in each of the PPA regions.

PPA	*Well Use*	*Database*			
		TWDB	*TCEQ**	*TDLR*	*All*
Carrizo-Wilcox PPA #1	Municipal	34	3	6	43
	Domestic	83	-	318	401
	Irrigation	137	-	44	181
	All	254	3	368	625
Carrizo-Wilcox PPA #2	Municipal	6	3	1	10
	Domestic	41	-	106	147
	Irrigation	140	-	39	179
	All	187	3	146	336
Queen City-Sparta PPA	Municipal	4	7	-	11
	Domestic	14	-	44	58
	Irrigation	11	-	4	15
	All	29	7	48	84

*Uniquely in the TCEQ PWS database, excludes overlap with the TWDB database.

Table 2. Numbers of wells by use category by aquifer in each PPA for the TWDB and TCEQ databases.

PPA	*Aquifer*	*Well Use*			
		Municipal	*Domestic*	*Irrigation*	*All*
Carrizo-Wilcox PPA #1	Wilcox	-	1	-	1
	Carrizo-Wilcox	-	1	-	1
	Carrizo Sand	24	36	115	174
	Jackson	-	8	2	10
	Yegua	-	1	-	1
	Queen City	13	25	18	54
	Sparta	-	10	2	12
	Cook Mountain	-	1	-	1
	All	37	83	137	254
Carrizo-Wilcox PPA #2	Carrizo Sand	9	17	134	160
	Queen City	-	8	3	11
	Sparta	-	6	1	7
	Cook Mountain	-	3	-	3
	Laredo	-	7	1	8
	Unknown	-	-	1	1
	All	9	41	140	190
Queen City-Sparta PPA	Alluvium	-	1	-	1
	Carrizo Sand	9	8	10	21
	Yegua	-	2	-	2
	Queen City	-	3	1	4
	Bigford	1	-	-	1
	All	10	14	11	29

Appendix B: Data Deliverables (on DVD)

B.1 GMA 13 BRACS Tables

tbl_Bracs_ForeignKey.xlsx
tblBracs_Ro_TDS_Main.xlsx
tblBracs_TDS_Well.xlsx
tblBracsInfrequentConstituents.xlsx
tblBracsWaterQuality.xlsx
tblBRACSWaterWellReports.xlsx
tblGeophysicalLog_Header.xlsx
tblGeophysicalLog_Porosity.xlsx
tblGeophysicalLog_Suite.xlsx
tblWell_Geology.xlsx
tblWell_Location.xlsx

B.2 Raster and Depth Calibration Files

612 geophysical log raster images
612 geophysical log depth calibration files
1 geophysical digital log LAS files for Well ID 77010
Excel list of folder contents

B.3 Aquifer Test Data

BRACS_format_INTERA_K_values.xlsx
Copies of Submitted Drillers Reports in PDF format

B.4 GIS Data

Procedural Overview

An overall two-stage process was used to generate the formation surface and water quality depth maps. In Stage 1, the well log depth picks were converted from depth values to elevations relative to mean sea level. The top and bottom formation surface elevation maps were then created using kriging methods. The respective top and bottom surfaces were inspected for internal consistency by subtraction of the bottom from top elevations to obtain formation thickness maps. Regions of negative thickness were adjusted. Negative thickness results from kriging the surfaces independently using different semivariogram models as tailored to each separate surface data set and in some cases the well log populations are also different for the different surfaces.

In Stage 2, the top and bottom elevation maps were converted to depths by subtraction from the ground surface elevation. These operations created a second round of adjustments imposed by local surface topography in up-dip areas near the outcrops that are not captured by the relatively low density well log point network.

Data preparation

There are 589 well logs with formation depth picks and 532 well logs with water quality thicknesses. All depths were converted to elevations. The ground surface elevation at each well log location was extracted from a 90m Digital Elevation Model (DEM) grid with integer meter elevation values that were converted to the nearest integer foot elevation value (STRM, Shuttle Radar Topography Mission, https://cgiarcsi.community/data/srtm-90m-digital-elevation-database-v4-1/). There is Kelly bushing (KB) and/or drill floor (DF) height information available for 516 (88%) of the wells. The well log depth-reference elevations were determined as either the KB or DF heights above ground surface added to the DEM elevation. The KB/DF heights generally ranged from 0 to 35 ft. For the remaining 73 wells having neither height available, the depth-reference elevation was set to a value of 12 ft above the DEM elevation, representing the median value for wells having KB or DF heights.

An additional 438 point elevations located along the intersections of the DEM with the Sparta, Queen City, and Upper Wilcox aquifer outcrop areas were incorporated into the raw surface point elevation data sets to provide supplemental control on formation surface elevations in these areas. The final Carrizo-Wilcox maps do not extend into the outcrop as there was no well log control in that area. The final Sparta maps do not extend into the outcrop as there was extremely limited data in that area. The Queen City has sufficient well logs located in the outcrop judged sufficient to justify the mapping requirements and the Queen City bottom surface map includes this area. Additionally, the Queen City and Sparta aquifer outcrops proper do not extend west of the Frio River. In this region, the extents of the assumed stratigraphic equivalents for the Queen City and Sparta top surfaces were clipped at the boundaries where the respective kriged surfaces intersected the DEM surface.

A single supplemental elevation point located at the far northeast extent of the Carrizo-Wilcox outcrop in GMA 13 was added to the data set to provide control on the elevations of the Carrizo-Wilcox formation surfaces by assigning formation surface elevations at that point based on thicknesses measured in nearby well logs.

Finally, the log pick depths were subtracted from the depth-reference elevation to obtain formation or water quality surface elevations. All elevations were then biased by upward by 20,000 ft so that all values were positive during the kriging procedures described below.

Kriging procedures

Surfaces elevation coverages for the tops and bottoms of each formation and water quality surface interval were generated using Empirical Bayesian Kriging with K-Bessel detrended semivariograms using routines in the Geostatistical Analyst extension of ArcMap ver. 10.3.1 software. Log-empirical data transformation was used for the formation surface data and empirical data transformation was used for water quality surface data. All other kriging parameters were left at their automated default values as determined by the software. The resulting kriged surfaces were converted to 500 m integer value grids and restored to actual elevation values by subtracting the 20,000 ft bias.

<u>Stratigraphic top and bottom surface depth GIS files</u>

The kriged formation elevation surfaces were used to calculate intermediate formation thickness maps that were inspected for negative values. Negative thickness values were locally present in all formations above the Carrizo-Wilcox, i.e., the Reklaw, Queen City, Wenches, and Sparta formations. Negative thickness values generally occurred in areas between or beyond the spatial extents of the well log locations and also in small regions adjacent to outcrop areas. Adjustments were made to the kriged surface elevation grids by imposing minimum thickness values for each formation as outlined in this work-flow sequence summary:

- Localized down-dip areas of the Sparta bottom surface elevation were adjusted downward to accommodate a minimum 20 ft thickness of the Sparta.
- Localized up-dip areas of the Queen City bottom surface elevation were adjusted downward to accommodate a minimum 10 ft thickness of the Queen City.
- Localized areas of the Sparta bottom surface elevation were adjusted upward to accommodate a minimum thickness of 35 ft for the Wenches Formation.
- No adjustments were necessary for any Wilcox formation surfaces.

All formation surface elevation maps were then converted to equivalent depth maps by subtraction from the ground surface DEM. Similar to the initial kriging results, small regions adjacent to the outcrops of some maps had negative depth values (i.e., elevations above ground surface). Another round of adjustments were made to the surface depths as outlined below.

- Localized up-dip areas along the outcrop of the Sparta bottom surface depth were adjusted downward to a minimum 20 ft depth.
- Localized up-dip areas along the outcrop of the Queen City top surface depth were adjusted to a minimum 20 ft depth and localized up-dip areas along the outcrop of the Queen City bottom surface depth were adjusted to accommodate a minimum 10 ft depth.
- Localized areas along the entirety of the outcrop area of the Carrizo-Upper Wilcox top surface depth were adjusted to a minimum depth of 10 ft.
- No adjustments were made to the Middle and Lower Wilcox formation depths.

Table B4-1. Formation surface depth kriging results summary for the Sparta (Sp), Queen City (QC), and the Upper (UW), Middle (MW), and Lower (LW) Wilcox. The numbers of model points based on the well logs (Log) and the outcrop (OC) areas, where used, are given. All semivariograms use the Stable model.

Surface	*Points*		*General Properties*			*Search Neighborhood*						*Prediction Error*		
	Well Logs	*OC*	*Subset size*	*Overlap factor*	*Number of Simulations*	*Search Type*	*Maximum Neighbors*	*Minimum Neighbors*	*Sector type*	*Angle (deg)*	*Radius (ft)*	*Mean (ft)*	*RMS (ft)*	*Avg. SE (ft)*
Sp Top	304	98	100	1	100	Std. Circular	15	10	1 Sector	0	41,002	-1.6	139	136
Sp Base	319	55									49,730	0.1	153	161
QC Top	424	96									37,822	-2.4	133	139
QC Base	427	64									47,831	0.0	160	157
UW Top	576	125									40,226	-3.1	137	140
MW Top	395	1*									51,445	0.9	166	161
LW Top	394	1*									52,060	1.7	212	199
LW Base	376	1*									52,494	3.4	198	192

*Supplemental point

Salinity zone top and bottom depth GIS files

The water quality depth maps represent the shallowest and deepest occurrences of the various water quality types. The maps represent the depths for each water quality type in the combined Queen City-Sparta system and in the combined Carrizo-Wilcox system (Upper, Middle, and Lower units).

Polygons representing the lateral extents of the various water quality types for each aquifer system were interpreted manually to approximately encompass the areas where the well log point network indicates the presence of a given water quality. In some instances, the polygons do not include "outlier" points where the given water quality extents were interpreted to be limited. Limited adjustments were made to some polygons to remove areas that had interpolated surface depths judged to be significantly above or below the formation depth.

The kriged water quality depth surfaces must be treated independently because of overlaps between the shallowest and deepest occurrences of the various water quality depth intervals. The only adjustments made to the kriging results for these coverages resulted from comparison of the various water quality surface elevations with the DEM and also with their respective formation top and bottom depth surfaces as appropriate. Kriged surface areas that strayed above the DEM were set to a minimum depth based on nearby non-negative values, generally ranging from 10 to 50 ft and associated with topographic lows. Kriged water quality surface areas that strayed above or below their respective formation top or bottom surface depths in sub-crop areas were adjusted to equal the respective formation top or bottom surface depth. Finally, the top and bottom water quality surface depths were compared and regions where thickness was less than zero were changed to null values.

The semivariograms and prediction error parameters for the salinity zone surfaces are summarized in **Table B4-2** and **Table B4-3** for the Queen City-Sparta and Carrizo-Wilcox salinity zone depth maps, respectively.

Table B4-2. Salinity zone depth kriging results summary for the Queen City-Sparta. The numbers of model points based on the well logs are given. All semivariograms use the K-Bessel Detrended model with Log Empirical data transformation. The surfaces represent the shallowest (Top) and deepest (Base) occurrences of fresh water (FR; <1,000 mg/L TDS), slightly saline water (SS; 1,000-3,000 mg/L TDS), moderately saline water (MS; 3,000-10,000 mg/L TDS), and very saline water (VS; 10,000-35,000 mg/L TDS).

Surface	*Well Logs*	*General Properties*			*Search Neighborhood*						*Prediction Error*		
		Subset size	*Overlap factor*	*Number of Simulations*	*Search Type*	*Maximum Neighbors*	*Minimum Neighbors*	*Sector type*	*Angle (deg)*	*Radius (ft)*	*Mean (ft)*	*RMS (ft)*	*Avg. SE (ft)*
FR Top	97	100	1	100	Std. Circular	15	10	1 Sector	0	75,735	9.1	376	365
FR Base											4.6	254	191
SS Top	207									67,255	2.6	397	398
SS Base											4.2	349	312
MS Top	232									67,994	4.1	269	264
MS Base											7.0	333	334
VS Top	168									86,269	29.7	360	355
VS Base											13.0	491	456

Table B4-3. Salinity zone depth kriging results summary for the Carrizo-Wilcox. The numbers of model points based on the well logs are given. All semivariograms use the K-Bessel Detrended model with Log Empirical data transformation. The surfaces represent the shallowest (Top) and deepest (Base) occurrences of fresh water (FR; <1,000 mg/L TDS), slightly saline water (SS; 1,000-3,000 mg/L TDS), moderately saline water (MS; 3,000-10,000 mg/L TDS), and very saline water (VS; 10,000-35,000 mg/L TDS).

Surface	*Well Logs*	*General Properties*			*Search Neighborhood*						*Prediction Error*		
		Subset size	*Overlap factor*	*Number of Simulations*	*Search Type*	*Maximum Neighbors*	*Minimum Neighbors*	*Sector type*	*Angle (deg)*	*Radius (ft)*	*Mean (ft)*	*RMS (ft)*	*Avg. SE (ft)*
FR Top	237	100	1	100	Std. Circular	15	10	1 Sector	0	72,387	5.5	142	146
FR Base											-0.3	135	141
SS Top	300									59,116	7.8	263	271
SS Base											7.1	367	401
MS Top	326									56,211	-2.4	363	370
MS Base											-2.0	407	477
VS Top	240									58,492	11.4	409	371
VS Base											0.1	393	391

<u>Sand thickness GIS files</u>

Net sand thickness values maps were also generated using Empirical Bayesian Kriging but with empirical data transformation rather than log empirical data transformation. The maps include net total sand thickness, net fresh water sand thickness, slightly saline water sand thickness, moderately saline water sand thickness, and very saline water sand thickness, and percent sand (i.e., total sand thickness divided by total formation thickness, expressed as a percentage) for each stratigraphic unit.

Each of the net sand thickness maps is a stand-alone product generated from the well log point network. They are not internally consistent for a given formation due to the nature of the kriging interpolation process. The result is that a set of the net sand water quality thickness maps cannot be summed to reproduce the associated total net sand thickness map, nor can the percent sand thickness map be generated by comparing the total net sand thickness to total formation thickness derived from the formation depth maps.

The model semivariogram and prediction error parameters are summarized in **Table B4-4** through **Table B4-8** for the Sparta, Queen City, and the Upper, Middle and Lower Carrizo-Wilcox sand maps, respectively.

Table B4-4. Sand thickness kriging results summary for the Sparta. All semivariograms use the Stable model. The results represent the net formation sand thickness (NS), the percent of the total formation thickness that is sand (PS), and the total formation thicknesses of sands bearing fresh water (FR; <1,000 mg/L TDS), slightly saline water (SS; 1,000-3,000 mg/L TDS), moderately saline water (MS; 3,000-10,000 mg/L TDS), and very saline water (VS; 10,000-35,000 mg/L TDS).

Surface	*Well Logs*	*General Properties*			*Search Neighborhood*						*Prediction Errors*		
		Subset size	*Overlap factor*	*Number of Simulations*	*Search Type*	*Maximum Neighbors*	*Minimum Neighbors*	*Sector type*	*Angle (deg)*	*Radius (ft)*	*Mean (ft)*	*RMS (ft)*	*Avg. SE (ft)*
NS	302	100	1	100	Std. Circular	15	10	1 Sector	0	56,859	-0.1	31	30
PS*											0.3	16	16
FR											-2.8	23	9
SS											-2.8	27	18
MS											-0.7	26	28
VS											-2.6	19	16

*Prediction Error units are in %

Table B4-5. Sand thickness kriging results summary for the Queen City. All semivariograms use the Stable model. The results represent the net formation sand thickness (NS), the percent of the total formation thickness that is sand (PS), and the total formation thicknesses of sands bearing fresh water (FR; <1,000 mg/L TDS), slightly saline water (SS; 1,000-3,000 mg/L TDS), moderately saline water (MS; 3,000-10,000 mg/L TDS), and very saline water (VS; 10,000-35,000 mg/L TDS).

Surface	*Well Logs*	*General Properties*			*Search Neighborhood*						*Prediction Errors*		
		Subset size	*Overlap factor*	*Number of Simulations*	*Search Type*	*Maximum Neighbors*	*Minimum Neighbors*	*Sector type*	*Angle (deg)*	*Radius (ft)*	*Mean (ft)*	*RMS (ft)*	*Avg. SE (ft)*
NS	424	100	1	100	Std. Circular	15	10	1 Sector	0	51,264	2.5	132	139
PS*											92.7	4851	1223
FR											-5.1	51	44
SS											-10.0	105	101
MS											-4.6	133	133
VS											-8.7	103	92

*Prediction Error units are in %

Table B4-6. Sand thickness kriging results summary for the Upper Wilcox. All semivariograms use the K-Bessel Detrended model and Empirical data transformation. The results represent the net formation sand thickness (NS), the percent of the total formation thickness that is sand (PS), and the total formation thicknesses of sands bearing fresh water (FR; <1,000 mg/L TDS), slightly saline water (SS; 1,000-3,000 mg/L TDS), moderately saline water (MS; 3,000-10,000 mg/L TDS), and very saline water (VS; 10,000-35,000 mg/L TDS).

Surface	*Well Logs*	*General Properties*			*Search Neighborhood*						*Prediction Errors*		
		Subset size	*Overlap factor*	*Number of Simulations*	*Search Type*	*Maximum Neighbors*	*Minimum Neighbors*	*Sector type*	*Angle (deg)*	*Radius (ft)*	*Mean (ft)*	*RMS (ft)*	*Avg. SE (ft)*
NS	392	100	1	100	Std. Circular	15	10	1 Sector	0	51,445	-7.9	182	198
PS*											-0.9	19	21
FR											-15.2	146	156
SS											-4.0	121	114
MS											-7.1	110	98
VS											-11.8	114	91

*Prediction Error units are in %

Table B4-7. Sand thickness kriging results summary for the Middle Wilcox. All semivariograms use the K-Bessel Detrended model and Empirical data transformation. The results represent the net formation sand thickness (NS), the percent of the total formation thickness that is sand (PS), and the total formation thicknesses of sands bearing fresh water (FR; <1,000 mg/L TDS), slightly saline water (SS; 1,000-3,000 mg/L TDS), moderately saline water (MS; 3,000-10,000 mg/L TDS), and very saline water (VS; 10,000-35,000 mg/L TDS).

Surface	*Well Logs*	*General Properties*			*Search Neighborhood*						*Prediction Errors*		
		Subset size	*Overlap factor*	*Number of Simulations*	*Search Type*	*Maximum Neighbors*	*Minimum Neighbors*	*Sector type*	*Angle (deg)*	*Radius (ft)*	*Mean (ft)*	*RMS (ft)*	*Avg. SE (ft)*
NS	394	100	1	100	Std. Circular	15	10	1 Sector	0	52,060	-0.4	60	62
PS*											-0.1	11	11
FR											-1.8	17	9
SS											-2.9	36	33
MS											-2.8	45	43
VS											-3.6	52	48

*Prediction Error units are in %

Table B4-8. Sand thickness kriging results summary for the Lower Wilcox. All semivariograms use the K-Bessel Detrended model and Empirical data transformation. The results represent the net formation sand thickness (NS), the percent of the total formation thickness that is sand (PS), and the total formation thicknesses of sands bearing fresh water (FR; <1,000 mg/L TDS), slightly saline water (SS; 1,000-3,000 mg/L TDS), moderately saline water (MS; 3,000-10,000 mg/L TDS), and very saline water (VS; 10,000-35,000 mg/L TDS).

Surface	*Well Logs*	*General Properties*			*Search Neighborhood*						*Prediction Errors*		
		Subset size	*Overlap factor*	*Number of Simulations*	*Search Type*	*Maximum Neighbors*	*Minimum Neighbors*	*Sector type*	*Angle (deg)*	*Radius (ft)*	*Mean (ft)*	*RMS (ft)*	*Avg. SE (ft)*
NS	376	100	1	100	Std. Circular	15	10	1 Sector	0	52,494	3.7	190	186
PS*											-0.2	16	16
FR											-0.6	11	3
SS											-15	95	76
MS											-11	157	134
VS											-10	168	199

*Prediction Error units are in %

Geodatabase

All GIS datasets were developed using ESRI ArcMap Ver. 10.3.1 software. All datasets use the Texas State Mapping System Albers Equal Area projection with units in US feet and projection parameters consistent with Texas Groundwater Availability Model (GAM) requirements.

Table B4-9. List of geodatabase Feature Datasets including polygon (P) and point (Pnt) Feature Classes.

Feature Dataset	*Feature Class*	*Type*	*Contents*
Boundaries1_CarrizoWilcox	CZWX_clip	P	Extent of Carrizo-Wilcox aquifer
	CZWX_u_clip	P	Extent of the Carrizo-Wilcox in the southern region
	CZWX _fr_clip	P	Extent of Carrizo-Wilcox fresh water
	CZWX _ss_clip	P	Extent of Carrizo-Wilcox slightly saline water
	CZWX _ms_clip	P	Extent of Carrizo-Wilcox moderately saline water
	CZWX _vs_clip	P	Extent of Carrizo-Wilcox very saline water
Boundaries2_QzueenCitySparta	QC_t_clip	P	Extent of Queen City aquifer top surface
	QC_b_clip	P	Extent of Queen City aquifer bottom surface
	Sparta_clip	P	Extent of Sparta aquifer top surface
	QCSP_fr_clip	P	Extent of Queen City-Sparta fresh water
	QCSP _ss_clip	P	Extent of Queen City-Sparta slightly saline water
	QCSP _ms_clip	P	Extent of Queen City-Sparta moderately saline water
	QCSP _br_clip	P	Extent of Queen City-Sparta brackish water

Feature Dataset	*Feature Class*	*Type*	*Contents*
	QCSP _vs_clip	P	Extent of Queen City-Sparta very saline water
Boundaries3_GAT	Bigford_GAT	P	Extent of Bigford Formation outcrop from the GAT
	ElPicoClay_GAT	P	Extent of El Pico Clay outcrop from the GAT
	Laredo_GAT	P	Extent of Laredo Formation outcrop from the GAT
Wells	SWD	Pnt	Locations of Salt Water Disposal wells in GMA 13
	WellLog_SalinityDepths	Pnt	Locations and well log salinity zone depths
	WellLog_SandThickness	Pnt	Locations and well log sand thicknesses
	WellLog_StratDepths	Pnt	Locations and well log stratigraphic depths
DEM	dem_gma13_ft	GeoTif	STRM Digital Elevation Model of study area region

Table B4-10. List of geodatabase Raster Catalogs and included raster data sets

Raster Catalog	*Raster*	*Contents*
Stratigraphy1_CarrizoWilcox	uw_t_d_ebk	Depth to the top of the Upper Wilcox Formation
	mw_t_d_ebk	Depth to the top of the Middle Wilcox Formation
	lw_t_d_ebk	Depth to the top of the Lower Wilcox Formation
	lw_b_d_ebk	Depth to the bottom of the Lower Wilcox Formation
Stratigraphy2_QueenCity	qc_t_d_ebk	Depth to the top of the Queen City Formation
	qc_b_d_ebk	Depth to the bottom of the Queen City Formation
Stratigraphy3_Sparta	sp_t_d_ebk	Depth to the top of the Sparta Formation
	sp_b_d_ebk	Depth to the bottom of the Sparta Formation
SalinityZones1_CarrizoWilcox	czwx_fr_t_d_ebk	Carrizo-Wilcox depth to top of fresh water
	czwx_fr_b_d_ebk	Carrizo-Wilcox depth to bottom of fresh water
	czwx_ss_t_d_ebk	Carrizo-Wilcox depth to top of slightly saline water
	czwx_ss_b_d_ebk	Carrizo-Wilcox depth to bottom of slightly saline water
	czwx_ms_t_d_ebk	Carrizo-Wilcox depth to top of moderately saline water
	czwx_ms_b_d_ebk	Carrizo-Wilcox depth to bottom of moderately saline water
	czwx_vs_t_d_ebk	Carrizo-Wilcox depth to top of very saline water
	czwx_vs_b_d_ebk	Carrizo-Wilcox depth to bottom of very saline water
SalinityZones2_QueenCitySparta	qcsp_fr_t_d_ebk	Queen City-Sparta depth to top of fresh water
	qcsp_fr_b_d_ebk	Queen City-Sparta depth to bottom of fresh water
	qcsp_ss_t_d_ebk	Queen City-Sparta depth to top of slightly saline water
	qcsp_ss_b_d_ebk	Queen City-Sparta depth to bottom of slightly saline water
SalinityZones3_QueenCitySparta	qcsp_ms_t_d_ebk	Queen City-Sparta depth to top of moderately saline water
	qcsp_ms_b_d_ebk	Queen City-Sparta depth to bottom of moderately saline water
	qcsp_vs_t_d_ebk	Queen City-Sparta depth to top of very saline water
	qcsp_vs_b_d_ebk	Queen City-Sparta depth to bottom of very saline water
Sands1_UpperWilcox	uw_fr_tk_ebk	Total fresh water sand thickness in the Upper Wilcox
	uw_ss_tk_ebk	Total slightly saline water sand thickness in the Upper Wilcox
	uw_ms_tk_ebk	Total moderately saline water sand thickness in the Upper Wilcox
	uw_vs_tk_ebk	Total very saline water sand thickness in the Upper Wilcox
	uw_ns_tk_ebk	Net sand thickness in the Upper Wilcox
	uw_ps_ebk	Percent sand in the Upper Wilcox
Sands2_MiddleWilcox	mw_fr_tk_ebk	Total fresh water sand thickness in the Middle Wilcox
	mw_ss_tk_ebk	Total slightly saline water sand thickness in the Middle Wilcox
	mw_ms_tk_ebk	Total moderately saline water sand thickness in the Middle Wilcox
	mw_vs_tk_ebk	Total very saline water sand thickness in the Middle Wilcox
	mw_ns_tk_ebk	Net sand thickness in the Middle Wilcox
	mw_ps_ebk	Percent sand in the Middle Wilcox
Sands3_LowerWilcox	lw_fr_tk_ebk	Total fresh water sand thickness in the Lower Wilcox
	lw_ss_tk_ebk	Total slightly saline water sand thickness in the Lower Wilcox
	lw_ms_tk_ebk	Total moderately saline water sand thickness in the Lower Wilcox
	lw_vs_tk_ebk	Total very saline water sand thickness in the Lower Wilcox
	lw_ns_tk_ebk	Net sand thickness in the Lower Wilcox
	lw_ps_ebk	Percent sand in the Lower Wilcox

Raster Catalog	*Raster*	*Contents*
Sands4_QueenCity	qc_fr_tk_ebk	Total fresh water sand thickness in the Queen City
	qc_ss_tk_ebk	Total slightly saline water sand thickness in the Queen City
	qc_ms_tk_ebk	Total moderately saline water sand thickness in the Queen City
	qc_vs_tk_ebk	Total very saline water sand thickness in the Queen City
	qc_ns_tk_ebk	Net sand thickness in the Queen City
	qc_ps_ebk	Percent sand in the Queen City
Sands5_Sparta	sp_fr_tk_ebk	Total fresh water sand thickness in the Sparta
	sp_ss_tk_ebk	Total slightly saline water sand thickness in the Sparta
	sp_ms_tk_ebk	Total moderately saline water sand thickness in the Sparta
	sp_vs_tk_ebk	Total very saline water sand thickness in the Sparta
	sp_ns_tk_ebk	Net sand thickness in the Sparta
	sp_ps_ebk	Percent sand in the Sparta
SnapRasters	cw_snap500	500ft snap raster used in the Carrizo-Wilcox analysis
	qcsp_snap500	500ft snap raster used in the Queen City-Sparta analysis

Acronyms used in the GIS dataset file names

Stratigraphy/aquifer/area of interest names

cw Carrizo-Wilcox
czwx Carrizo-Wilcox
qc Queen City
sp Sparta
qs Queen City-Sparta
qcsp Queen City-Sparta
uw Upper Wilcox
mw Middle Wilcox
lw Lower Wilcox

Water quality designations

fr fresh (TDS <1,000 mg/L)
ss slightly saline (TDS = 1,000 – 3,000 mg/L)
ms moderately saline (TDS = 3,000 – 10,000 mg/L)
br brackish (TDS = 1,000 – 10,000 mg/L)
vs very saline (TDS = 10,000 – 35,000 mg/L)

Physical extent or property

t top
b bottom
d depth in feet below ground surface
tk thickness in feet

Data processing method or use

ebk Empirical Bayesian Kriging
clip lateral extent of analytical area

Data source

GAT Geologic Atlas of Texas

B.5 GMA 13 Volume Calculator & Visualization Toolbox

Appendix C: Comments and Responses

General comments

1. Per Scope of Work Subtask 2.1, please add geochemical database mentioned in Section 3.2 to the deliverables. **Response: Done**

2. Please change “ug” to “µg”, the standard SI prefix abbreviation, per Exhibit C, Attachment 3, Section 3. **Response: Done**

3. Per the contract (Exhibit C, Attachment 1, page 2), please place the GIS data in a geodatabase with GAM standard metadata. This geodatabase should include all GIS data used to construct the figures in the text and as input and output data in the various calculations. **Response: Done**

4. Per Exhibit C, Attachment 3, Section 5, please use thousand separating commas (for example, “1,000”) in appropriate numbers in the text. **Response: Done**

5. Please spell out abbreviations such as “AF”. **Response: Done**

6. Please reformat Table of Contents and please update the report so it complies with accessibility requirements per Contract Exhibit C, Attachment 1, Section C: In compliance with Texas Administrative Code Chapters 206 and 213 (related to Accessibility and Usability of State Web Sites), the digital copy of the final report will comply with the requirements and standards specified in statute. **Response: Done**

7. Per Exhibit C, Attachment 1, page 3 of 3: The reports should be of high quality and therefore proper grammar, punctuation, and spelling are important. Please proofread the entire report and please correct spelling, punctuation, and grammatical errors. As an example, please revise Chapter 6 to remove numerous grammatical errors, punctuation, and repetition. **Response: Done**

8. Per Exhibit C, Attachment 3, Section 4.1: Please change all occurrences of “et al.” to “and others”. **Response: Done**

9. Please clarify where in the text of the report the stakeholder concerns related to the occurrence of areas where the Middle Wilcox Group aquitard is missing was addressed. If needed, please update the text in the report to address this concern. **Response: Done in Section 4.1.2.2 first paragraph.**

10. Per Exhibit C, Attachment 3, Section 4.2, page 4 of 9: Please cite source references for all tables and figures either in the caption, legend (for figures) or below the table and include in the Reference Section. **Response: Done for Section 4.**

11. Per Exhibit C, Attachment 3, Section 2.2.1: Please place figures and tables as close as possible to their citation in the text. **Response: Not done due to time constraints.**

12. For clarity, please update the legends in figures to include all symbols and features featured, such as county, aquifer outcrop, aquifer subcrop, water features, and groundwater management area boundaries. **Response: Done**

13. Contract Amendment #1 Task 6 was to assemble aquifer hydraulic properties. The draft report discussion needs to include this task and all deliverables associated with this task need to be provided. **Response: The aquifer hydraulic properties that were assembled are from existing TWDB databases. These databases are cited in the report and have not be reproduced.**

14. Contract Amendment #1 Task 7 includes the task of assembling additional geophysical well logs to assess a more detailed evaluation of growth faults or other faults in these regions. Please clarify in the report and maps how this task was addressed and the outcome of this additional work. **Response: Done in Section 4.1.2.5.**

15. Contract Amendment #1 Task 7 includes calculating the amount of brackish groundwater that each Potential Production Area (PPA) is capable of producing over a 30-year and 50-year period without causing significant impact. Please provide this analysis. **Response: Volumes of brackish groundwater from each of the three PPAs for three pumping scenarios are provided in the report. It is our understanding that TWDB may accept, modify or reject the proposed PPAs, and recommend brackish water production zones to their Executive Administrator.**

16. Contract Amendment #1 Task 7 includes the statement "The purpose of using the modeling metrics is to determine the amount of brackish groundwater that the potential production areas are capable of producing over a 30-year period and a 50-year period without causing significant impact to water availability or water quality to fresh water resources." Please clarify where in the report the discussion of how the evaluation of water quality was evaluated and the results of this evaluation. If missing, please update the report as needed. **Response: We propose to perform particle tracking to evaluate the movement of water near the base of fresh water but was told by TWDB that the additional work was not required. We agree that changes to the water quality in the fresh water zone will be minimal.**

17. For ease of understanding, please list formation names alongside layer numbers on the simulated drawdown plots/cross-sections, such as Figure 6-55, and on all tables showing K values, such as Table 6-28. **Response: Tables updated, figures not updated.**

18. Data in tables showing simulated drawdowns are sometimes in single precision, other times in double (see tables 6-21 vs 6-22, for example). Please revise for consistency. **Response: For consistency we reported values to one decimal, or tenth of a foot.**

19. Please revise all figures showing pumping drawdown for the potential production areas to also show the locations of the pumping well fields. Example figures for potential production area 1, GAM based model parameters, are Figures 6-23 through 6-26. **Response: We added the location of monitoring wells and pumping wells on appropriate figures.**

20. Porosity interpretation was performed using approximately 12 geophysical well logs at multiple depth intervals per log using the method "Asquith and others (2004)" according to the table tblGeophysicalLog_Porosity.xlsx. Please provide a detailed step-by-step analysis of this method using one of the logs so the reader understands the process and any correction factors used in the analysis and in fulfillment of Exhibit C, Attachment 1 of the contract. **Response: Done**

21. Contract Amendment #1, BRACS Program Contract Data Requirements, Section 3 e and 3 g: Please include an appendix listing the data deliverables. In this appendix, please list the GIS and Modeling datasets, filenames, acronyms used in filenames and a description of how the GIS files were developed and analyzed. **Response: Done**

22. Comments on the suitability of the middle Wilcox layer as an adequate aquitard in Potential Production Area 1 (PPA #1). **Response: PPA #1 removed from report.**

    a. By overlapping Potential Groundwater Production Area 1 (PPA #1) in Figure 4-37 with the Middle Wilcox Percent Sand Thickness map in Figure 4-14, it is evident that there exists several areas where the sand percentages are at or greater than 30% (shale <70%) increasing the likelihood that a leaky aquitard situation may exist within some areas of PPA #1. By overlapping Potential Groundwater Production Area 1 (PPA #1) in Figure 4-37 with the Fault Zones shown in Figures 4-21 and 4.22, it is evident that faulting exists within some areas of PPA #1 which could affect groundwater flow by increasing vertical flow and groundwater mixing.

    b. The simulated drawdown from the Geohydrostratigraphic Model (GHSM) indicates that after 30 years of pumping at 15,000 acre-feet per year there will be more than 30 foot of drawdown in the Carrizo Aquifer above the location of the pumping wells in the lower Wilcox.

    c. All of this evidence taken together indicates that the middle Wilcox may not be an effective barrier to vertical flow in the PPA #1 area due to faulting and/or sand percentages greater than 30% (shale <70%) and that production in the brackish water zone of the lower Wilcox may potentially have a significant impact on the Carrizo Aquifer fresh water zone. Please also see comments on Section 6.1.2.

23. Comments on injection wells within a PPA. **Response: Done**

a. In the first draft report released by the TWDB for public comment, PPA #1 and PPA #2 were eliminated from the report because of the location of the injection wells. A 15-mile buffer was imposed around each injection well as a potential radius of influence. The current draft report does not provide any radius of influence assessment for the injection wells that overlap with the base of brackish groundwater nor for the injection wells that extend a few feet to at least 500 feet from the brackish groundwater that may not have sufficient contiguous impervious strata between the two to prevent injection fluids from moving into the brackish groundwater. Please include this information because it would be very helpful to someone contemplating installation of a large very expensive brackish water well field meeting the requirements of House Bill 30 (see Contract Amendment #1, Exhibit A, Attachment 2, page 2 of 4, paragraph 3, sentence 1).

b. House Bill 30 (84th Regular Session) required identification and designation of local or regional brackish groundwater production zones in areas of the state with moderate to high availability and productivity of brackish groundwater that can be used to reduce the use of fresh groundwater that is not in an area of a geologic stratum that is designated or used for wastewater injection through the use of injection wells or disposal wells permitted under Chapter 27. Please ensure that all potential production areas meet the requirements of House Bill 30 (see Contract Amendment #1, Exhibit A, Attachment 2, page 2 of 4, paragraph 3, sentence 1).

c. The report identifies injection wells within PPA #1 with vertical distances from the PPA to deeper injection zones ranging from a few feet to over 6,000 ft. In PPA #1, four injection wells have injection intervals that overlap with the base of brackish groundwater. It appears from this information that some areas of PPA #1 have been designated or used for wastewater injection through the use of injection wells or disposal wells permitted under Chapter 27. Please eliminate these areas from PPA #1 along with any others that have injection wells with vertical distances that extend from a few feet to at least 500 feet from the brackish water to the injection zones and may not have sufficient contiguous impervious strata (shale) between the two to prevent injection fluids from moving into the brackish groundwater.

24. Comments on identifying the impacts of brackish water pumping on the fresh water zone.

a. One of the purposes of the report is to identify the impacts that pumping in the brackish water PPA will have on the fresh water zones. While predicted drawdowns identified in the tables establish that the brackish water and fresh water zones may be connected, please identify the volume of water this drawdown would remove from the fresh water zones, if any. For instance, the simulated drawdown from the GAM indicates that after 30 years of pumping 15,000 acre-feet per year from Well Field #1 the groundwater model predicts 5 to 6 feet of drawdown in the lower Wilcox at the 2.5 mile monitoring point location and 7 to 13 feet in the lower Wilcox at the 5.5 monitoring point location. This type of information provides only a single drawdown measurement at a given point making it difficult to identify the full impact of the Well Field pumpage. A drawdown map showing the extent of the drawdown around the Well Field and an estimate of the amount of fresh water removed, if any, would be a better indicator of the impacts of pumping. Similarly, the simulated drawdown from the Geohydrostratigraphic Model (GHSM) for PPA #1 indicates that after 30 years of pumping 15,000 acre-feet per year there will be more than 30 foot of drawdown in the Carrizo Aquifer above the location of the pumping wells in the lower Wilcox. Equating this drawdown with an amount of water would be helpful in assisting groundwater districts in determining the impacts to the fresh water zone. **Response: PPA #1 was removed. For the baseline, or mid-range pumping scenario, for each PPA we included a map of drawdown along the centerline the cone of drawdown. An estimate of the amount of freshwater removed can be estimated by multiplying the drawdown in a fresh water zone by the specific storage for that freshwater zone. The methodology for doing this calculation is explained in Section 5.**

25. Comments on designation of brackish water zones that are not serving as significant sources of water supply for municipal, domestic, or agricultural purposes.

    a. House Bill 30 (84th Regular Session) required identification and designation of local or regional brackish groundwater production zones in areas of the state with moderate to high availability and productivity of brackish groundwater that can be used to reduce the use of fresh groundwater and are not serving as a significant source of water supply for municipal, domestic, or agricultural purposes at the time of designation of the zones. Please include any information on sources of water supply for municipal, domestic, or agricultural purposes within any of the PPA areas in the report (see Contract Amendment #1, Exhibit A, Attachment 2, page 2 of 4, paragraph 3, sentence 1). **Response: Done, included in Appendix A.**

26. The Queen City and Sparta aquifers PPA #1 contains over one dozen Class II injection wells permitted by the Railroad Commission of Texas with injection zones within the Queen City and Sparta aquifer depth range and therefore cannot be considered for a potential production area. Please delete all discussion of PPA #1 in the text. **Response: Done**

Specific comments

27. Front matter: Per Contract Amendment #1, BRACS Program Contract Data Requirements, Section 11 h: Please include the TWDB contract number on the cover page. **Response: Done**

28. Front matter: Per Exhibit C, Attachment 1 (c), page 3: Please abide by Texas Occupation Code, Title 6, Chapter 1002, Subchapter F on license requirements. **Response: Done**

29. Front matter: Abbreviations and acronyms, page xxiv: Please change "Ft" to "ft". **Response: Done**

30. Front matter: Abbreviations and Acronyms, page xxiv: Please update with µg/L, pCi/L, AFY, and QCSP GAM. **Response: Done**

31. Front matter: Abbreviations and Acronyms, page xxv: Please remove STEER as this was not used in the report. **Response: Done**

32. Front matter: Per Exhibit C, Attachment 1 (b), page 1 of 3, please include "Executive Summary" and "Conclusions and Recommendations" sections to the report. For example, please include a brief discussion of why this study was undertaken: such as House Bill 30 (84th Texas Legislative Session) and in support of future updates to the existing groundwater availability model) in the executive summary and introduction. **Response: Done**

Section 1

33. Section 1, paragraph 1: Please change "The Texas Water Development Board (TWDB) divides groundwater salinity …" to "Groundwater salinity is divided …" **Response: Done**

34. Section 1, paragraph 1: Please add "municipal" to the list of potential uses of brackish groundwater. **Response: Done**

Section 2

35. Section 2: Please add a map showing the location of Rio Grande Embayment, San Marcos Arch, relevant aquifers, etc., mentioned in the text. **Response: Done**

36. Section 2, paragraph 1: Please add a simple stratigraphic column showing the stratigraphic units mentioned in this Hydrogeologic Setting section of the report. **Response: Done**

37. Section 2.1, paragraph 1: Please clarify why or how Maverick County is excluded from the study area. Figures in subsequent sections include water quality in Maverick County. **Response: Done in text.**

38. Section 2.1, paragraph 1: Please change "… for a few …" to "… from a few …". **Response: Done**

Section 3

39. Section 3.2, paragraph 1: Text refers to the USGS produced water database. Please provide citation or online source for these data. **Response: Done**

40. Section 3.2, paragraph 1: Please change "silicate" to "silica". **Response: Done**

41. Section 3.3, paragraph 2: Please indicate whether there is a hydrostratigraphic relationship between the band of fresher groundwater downdip of the more saline groundwater in the outcrop. Please clarify in the report if the two types of groundwater occur within the same stratigraphic unit or if one occurs at greater depths than the other. **Response: Done**

42. Section 3.3, paragraph 2: Please discuss the localized occurrence of groundwater with TDS above 3,000 mg/l in the Carrizo-Wilcox Aquifer, is it related to vertical variation of groundwater quality? **Response: Done**

43. Section 3.3, paragraph 3: The average TDS for the Sparta Aquifer (2,307 mg/l) is higher than the range of TDS values (117 to 1,142 mg/l), please correct. **Response: Done**

44. Section 3.3, paragraph 3: Please place Sparta and Queen City aquifers water quality data on separate figures. That will allow better determination of whether or not there is systematic variation of TDS with aquifer depth. **Response: Done, new figures 3-4a and 3-4b replaced old figure 3-4.**

45. Section 3.3, paragraph 5: For consistency between text and figures, please update Figure 3-6 with the Carrizo-Wilcox Aquifer outcrop boundary since text discusses outcrop and downdip locations of disposal wells. **Response: Done**

46. Section 3.3, paragraph 5: Please specify which formations are being used by the Underground Injection Control Class II wells, if known. **Response: Not possible because information is not reliable or not available.**

47. Section 3.4, paragraphs 1 and 2: Please clarify in the report if higher silica and iron concentrations in the Carrizo-Wilcox Aquifer occur in the same stratigraphic unit or if they tend to occur at greater depths. **Response: Done**

48. Section 3.4, paragraph 2: Considering the iron concentrations occurring in the study area, please use mg/l instead of μg/l. **Response: Done, also modified legends in figures 3-14 and 3-15.**

49. Section 3, Figures 3-1, and 3-3 through 3-24: All of these figures should have legends that indicate the respective aquifer outcrops and subcrops, please revise. See Figure 3-2 for example. **Response: Done**

50. Section 3, Table 3-1: Please spell out water quality parameters in header or include all abbreviations in Abbreviations and Acronyms. Please verify caption, header and remaining table are on the same page. **Response: Done**

51. Section 3, Figures 3-1 to 3-24: Please update legends to include Groundwater Management Area 13 boundary, aquifer outcrop/downdip, counties, water features, and Mexico, as applicable. **Response: Done**

52. Section 3, Figures 3-3, 3-4, and 3-5: Per Contract Amendment #1, BRACS Program Contract Data Requirements Section 4 c, please use consistent colors for the different salinity ranges in Figure 3-4. **Response: Done**

53. Section 3, Figure 3-4: Please identify Frio River on the map, as it mentioned in Section 3.3; or, specify in text Frio is the aquifer boundary to the SW. **Response: Done, added to map.**

54. Section 3, Figure 3-5: The Class II injection well data should distinguish wells injecting into the Carrizo Wilcox, Queen City, or Sparta aquifers (using symbols for each aquifer). Wells injecting into other geologic strata, should be identified with a different symbol. **Response: Not possible because information is not reliable or not available.**

55. Section 3, Figures 3-10 to 3-12, 3-14, 3-16, 3-20, 3-22, and 3-24: Please revise captions to indicate that samples outside official aquifer boundaries were collected from Queen City/Sparta-equivalent strata (Bigford, Laredo) in South Texas. **Response: Done**

Section 4

56. Section 4.1.1.1: Please change “publically” with “publicly”. **Response: Done**

57. Section 4.1.1.3 and Section 4.2.1.3: The statement is made that groundwater salinity is the dominant control of formation resistivity based on the R_0 and TDS regressions that were performed. Please discuss the problems encountered when applying the R_0 cutoff technique to every sand in the formation. For example, shale concentration has a significant impact on the resistivity signature of a sand and few sands within the Gulf Coast Tertiary sediments are pure sand. Most of the sand units contain some shale, and the presence of

shale reduces the resistivity response which implies higher groundwater salinity. When applying RO cutoffs to classify sands, lower salinity sands could inadvertently be classified as a higher salinity due to shale. **Response: Many Gulf Coast Tertiary sands are composed of almost 100% "clean" sand (only traces of clay). For this analysis, we selected only clean sands. Furthermore, we did not attempt to calculate salinity down to the milligram of dissolved solids. Instead we developed cutoffs for mapping broad salinity classifications. Text in sections 4.1.1.3 and 4.2.1.3 has been updated to emphasize this point.**

58. Section 4.1.1.3, paragraph 2: It appears unclear whether or how many wells with water quality data had screen information. Please include assumptions used for identifying the common aquifer zone in well pairs when wells did not have screen data. **Response: Done in sections 4.1.1.3 and 4.2.1.3.**

59. Section 4.1.1.3, paragraph 1: Please discuss whether R_0 better relates to R_t or to groundwater salinity. **Response: R_0 approximates R_t under conditions stated in text, and R_t is controlled by salinity**

60. Section 4.1.1.7, paragraphs 1 and 2: The text discusses counties in relation to growth-fault zone and water quality in Figure 4-7. Please update figure with county names so text and figure correlate. **Response: Done**

61. Section 4.1.1.7, paragraph 2: The text references Figure 3-4 which is for the Queen City and Sparta aquifers. Please update text to reference the correct figure, possibly Figure 3-5. **Response: Done**

62. Section 4.1.2.2, paragraph 1: Please change "… less than about 30 …" to "…less than 30 percent ...". **Response: Done**

63. Section 4.1.2.3: Please elaborate on this statement: "fault-related groundwater mixing probably controls the distribution of brackish groundwater in the lower Wilcox in the NE". **Response: Done**

64. Section 4.1.2.5, paragraph 1: Please refer to Figure 4-37 at the end of the first sentence. **Response: Done**

65. Section 4.1.2.6, paragraph 2: Please clarify in the first sentence that the PPAs in the Lower Wilcox are separated from the fresh groundwater in the Carrizo-upper Wilcox by the Middle Wilcox. Also, please include discussion of the potential thickness and influences of the respective aquitards. **Response: Done**

66. Section 4.1.2.6, paragraph 2: Please change potential production "zone" to potential production "area". **Response: Done**

67. Section 4, Figure 4-3: Unclear which wells have both TDS data and R_0 data from logs. Please use different color or symbol to indicate wells with both TDS and R_0 data. **Response: Done**

68. Section 4, Figure 4-5: Please add the dots to figure the legend. **Response: Done**

69. Section 4, Figure 4-5: Please include the correlation coefficient (R^2) values for the respective hydrogeologic regions. **Response: Done**

70. Section 4, Figure 4-6 and discussion in text: Most of this data is for the Carrizo-Upper Wilcox. Please note this in the figure caption, for this relationship may not be valid for the Middle and Lower Wilcox. **Response: Done**

71. Section 4, Figure 4-6: The number of wells used in this figure is 2,619. The discussion in Section 3.2 and Table 3-1 lists 1,462 for TDS. Please explain the apparent discrepancy and please update the text and/or table as needed. **Response: Section 3 used a different data set from Section 4 (explained in text).**

72. Section 4, Figure 4-6: The caption and label for x-axis should read either “specific conductance” or “conductivity”. Please double-check the units and revise the figure as appropriate. **Response: Done**

73. Section 4, Figure 4-7: Please add TDS units to the legend. **Response: Done**

74. Section 4, Figures 4-9 to 4-12: It is difficult to distinguish modified fault zones from contours. Please consider using a distinct color or wider line to represent faults and noting this in the legend. This applies to the figures for the middle- and lower Wilcox as well. Please add boundary for Groundwater Management Area 13 to the legends. **Response: Done**

75. Section 4, Figures 4-35 and 4-36: Please label stratigraphic units as was done in Figures 4-33 and 4-34. **Response: Done**

76. Section 4, Figure 4-37: Please use a unique symbol to indicate which well points are from the cross-sections (Figures 4-33 to 4-36). It is difficult to review the cross-sections (Figures 4-33 through 4-36) along with the map to determine exactly where each cross-section log is on the map in Figure 4-37. Please note symbol in legend as well. **Response: Done**

77. Section 4, Figure 4-37: Please update caption to refer to Figures 4-33 to 4-36. **Response: Done**

78. Section 4, Figure 4-37: This figure should appear before figures 4-33 through 4-36. Please move and renumber. **Response: Not possible since 4-33 to 4-36 are discussed in text before 4-37.**

79. Section 4, Figure 4-42: Please add the API numbers to each well used on this cross-section. **Response: Done**

80. Section 4, Figure 4-64: Please use a unique symbol to indicate which well points are from the cross-sections (Figures 4-54 through 4-61). It is difficult to review the cross-sections (Figures 4-55 through 4-35) along with the map (Figure 4-64) to determine exactly where each cross-section log is on the map. Please note symbol in legend as well. **Response: Done**

81. Section 4, Figures 4-24 through 29 and Figures 4-33 through 36: Please include a small map showing the location of the respective cross sections relative to the southern portion of the Carrizo-Wilcox Aquifer. **Response: Figures too crowded already, location noted in caption.**

82. Section 4, Figure 4-38: There is a slight difference in the color of the dots on the map and in the legend. Please correct this. **Response: Done**

83. Section 4, Table 4-5: Please change "… (Figure 4-5) …" to "… (Figure 4-43) …". **Response: Done**

84. Section 4, Figures 4-41 and 4-42: Please interchange figures 4-41 and 4-42. **Response: Done**

85. Section 4, Figures 4-44 through 4-53 and 4-62 through 4-65: Please remove the Sparta and Queen City aquifers outcrops from these figures. They cover much of the data being shown in these figures. **Response: Done except 4-64 and 4-65.**

86. Section 4.2.2, all x-sections: Please label (identify in caption) cross-sections as CS1, CS2,…, CSn to be consistent with Figure 4-39 nomenclature. **Response: Done**

87. Section 4.2.2.2, paragraph 1: Please change "Figure 4-41" to "Figure 4-49". **Response: Done**

88. Section 4.2.2.2, paragraph 3: Per Exhibit C, Attachment 1, page 3 of 3, please revise the sentence "Similar to the Reklaw …" to correct grammatical errors. **Response: Done**

89. Section 4.2.2.2, paragraph 3: "Thick brackish groundwater sands in both Queen City and Sparta are stacked in the southwest …". Please change "southwest" to "northwest". **Response: Southwest is correct.**

90. Section 4, Figure 4-43: Please label axes on this graph. **Response: Done**

91. Section 4, Figure 4-58: (a) Well 77012 (API 4231133397) on cross-section 5 is the updip well within the designated PPA #2. The 80 foot thick sand on this cross-section is colored yellow (slightly saline) in the lower Queen City Formation. Review of the geophysical well

log shows a sand from 2,210-2,290 feet below ground surface in the Queen City Formation with a resistivity greater than 23 ohm-meters. According to Table 4-5, sands greater than 20 ohm-meters are fresh water. This indicates that fresh water is within the designated PPA #2 on the cross-section. The two wells along cross-section 5 updip of well 77012 (wells 21097 and 59111) also show fresh water in the lower Queen City; these two wells are within the boundaries of the PPA #2 ellipse. Review of all Queen City and Sparta records in the Excel file for well geology hydrochemical records indicates that the northern half of PPA #2 contains fresh water. Review of TWDB Groundwater Database and Texas Department of Licensing and Regulation Submitted Driller Report Database indicates existing fresh and brackish wells within PPA #2. House Bill 30 (84th Regular Session) prohibits designation of a brackish zone in fresh water or if existing fresh, brackish, or injection wells are in the area. Please modify the boundary of PPA #2, if possible, so that no fresh water is within the PPA boundary or is significantly impacted by the hypothetical pumping of the up- and down-dip wellfields. Please modify all figures, tables, GIS datasets, and database tables accordingly. **Response: Done**

92. Section 4, Figure 4-63: Please add contour lines and units that are missing from the legend. **Response: Done**

Section 5

93. Section 5, Table : The information in this table also appears in Section 1 and Table 4-5 and is therefore redundant. Please delete the table and cite Section 1 instead. **Response: Done**

94. Section 5, Figure 5-1: Please revise the caption for clarity. **Response: Done**

95. Section 5, Figure 5-2: Please delete the word “graph”. **Response: Done**

96. Section 5, Figure 5-3: This figure is difficult to read. Please use larger fonts and symbols and heavier line weights. The equation on this figure should use the same terms as Equation 5-5. **Response: Done**

97. Section 5, Figure 5-5: Please re-word the caption for clarity. **Response: Done**

98. Section 5.1.2: Please change the title for this section by either removing “…for the Carrizo-Wilcox Aquifer” or adding all aquifers studied, “…for the Carrizo-Wilcox, Queen City and Sparta aquifers” **Response: Done**

99. Section 5.1.2: The porosity relationship (Equation 5-5) appears to include data from the following formations: Queen City, Sparta, and Carrizo-Wilcox. This assumes that the porosity relationship with depth is the same for each geological formation. Please justify this assumption in the text. **Response: Done in Section 4.1.1.4.**

100. Section 5.1.2, paragraph 2: Please cite McBride and others (1991) in the text related to the development of a relationship between sand porosity and depth. **Response: Done**

101. Section 5.1.3: Please re-write this section to include the Queen City and Sparta aquifers. For paragraph 1, please describe that TWDB selected all cells from the model in "each" aquifer in the groundwater management area. For example, we used layer 1 for the Sparta Aquifer, layer 3 for the Queen City Aquifer, and for the Carrizo-Wilcox Aquifer we summed the cells in layers 5 through 8. **Response: Done**

102. Section 5.1.3: The groundwater volume is based on the Kelley and others (2004) GAM layers and not on the stratigraphy generated by this study. Since the stratigraphy generated by this study is probably better and, at least, documented by log interpretation as opposed to the GAM layers, we request a comparison of each of the stratigraphic surfaces: Hamlin (this study) versus Kelley and others (2004). Please provide maps and GIS raster files showing the differences. If there are significant differences, please provide a discussion of the justification for using this approach. **Response: Not done because surfaces correlated for this study do not extend to outcrop.**

103. Section 5.1.3: The southern extent of the study area shown on Figure 5-4 is south of the QCSP GAM grid boundary. Please discuss how the volume calculations were handled in this region. **Response: Done**

104. Section 5.1.3, Paragraph 2: Stratigraphic picks made by Hamlin in this study subdivided the Carrizo-Wilcox Aquifer into the Carrizo-Upper Wilcox, Middle Wilcox, and Lower Wilcox. For the Carrizo-Wilcox Aquifer, please calculate volumes that match the Hamlin subdivisions: Carrizo-Upper Wilcox, Middle Wilcox, and Lower Wilcox. **Response: Not done because surfaces correlated for this study do not extend to outcrop.**

105. Section 5.1.3: This section describes the steps to calculate volumes for the "unconfined" portions but does not describe the process for Equation 5-2. As noted in Section 5.2, please add this step to Section 5.1.3. **Response: Done**

106. Section 5.1.3, Step 3: This step describes what was done for the Queen City and Carrizo-Wilcox aquifers. Please clarify what was done for the Sparta Aquifer. **Response: Done**

107. Section 5, Table 5-3: Please add a row summing volumes for the entire Carrizo-Wilcox Aquifer. **Response: Done**

108. Section 5.2 and Tables 5-3 to 5-7: Please clarify in the text of the report if the assumption was to use the model extent or official aquifer extent within the boundaries of Groundwater Management Area 13. In addition, please clarify why the analysis was not performed in the areas within Groundwater Management Areas 15 and 16 as displayed in the figures in Section 4. **Response: Done in GMA 13 only.**

109. Section 5.2: Please update this section with the assumption from the geophysical log analysis that water quality has not changed over the time the geophysical logs were completed (please include range of years of the geophysical logs analyzed). **Response: Done**

110. Section 5, Tables 5-3 to 5-7: The tables switch from acre-feet (AF) in Table 5-3 to acre-feet per year (AFY) as units of volume in the remaining tables. Please use acre-feet (AF) to be consistent with the text in Chapter 5 and Table 5-3. Also note that the water levels were assumed from 1999 water-level conditions in the captions. **Response: Done**

111. Section 5, Table 5-6: Please review the analysis for groundwater conservation districts as the other tables suggest the total volume using specific yield was 1,241.9 million acre feet instead of 1242.4 million acre feet. **Response: Done**

Section 6

112. Section 6: Per House Bill 30 (84th Regular Session) an area of a geologic stratum that is designated or used for wastewater injection through the use of injection wells or disposal wells or is serving as a significant source of water supply for municipal, domestic, or agricultural purposes at the time of designation of the zones is disqualified from consideration as a production zone [or area] (see Contract Amendment #1, Exhibit A, Attachment 2, page 2 of 4, paragraph 3, sentence 1). As noted in Figure 4-38, this criterion eliminates potential production areas 1 and 4 for the Carrizo-Wilcox Aquifer. Injection wells noted in Figure 4-65 eliminates potential production area 1 for the Queen City and Sparta aquifers. Therefore, this section of the report should only discuss modeling results for potential production areas 2 and 3 in the Lower Wilcox for the Carrizo-Wilcox Aquifer and potential production area 2 for the Queen City and Sparta aquifers. **Response: Done**

113. Section 6: Please place and renumber the figures in order of citation in the text. **Response: Done**

114. Section 6, paragraph 1: Please change from “Carrizo-Wilcox, Queen City, and Sparta aquifers” to “Carrizo-Upper Wilcox portion of the Carrizo-Wilcox Aquifer”. **Response: Done, rewrote first paragraph.**

115. Section 6, paragraph 1: Please remove “years” at the end of the sentence or re-write for clarification. **Response: Done, rewrote first paragraph.**

116. Section 6, paragraph 1: Please re-write sentences 4 and 5 for clarity. Also, please change “For the two PPAs in the Queen City and Sparta aquifers, …” to “For the one PPA in the Queen City and Sparta aquifers, …” **Response: Done, rewrote first paragraph.**

117. Section 6.1.1: Per Table 6-2 and the associated text. Please clarify the text to indicate which PPA and for which well field the models were run. **Response: Done, rewrote first paragraph.**

118. Section 6.1.1: Please discuss the range of differences between the layers from the southern portion of the Queen City, Sparta, and Carrizo-Wilcox aquifers groundwater availability model for the Carrizo-Upper Wilcox, Middle Wilcox, and Lower Wilcox and this study. Please clarify if the differences are a couple of hundred feet, smaller, or larger. **Response: Differences range from 0 feet to hundreds of feet.**

119. Section 6.1.1, paragraph 2: Please define "scooping-level" or possibly change to "…model simulations are considered preliminary because…", please change "Groundwater Availability Program" to "Groundwater Availability Modeling Program", and please re-word "…have not yet be thoroughly evaluated" or revise sentence to more clearly convey that model run results based on inaccurate input data sets will be similarly inaccurate. **Response: Done**

120. Section 6.1.1, paragraph 3: Please check grammar, clarity, and punctuation; for example: "One problems…", "…in the area of the PPAs is that there…" is redundant and should be removed, missing period, please replace "leads" with "lead", and "…, the model approach includes four investigations." should possibly be re-worded to "…, the modeling approach includes four investigations." **Response: Done**

121. Section 6.1.1, paragraph 4: It is unclear from Table 6-1 how a total of 76 model simulations were done for each PPA. Please provide more detail in Table 6-1 or in the text to explain the 76 simulations. **Response: Done, paragraph rewritten.**

122. Section 6.1.1, paragraph 4: Please change "different well fields" to "different hypothetical well fields". **Response: Done**

123. Section 6.1.1, paragraph 6: Please change "… (see runs 2 through 8 in Table 6-2)" to "… (see runs 1 through 6 in Table 6-2)" and please add to the end of the last sentence (see runs 7 and 8 in Table 6-2). **Response: Done**

124. Section 6.1.1, Table 6-2: Caption appears to be a repeat of the caption for Table 6-1. Please redo caption for Table 6-2 to reflect that this table summarizes the runs for the sensitivity analysis. **Response: Done**

125. Section 6.1.1, paragraph 7: "PPAs" 2 and 3 (Figure 4-38) are the only two areas that qualify as potential production areas and Figure 4-38 suggest they are located close to the outcrop area of the other layers. In addition, at least in 1990, pumping was occurring in the Middle Wilcox above the two potential production areas and nearby in the Lower Wilcox (please ¬¬see the following figures from the original model for the southern portion of the Carrizo-

Wilcox Aquifer model). Modeling existing pumping in the surrounding area appears more reasonable to achieve the objective than excluding this pumping from the analysis. Please revisit assumptions or provide different justifiable reasoning for only including pumping in the PPA. **Response: Done, PPAs removed and rationale for not including other sources of pumping were modified.**

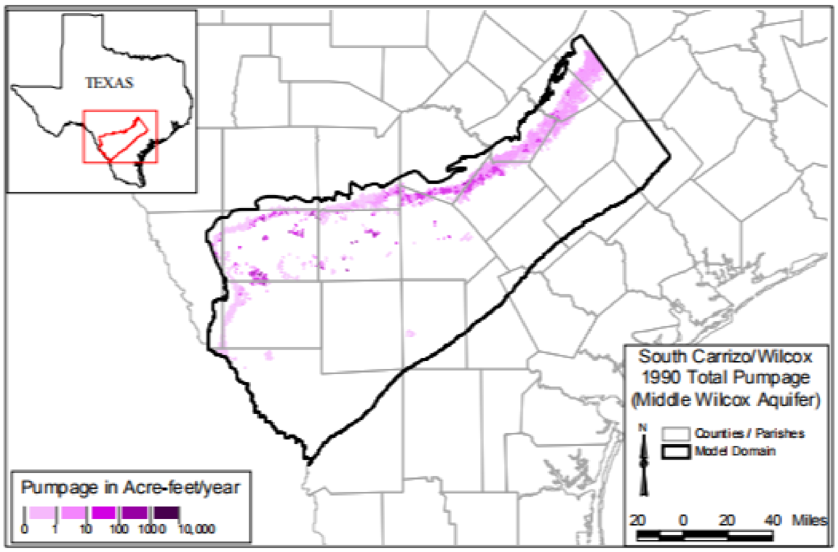


Figure 4.7.6 Middle Wilcox (Layer 5) Pumpage, 1990 (AFY).

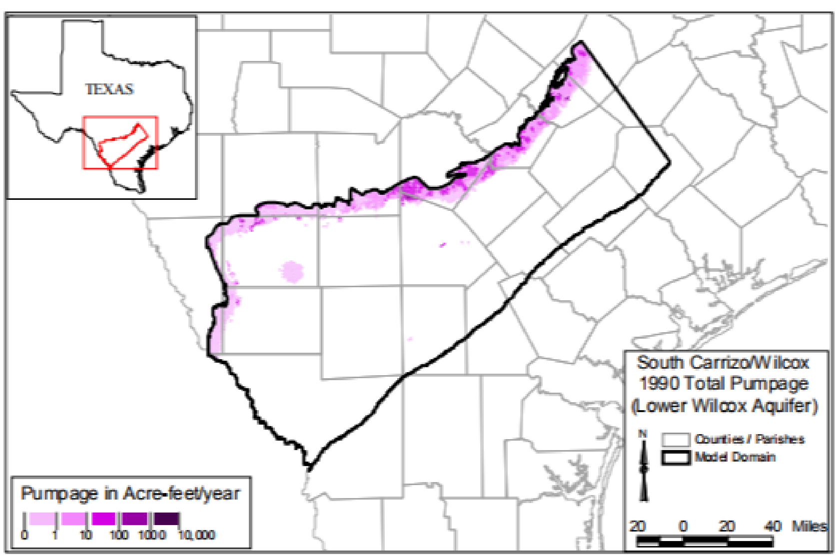


Figure 4.7.7 Lower Wilcox (Layer 6) Pumpage, 1990 (AFY).

Figure 1. Pumping figure extracted from Deeds and others (2003).

126. Section 6, Figure 6-1: Please label the PPAs on the map and specify the aquifer(s) the PPAs belong to. **Response: Done**

127. Section 6, Table 6-3: Please edit "slightly to moderately salinity" for grammar. **Response: Done**

128. Section 6.1.2: Please edit this section to eliminate PPAs 1 and 4 from the text and tables (Tables 6-3 and 6-4). "PPAs" 1 and 4 do not meet the requirements in statute to be considered as a potential production area per House Bill 30 (see Contract Amendment #1, Exhibit A, Attachment 2, page 2 of 4, paragraph 3, sentence 1). Related to this, please re-do Figure 6-1 and please delete figures 6-2, 6-5, 6-6, and 6-9. In addition, for clarity please clearly state in the caption if these cross sections represent the GHSM, GAM, or both instead of "groundwater model". **Response: Done**

129. Section 6.1.2: Please clarify in the text of the report the reasoning for not using the elevations for the Sparta, Weches, Queen City, and Reklaw from this study as was done for the Carrizo-Upper Wilcox, Middle Wilcox, and Lower Wilcox. In addition, please discuss process/assumptions and reasoning for further subdividing the Lower Wilcox as noted in Table 6-4. **Response: Done**

130. Section 6.1.3, paragraph 1: Please add a little more detail as to the advantages of using MODFLOW-USG as opposed to previous MODFLOW versions for this project; such as the capability of refining the grid in an area of interest. **Response: Done in Section 6.2.3.**

131. Section 6.1.3.1: Please discuss the benefits of using grid refinements without adding high-resolution hydraulic property data to the model considering the regional scale resolution of the source data (the QCSP GAM) and please discuss the reasoning/ambiguity for converting a two-dimensional cross section into three dimensions without adding additional data in the third dimension since the geology is not homogeneous. **Response: Done, added Step 3 in Section 6.2.3.1.**

132. Section 6.1.3.1, paragraphs 1 and 2: Please update references to figures to refer to the re-numbered figures for the cross-sections for "PPAs" 2 and 3 only. **Response: Done**

133. Section 6.1.3.1, paragraph 1: Please explain in the text of the report the advantages of relying on a cross-section-derived 3-D model over using structure data from the GAM. **Response: Not done**

134. Section 6.1.3.1: Please clarify in the text of the report the reasoning for assigning aquifer properties in Step 2 prior to refining the grid in Step 4. **Response: Done**

135. Section 6.1.3.1, page 141, Step 3: Please add justification for using this methodology versus a true three-dimensional model based on all the data in the study area or analytical modeling. Please indicate that the methodology being used is a "back-of-the-envelope"

methodology and that more detailed modeling would be required before specific brackish water projects are initiated. **Response: Done**

136. Section 6.1.3.1, page 141, Step 4: Please use an example from either PPA #2 or PPA #3 and please update Figure 6-11 as needed. In addition, where the grid was refined to 1/8 mile, please clarify if there are real-world data (heads or properties) in the faulted areas to indicate if the faults were barriers or conduits to flow. Please explain in more detail the reasoning for refining the grid around the faults and/or refer to Section 6.1.5.6. **Response: Done**

137. Section 6, Table 6-5: Please remove PPA #1 and 4 from the table. **Response: Done**

138. Section 6, Equation 6-1: This equation is a weighted average of K_s, with D_n being the weight, not an arithmetic average. Please revise the text to correct this. **Response: Done**

139. Section 6.1.4: Please rewrite section to refer to only PPAs 2 and 3. In addition, the text states the well fields were comprised of 9, 12, and 15 wells; however, Table 6-6 lists 3, 9, and 15 wells. Please update so text, table, and modeling agree. **Response: Done**

140. Section 6.1.5, paragraph 2: The text references Young and others (2003). Please clarify if this refers to Young, S.C., D. Barton, and T. Budge, 2003, "Constraining Ground Water Model Calibration Using Geological Information." MODFLOW and More 2003: Understanding through Modeling—An International Ground Water Modeling Conference and Workshops, Golden, CO. **Response: Young and others (2003) is the cited conference proceedings.**

141. Section 6.1.5, paragraph 2: Please change "(Deeds and others, 2004)" to "(Deeds and others, 2003)". **Response: Done**

142. Section 6.1.5.1: Please delete figures 6-12 and 6-15. Please only refer to the remaining figures and only discuss sand fractions for PPAs 2 and 3. **Response: Done**

143. Section 6.1.5.2 and Figure 6-16: Please clarify and update the text (as needed) since it appears the "arithmetic average" discussed here and on Figure 6-16 is really a weighted arithmetic mean/average (with Dn being the weight). The "harmonic average" formula in Figure 6-16 is not that of Kh1,…,Khn, but the harmonic mean/average of the Khn*Dn products, and the calculation does not result in a quantity measured in K units. It is our understanding that D1,…,Dn should be summed up at the numerator to obtain a true harmonic mean of hydraulic conductivities and [L/T] units. Also, Kv1 in legend does not appear in figure. **Response: Done in text and on figure.**

144. Section 6.1.5.3, paragraph 2: Please change citation from Deeds and others (2010) to Deeds and others (2003). **Response: Done**

145. Section 6.1.5.5: Please confirm that surface features, such as incising of surface water features is not propagated using the depth function. The topography of the study area shows approximately 300 feet or more of variation per Deeds and others (2003). It is the understanding of the reviewers that incising of river channels is a localized feature that should not be reflected in properties at depth. **Response: We agree.**

146. Section 6, Table 6-7: Please change citation from Deeds and others (2004) to Deeds and others (2003). **Response: Done**

147. Section 6, Equation 6-4: g = gravitational acceleration (980.6 cm/s^2). Please correct this. **Response: Done**

148. Section 6, Equation 6-5 and Equation 6-12: The calibrated parameter appears as z0 in the equation but is list below as Zo. Please revise for consistency. **Response: Done**

149. Section 6.1.5.6: Please clarify in the text of the report if your assumption of increasing vertical hydraulic conductivity around faults was that the faults act as conduits for vertical flow. If not, please clarify in the report the reasoning for this assumption. In addition, please discuss the basis and justification for the factors used for adjusting vertical hydraulic conductivity and what is meant by the range 1.0 through 6.0 (for the same fault or this changes for different faults). **Response: Done**

150. Section 6.1.6: Please delete this entire section including tables and figures. **Response: Done**

151. Section 6.1.7.1, paragraph 1: Please cite reference and/or explain the reasoning for using 1.5 inches per year of recharge. Average precipitation decreases from northeast to southwest in the study area and the average recharge from the original groundwater availability model for the southern portion of the Carrizo-Wilcox Aquifer for the steady state was 0.51 inches per year (Deeds and others, 2003). Adding more recharge may lessen the impacts of pumping in this exercise. **Response: Done**

152. Section 6.1.7.1, paragraph 3: Please revise the text such that "Table 6-8" should read "Table 6-18"; and "GMA-based" should read "GAM-based". "Simulated Drawdown Produced by Pumping from Potential Production Area #2" is the title of a section. Please adjust the text and renumber the following sections as appropriate. **Response: Done**

153. Section 6.1.7.1, paragraph 3; Table 6-18; and Figures 6-35 to 6-36: Please change reference from Table 6-8 to Table 6-18. Please clarify that Figures 6-35 and 6-36 represent values from Table 6-18. Please clarify why Figure 6-35 has 9 layers from the QCSP GAM while Figure 6-36 only shows 5 layers from the GHSM. **Response: Done**

154. Section 6.1.7.1, paragraph 4: Please clarify if the pumping discussed is for PPA #1 or PPA #2 as the first sentence still refers to PPA #1 and Figure 6-7, which refers to PPA #2. **Response: Done**

155. Section 6.1.7.1: Please add a bullet that the GHSM-based model shows more widespread drawdowns for well #2 in the Carrizo Formation. **Response: Done**

156. Section 6.1.7.1, paragraphs 7 and 9, and Section 6.1.8.1, page 179-180, paragraphs 7 and 8: Please change "… 30,000 years …" to "… 30,000 acre-feet per year …" **Response: Done**

157. Section 6.1.7.1, page 165, first bullet; page 166, first bullet; and Section 6.1.8.1, page 180, first bullet: Please clarify, "Except for a small area near the model up-dip boundary at the outcrop, the model exhibits a linear response between increase pumping and increase aquifer drawdown" as it is not clear if it is meant spatially (between monitoring points) or temporally. (The drawdown scale is logarithmic). **Response: Done**

158. Section 6.1.7.1, page 165, last bullet: Please clarify if after 30 years of pumping at 15,000 acre-feet per year, the groundwater model (GAM-based properties) predicts around 100 feet of drawdown at well field #2 instead of 400 feet. **Response: Value from plot is 400 feet.**

159. Section 6.1.7.1, paragraph 9: Please change reference from Table 6-9 to Table 6-19. **Response: Done**

160. Section 6.1.7.1, paragraph 2: Please change reference from Figures 6-31 through 6-34 to Figures 6-45 through 6-48. **Response: Done**

161. Section 6.1.7.1, page 166, last three bullets: The drawdowns noted in the text do not appear to match drawdowns in Tables 6-22 and 6-23. Please update bullets as needed. **Response: Done**

162. Section 6.1.7.2, paragraph 1: The text references figures 6-27 to 6-31, which refer to PPA#1, Please update to figures 6-41 to 6-48, which refer to PPA#2. **Response: Done**

163. Section 6.1.7.2, page 171 and Section 6.1.8.3, page 185: Please re-phrase the third and fourth sentence for clarity, deleting "in Table drawdown". **Response: Done**

164. Section 6.1.7.2, page 171 and Tables 6-24 to 6-27: Please review drawdown ranges in Tables and verify they agree in the bullets. It appears values in the text do not match the tables. **Response: Done**

165. Section 6.1.8.1, paragraph 1: Please cite references and/or explain the reasoning for using 1.5 inches per year of recharge. Average precipitation decreases from northeast to southwest in the study area and the average recharge from the original groundwater

availability model for the southern portion of the Carrizo-Wilcox Aquifer for the steady state was 0.51 inches per year (Deeds and others, 2003). Adding more recharge may lessen the impacts of pumping in this exercise. **Response: Done, 1.5 inches is total recharge not net recharge and most recharge at outcrop leaves through drains with elevations set at about 50 feet below surface, additional description in text.**

166. Section 6.1.8.1, paragraph 3: Please change reference from Table 6-8 to Table 6-28, referenced twice in this paragraph. Please clarify why the GSHM model in Figure 6-50 only has 5 layers. **Response: Done**

167. Section 6.1.8.1, paragraph 3: Please clarify if "GMA-based properties" should be "GAM-based properties" and please update text as needed. **Response: Done**

168. Section 6.1.8.2: It appears there is more drawdown in the GHSM model than the GAM-based and pumping in well #2 causes drawdown in layers above well#1. Please clarify in bullets. **Response: Done**

169. Section 6.1.8.2, bullets: The drawdowns noted in the text do not appear to match drawdowns in Tables 6-32 and 6-33. Please update bullets as needed. **Response: Done**

170. Section 6.1.8.2, page 180, last two bullets: The drawdowns noted in the text do not appear to match drawdowns in Tables 6-30 and 6-31. Please update bullets as needed. **Response: Done**

171. Section 6.1.8.3, paragraph 1: The text references Figures 6-27 to 6-34, which refer to PPA#1, Please update to Figures 6-55 to 6-62, which refer to PPA#3. **Response: Done**

172. Section 6.1.8.3: Please re-phrase the third and fourth sentence for clarity, deleting "in Table drawdown". **Response: Done**

173. Section 6.1.8.3 and Tables 6-34 to 6-37: Please review drawdown ranges in tables and verify they agree in the bullets. It appears values in the text do not match the tables. **Response: Done**

174. Section 6.1.9: Please delete this entire section including tables and figures. **Response: Done**

175. Section 6, Figures 6-7 and 6-8: Section 6.1.3.1, Step 4 states the grid is refined around the wells and faults. Please adjust the grid around both well fields in the same way or please explain in Section 6.1.3.1 or caption the reasoning the grid refinement appears different between the two well fields displayed. **Response: Done. Different cross-sectional models were used for well field #1 and well field #2; Figures 6-7 and 6-8 only show one of the refined well fields.**

176. Section 6, Figures 6-7 and 6-8: Both captions state there are three fault zones along the transect; however, Figure 6-7 only shows one and Figure 6-8 only shows two. Please adjust figures and caption such that they agree. **Response: Done**

177. Section 6, Figures 6-12 through 6-15, 6-21 through 6-26, and the others K-sections like them: Please label the layers/aquifers cited in the captions, as the layer boundaries are not always visible. Also, double check all figure captions to ensure all "well fields #2" are referred to as "downdip". **Response: Done**

178. Section 6, Figure 6-16: Please revise the formulae for the K averages, as per comment 118 in Attachment 1 in Review of Draft Report (2016). **Response: Done**

179. Section 6, Figure 6-16: Please correct the harmonic mean equation. **Response: Done**

180. Section 6, Figure 6-18: This figure is difficult to read. Please use larger fonts and heavier line weights. **Response: Done**

181. Section 6, Figures 6-19 and 6-20: Please enlarge these figure for clarity. **Response: Done**

182. Section 6, Figure 6-41 through 6-47: All captions show drawdowns based on the GHSM model. Please correct the captions to show which of the runs displayed were GAM-based. **Response: Done**

183. Section 6, Figures 6-57, 6-58, 6-61, and 6-62 and all others: Please modify captions related to "Field #2" to read "downdip" instead of "up dip". **Response: Done**

184. Section 6, Figures 6-66 and 6-68: Please check these two figures, as they seem to be identical. **Response: Done**

185. Section 6, Figure 6-77: Please revise this figure such that it shows the Queen City and Sparta (and equivalents) outcrops. Please revise the figure caption for clarity. **Response: Response: Done. Figure 6-77 is now 6-42.**

186. Section 6, Figure 6-80: Since this figure is a duplicate of Figure 6-10, please delete and reference Figure 6-10. **Response: Done**

187. Section 6.2: Per House Bill 30 (84th Regular Session) an area of a geologic stratum that is designated or used for wastewater injection through the use of injection wells or disposal wells or is serving as a significant source of water supply for municipal, domestic, or agricultural purposes at the time of designation of the zones is disqualified from consideration as a production zone [or area]. As noted in Figure 4-65, this criterion eliminates potential production area 1 for Queen City and Sparta aquifers. Therefore, this section of the report should only discuss modeling results for potential production area 2 for the Queen City and Sparta aquifers. However, please confirm pumping in LaSalle County in the Queen City and Sparta aquifers shown in Figure 2 (below) does not

disqualify Well #1 from PPA #2. In addition, please verify large pumping in McMullen in the Queen City and Sparta aquifers shown in Figure 2 (below) does not disqualify Well #2, or possibly interfere with the analysis, from PPA #2. Please adjust section, figures, and tables, as needed. **Response: Done**

188. Section 6.2.1, paragraph 1, and Figure 6-77: Please update text and figure to only show potential production area 2. **Response: Done**

189. Section 6.2.1, paragraph 1: Please discuss the reasoning for the range of pumping that differs between the Queen City and Sparta aquifers. **Response: Done**

190. Section 6.2.1, paragraph 2: Please update reference section with details concerning Hamlin and others, 2016, which is cited throughout this section. **Response: Done**

191. Section 6.2.1, paragraph 4: Please reword section and all sections that follow to refer to the singular PPA #2. **Response: Done**

192. Section 6.2.3: Please add a comment on the benefits of using USG in particular for these models. **Response: Done**

193. Section 6.2.3: The Cook Mountain Formation is set as a general head boundary allowing groundwater to flow between Sparta and the overlying Yegua aquifers. Please explain how the Cook Mountain (and its lateral equivalent upper Laredo) which is a predominantly clay/shale interval acts as a general head boundary whereas the middle Wilcox is set as a no flow boundary. **Response: Done**

194. Section 6.2.3.1: Please delete all references to PPA#1 and please delete Figure 6-78. **Response: Done**

195. Section 6.2.3.1: Please explain the advantages of the "replicating cross-section method" over using a regular 3-D numerical model based on both the newly-generated data and GAM data. **Response: Done**

196. Section 6.2.3.1, Step 2: Please comment on the reasons for assigning Cook Mountain hydraulic properties based on the hydraulic properties for the Reklaw Formation. **Response: Done**

197. Section 6.2.3.1, Step 3: Please re-word the following for clarity: "Figure 6-80 illustrates the process of constructing a three-dimensional model by combining replicates of the two-dimensional grids". **Response: Done, section was removed and new section added (6.2.3.1).**

198. Section 6.2.3.1, Step 3: "With each replication, the width of vertical cross-section is expanded by another grid cell until the total width of the three-dimensional groundwater model is 100 miles wide. This procedure maintains the structure, hydraulic properties, and

hydraulic boundaries in the original vertical cross-sectional model throughout the entire model domain.” Please clarify that the aquifers’ parameters associated with the cross-section have been replicated for 100 miles along geologic strike, and the existing GAM- or GHSM-generated data were “overridden/replaced” in the process. **Response: Done, section was removed and new section added (6.2.3.1).**

199. Section 6.2.4, paragraph 1: “The locations of the well fields for the Sparta Aquifer and the Queen City Aquifer are the same except for the model layer”. Please clarify which well field in which PPA pumps from which layer. **Response: Done**

200. Section 6.2.4, paragraph 2: Please revise the sentence “Pumping rates in the Sparta Aquifer …” for clarity. **Response: Sentence was removed.**

201. Section 6.2.4, paragraph 2: The sentence “Pumping rates in the Queen City Aquifer …” is not consistent with the information in Table 6-51, please revise. **Response: Sentence was removed.**

202. Section 6.2.4, paragraph 2: Please delete the first sentence. **Response: Done**

203. Section 6, Table 6-50: Please remove PPA#1 from table. **Response: Done**

204. Section 6, Table 6-51: The pumping rate for Queen City Formation wells is set at 826 gpm but the text in the preceding paragraph indicates the pumping rate varies from 688 to 1033 gpm. Please explain this discrepancy and correct the report as needed. **Response: Done**

205. Section 6.2.5, paragraph 1: Please revise the sentence “Once this these …” for clarity. **Response: Done**

206. Section 6.2.5, paragraph 1: Second sentence cites figures 6-8b and 6-9b, please replace with Figures 6-84b and 6-85b. In addition, text cites Kelley and others 2014, please update reference section with corresponding information and please re-word last sentence for clarity and grammar. **Response: Done**

207. Section 6.2.5, paragraph 2: Please change “(Deeds and others, 2004)” to “(Deeds and others, 2003)”. **Response: Done**

208. Section 6.2.5.1, paragraph 1: There are no figures 6-8b and 6-9b in this report. Please revise this sentence. **Response: Done**

209. Section 6.2.5.1, paragraph 4: Please correct the incorrect aquifer reference in this sentence, “For the Queen City Aquifer, **Equation 6-8** predicts a hydraulic conductivity of 13.3 ft/day at the 0.9 percentile for the Sparta Aquifer based on a measured sand fraction of 0.43.” **Response: Done**

210. Section 6.2.5.1, paragraph 3: Please update first sentence from Figures 6-86 to Figure 6-86 (a) and in the second sentence please change Figure 6-87 to Figure 6-86 (b). Please revisit the remaining figures cited in this paragraph as they do not appear relate to each other or the text. **Response: Done**

211. Section 6.2.5.1, Table 6-52: Please expand table to include 0.9 percentile so text and table agree. **Response: Done**

212. Section 6.2.5.1, paragraph 3: "Our analysis of the sand fraction and the hydraulic conductivity data …", please show, or refer to, the analysis referred to in this sentence. Please be consistent with the use of "sf" versus "Sf" in text and equations themselves. **Response: Done**

213. Section 6.2.5.1, paragraph 4: Please elaborate on the "field data" mentioned here: where is it, what type, how it was analyzed, etc.; also please show a chart (histogram?) of K and Sf by percentile. **Response: Done in Table 6-23.**

214. Section 6.2.5.1, paragraph 4: "… we developed Equations 6-7 and 6-8 using percentile values from the sand fraction and hydraulic conductivity data …". Please indicate which data is being referred to: GAM or GHSM? **Response: Done**

215. Section 6, Figures 6-21, 22, 35, 36, 49, 50, 63, 64, 84, 85, 86, 93, 94, 107, 108: Please change "Kx" to "Horizontal Hydraulic Conductivity". **Response: Done**

216. Section 6.2.5.2, paragraph 1: Please change "… Equation 6-7 or Equation 6.7 …" to "… Equation 6-7 or Equation 6.8 …". **Response: Done**

217. Section 6.2.5.2, paragraph 1: Please clarify which groundwater model is referenced in the first sentence. **Response: Done**

218. Section 6.2.5.2, paragraph 2: Please delete Figure 6-87 and first sentence should begin," Figure 6-88 shows the sand fraction along cross-section 2." Please check the figure numbers in the rest of the paragraph since they appear to be shifted from the figures that correspond to the text. **Response: Done**

219. Sections 6.2.5.2 and 6.2.5.3: Please correct the figure numbers cited in this paragraph. **Response: Done**

220. Section 6.2.5.2, paragraph 4: "The GHSM assumed that at shallow groundwater at GMA 13 is at 77°F and a geothermal gradient of about 20°F per 1,000 feet.": please include a citation for the geothermal gradient and groundwater temperature; also rewrite the sentence for clarity. **Response: Done and references added in Section 6.2.4.3.**

221. Section 6.2.5.3, paragraph 2: "… Kzs , is calculated by dividing the horizontal hydraulic conductivity of the sand layer by 10. The vertical hydraulic conductivity of clay, Kzc, is

set to 0.028 feet per day (ft/day) (0.00001 centimeter per second [cm/s]) for the vertical hydraulic conductivity of clay." Please cite literature or otherwise justify the baseline K= 0.028 ft/d and the Kh:Kv ratio of 10. **Response: Done**

222. Section 6.2.5.3 and Figure 6-92: Please clarify and update the text (as needed) since it appears the "arithmetic average" discussed here and on Figure 6-92 is really a weighted arithmetic mean/average (with Dn being the weight). The "harmonic average" formula in Figure 6-92 is not that of Kh1,…,Khn, but the harmonic mean/average of the Khn*Dn products, and the calculation does not result in a quantity measured in K units. It is our understanding that D1,…,Dn should be summed up at the numerator to obtain a true harmonic mean of hydraulic conductivities and [L/T] units. Also, Kv1 in legend does not appear in figure. **Response: Done**

223. Section 6.2.5.4: Please rewrite Equation 6-12 for concordance with the definition of terms under it. ("e" is missing from equation, also see z0 vs Zo. Please rewrite the following sentence for clarity "… that allows accounting for mixed sands and clay layers over thick intervals, a minimal value of specific storage prevent over extrapolation of the data used to developed Equation 6-13." **Response: Equation 6-13 deleted, and corrections made to Equation 6-5.**

224. Section 6, Figure 6-92: This figure is identical to Figure 6-16. Please delete and instead reference Figure 6-16. **Response: Done**

225. Section 6, Figure 6-94: Please add another K cut-off on the scale bar to the right. Also, please consider labeling the layers in all pertaining chapter 6 figures, because layer boundaries are not visible due to the color scheme. **Response: Done**

226. Sections 6.2.6 to 6.2.6.3: Please delete these sections, tables, and any corresponding figures (6-93 to 6-106). **Response: Done**

227. Section 6.2.7.1, paragraph 2: "The groundwater has been set up to down …"—please revise for clarity. **Response: Done**

228. Section 6.2.7.1: Please revisit discussion of model layers and properties since Layer 3 is cited from two different approaches and Reklaw Formation is stated to be Layer 3, however, Table 6-49 indicates the Reklaw is Layer 6. **Response: Done**

229. Section 6.2.7.1, paragraph 2: Please re-write first sentence for clarity. It is also unclear how the "distances of 41, 45, 49, 53, and 57 miles" correlate to Table 6-64 monitoring locations of 18, 22, 26, 30, and 34. **Response: Done**

230. Section 6.2.8, paragraph 1, second sentence; and Section 6.2.8, paragraph 3, second sentence: Please clarify if this should reference cross-section #2 (since section is discussing PPA#2), and please update text as needed. **Response: Done**

231. Section 6.2.8.1, first bullet: Please specify run numbers that illustrate "drawdown at the monitoring wells are most sensitive to changes in specific storage and horizontal hydraulic conductivity", and revise the previous sentence for verb-subject agreement. **Response: Done, sentence changed to identify the less sensitive parameters to minimize number of runs to list.**

232. Section 6.2.8.1, paragraph 2: The text references Figures 6-107 to 6-120 for five monitoring locations. Please note that Figures 6-107 and 6-108 do not have monitoring locations. Please update figure reference to Figures 6-109 to 6-120. **Response: Done**

233. Section 6, Table 6-28: Please consistently report values to one or two significant values and please round up values with significant values greater than two. Please update all other tables as needed. Also please confirm values in table for GHSM model as Figure 6-46 and text does not agree with table values. **Response: Done, tables are consistent in reporting one decimal for drawdown, each value in text was checked with tabulated values, changes made where appropriate.**

234. Section 6.1.9.1: Please clarify the difference in Layer 6 based on sand percentages shown in Figure 6-14, horizontal hydraulic conductivity in Figure 6-64 and values in Table 6-38. The sand percentages suggest Layer 6 is confining yet the values appear comparable to surrounding layers. **Response: Figure 6-14 is for PPA#3. Figure 6-64 is for PPA #4. Table 6-38 is for PPA #4. No changes in report were made. PPA #4 was deleted from report Figure 6-14 should not be compared to Figure 6-64.**

235. Section 6.1.9.2: Please clarify the first bullet since the Queen City or Sparta aquifers do not exist in Webb County. Please use geologic formation names. **Response: Section deleted.**

236. Section 6, Equation 6-10: This equation is identical to Equation 6-4. Please delete and adjust the text accordingly. **Response: Done**

237. Section 6, Figures 6-12 through 6-15: Please specify the stratigraphic units represented by layers 5 through 9. Please maintain the same graduated colors scale range in all four figures for ease of understanding. **Response: Done**

238. Section 6, Figures 6-21 and 6-22, Figures 6-35 and 6-36, Figures 6-49 and 6-50, and Figures 6-63 and 6-64: It is difficult to compare values on these sets of figures because they use different color scales. Please use the same color scale on both pairs of figures for easier comparison. **Response: Done**

239. Section 6, Figures 6-23 through 6-26; Figures 6-37 through 6-40; Figures 6-51 through 6-54; and Figures 6-65 through 6-68: Please indicate the location of the respective well fields on these figures. **Response: Done**

240. Section 6, Figures 6-27 through 6-34; Figures 6-41 through 6-48; Figures 6-55 through 6-62; and Figures 6-69 through 6-76: Please specify the hydrostratigraphic unit represented by each model layer in these figures. **Response: Done**

241. Section 6, Figure 6-79: Please clarify why the "well field" extends vertically into the Reklaw and Carrizo-Upper Wilcox. **Response: Well field does not extend into the Reklaw and Carrizo-Upper Wilcox, model discretization, however, is extended through the entire vertical section.**

242. Section 6, Figure 6-81: Please use an example from PPA#2, since PPA#1 does not meet the criteria listed in House Bill 30. **Response: Done**

243. Section 6, Figure 6-82: Please delete this figure and renumber the rest, as needed. **Response: Done**

244. Section 6, Figures 6-84, 6-85, and 6-86: Please remove cross-section 1 and PPA #1 from the figures. **Response: Done**

245. Section 6, Figure 6-86: The caption does not fully describe the two figures. Please correct this. **Response: Done**

Section 7

246. Section 7.2.1, paragraph 1: Please cite Figure 7-7 to be consistent with the figure (top/bottom instead of a/b or vice versa). **Response: Done**

247. Section 7.1.2, paragraph 2: Please change the text to indicate that Figure 7-2 shows groundwater volumes in the sands, not sand fractions. Please change the text to indicate that Figure 7-3 shows sand fractions, not groundwater volumes. **Response: Done**

248. Section 7.1.2, paragraph 3: "… Figure 7-4b shoes a map …" Please check the spelling and reconcile this sentence with the figure 7-4b caption. **Response: Done**

249. Section 7, Figure 7-4: Please label the figure "a" and "b" as cited in the text. **Response: Done**

Section 8

250. Section 8: This section is listed both as Chapter 8 and Appendix A. Please either delete "Appendix A" and change figure numbers from "A.*" to "8.*", or move this section to the end of the report, change section numbers from "8.*" to "A.*", and renumber chapters as appropriate. **Response: Done**

251. Section 8.3.1, Appendix A: In item d, please remove the “f.” before “Point …”. **Response: Done**

252. Section 8.3.1, Appendix A: In item g, please remove the “d.” before “Polygon …”. **Response: Done**

253. Section 8.3.1, Appendix A: In item I, please remove the “f.” before “Binary …”. **Response: Done**

Section 9

254. Section 9: Please add the reference for George and others (2011) to the list of references, per Exhibit C, Attachment 3. **Response: Done**

255. Section 9: Please add the reference for Castro and Goblet (2003) to the list of references, per Exhibit C, Attachment 3. **Response: Done**

256. Section 9: Please revise the reference for Brown (1997) to include the report number (Hydrologic Atlas no. 6) , per Exhibit C, Attachment 3. **Response: Done**

257. Section 9: Please revise the reference for Biri (1997) to include the report number (Hydrologic Atlas no. 5) , per Exhibit C, Attachment 3. **Response: Done**

258. Section 9: Please add the reference for Zhang and others (1988) to the list of references, per Exhibit C, Attachment 3. **Response: Done**

259. Section 9: Please add the reference for Lebas and others (2013) to the list of references, per Exhibit C, Attachment 3. **Response: Done**

260. Section 9: Please revise the reference for Ewing (1990), changing the publication to 1991, per Exhibit C, Attachment 3. **Response: Done**

261. Section 9: Please add the reference for Kelley and others (2014) to the list of references, per Exhibit C, Attachment 3. **Response: Done**

262. Section 9: Please add the reference for Hamlin and others (2017) to the list of references, per Exhibit C, Attachment 3. **Response: Done**

263. Section 9: Please add the reference for Razack and Huntley (1991) to the list of references, per Exhibit C, Attachment 3. **Response: Done**

264. Section 9: Please add the reference for Young and others (2017) to the list of references, per Exhibit C, Attachment 3. **Response: Done**

265. Section 9: Please add the reference for Rumbaugh and Rumbaugh (2010) to the list of references, per Exhibit C, Attachment 3. **Response: Done**

266. Section 9: The reference McVay and others (2015) is not cited in the text. Please delete it from the list of references, per Exhibit C, Attachment 3. **Response: Done**

267. Section 9: The reference Dutton (1999) is not cited in the text. Please delete it from the list of references, per Exhibit C, Attachment 3. **Response: Done**

268. Section 9: The reference Baker (1995) is not cited in the text. Please delete it from the list of references, per Exhibit C, Attachment 3. **Response: Done**

269. Section 9: Please delete the Dutton (1999) and LBG-Guyton Associates and INTERA (2012) references as they do not appear in the text, per Exhibit C, Attachment 3. **Response: Done**

270. Section 9: Kelley et al (2004) concerning the Queen City and Sparta aquifers. Please change the reference to *Kelley, V.A., N.E. Deeds, D.G. Fryar, J.P. Nicot, T.L. Jones, A.R. Dutton, G. Bruehl, T. Unger-Holtz, and J.L. Machin, 2004, Groundwater Availability Models for the Queen City and Sparta Aquifers. Prepared for the Texas Water Development board, Final Report; Prepared by INTERA, Austin, TX, 864 p.* In addition, please update Reference Section for Kelley et al. (2004) to report located: *http://www.twdb.texas.gov/groundwater/models/gam/qcsp/QCSP_Model_Report.pdf?d=12230.400000000001*, per Exhibit C, Attachment 3. **Response: Done**

271. Section 9: Please change the reference Kreitler et al. (2013) to *Kreitler, C.W., R. Bassett, J.A. Beach, L. Symank, D. O'Rourke, A. Papafotiou, J.E. Ewing, and V.A. Kelley, 2013, Evaluation of the Hydrochemical and Isotopic Data in Groundwater Management Areas 11, 12, and 13: Final Contract Report 1148301234, prepared for Texas Water Development Board, 454 p.*, per Exhibit C, Attachment 3. **Response: Done**

Visualization Tools

272. Brackish Estimator: This tool does not work. An error message stating "***Error 000576**: Script associated with this tool does not exist. Failed to execute (BrackEstimator).*" appears. Please correct this. **Response: INTERA will schedule a time to walk TWDB through this error. INTERA believes there is a problem with a path being set incorrectly.**

273. Plot 2D Sand Fractions by Layer: Please revise this tool such that the Queen City and Sparta aquifers maps both use the same scale. This is necessary because these figures are supposed to be publication-ready and cannot be edited external to the tool. **Response:**

INTERA has created an option to set the scales to be the same for the Queen City and Sparta aquifers.

274. Please provide metadata for all GIS files associated with the visualization tools. The majority of the Queen City and Sparta files do not have metadata. GIS metadata is a requirement for each file, please refer to contract attachment II, Exhibit C, Attachment 4, GIS files. **Response: We have added metadata for all input shapefiles associated with the Visualization tools. We do not provide metadata for the output shapefiles/rasters as these files get overwritten whenever the tools are re-run, and are dependent on user-defined inputs to the tools.**

The inputs for the Volume Calculator tool are provided in ../VolumeCalculator/input_shp
The inputs for the other visualization tools are provided in ../SandPlots/inputs

GIS Data

275. All GIS files must contain metadata. The majority of the Queen City and Sparta files do not have metadata. Refer to contract attachment II, Exhibit C, Attachment 4, GIS files. **Response: Metadata has been added to all GIS files.**

276. All GIS files must use the same map projection. Multiple projections were used to prepare the GIS files. Please correct this error and refer to Refer to contract attachment II, Exhibit C, Attachment 4, GIS files, Section 3.b for the map projection parameters. **Response: All GIS files now all have the same projection (GAM).**

277. Because groundwater model calculations used surfaces from three different sources (listed below) instead of the geological surfaces prepared in this study, please provide all GIS files used for model calculations including, but not limited to: GAM layer top, bottom and thickness, net sand and sand percent, groundwater volume, and salinity:

    a. Cook Mountain (Yegua-Jackson GAM, Deeds and others 2010)

    b. Sparta (Southern QCSP GAM, Kelley and others 2004)

    c. Weches (Southern QCSP GAM, Kelley and others 2004)

    d. Queen City (Southern QCSP GAM, Kelley and others 2004)

    e. Carrizo

    f. Upper Wilcox

g. Middle Wilcox

h. Lower Wilcox

Response: The model calculations used the Yegua-Jackson GAM and the Southern QCSP GAM to obtain the elevations for the top and bottom of the formation but no GIS files were created nor used. The elevation for the top and bottom of the surfaces were extracted directly from the GAM model files that were obtained from the TWDB.

278. GIS file qcsp_ppa_b_d_idw.tif contains the following errors:

a. The bottom depth values for PPA #2 appear to be much deeper than the bottom of the Queen City Formation. For example, four wells along cross section 5 are compared with GIS surfaces. It appears the bottom depth of the PPA #2 is within the Carrizo Formation and Wilcox Group. **Response: The PPA area boundaries have been refined, and new top and bottom depth surface grid files have been created.**

Well ID	59111	77012	77013	58632
API	4228300038	4228333397	4231133527	4231101245
QC B D	2212	2520	2884	3200
QCSP PPA BD	3937	4439	4418	4884
Cz UW B D	3220	3975	4497	4896
MW B D	3858	4694	5252	5655
LW B D	4685	5425	6076	6592

In PPA #1 the bottom depth value at well 75295, API 4247931169 is 4067 feet below ground surface, within the Carrizo Formation.

b. The QcSp PPA ellipse boundaries do not match the up- and down-dip limits expressed on cross-sections 2 and 5. For example, the up-dip boundary of the PPA #2 includes wells 4216301533 and 4228300038 which contain fresh water sands at the base of the Queen City. Please provide correct polygon and raster files for PPA #1 and 2. **Response: Original QCSP PPA2 (now the only QCSP PPA) boundary changed to exclude freshwater sands.**

c. Please provide a corrected raster file for the bottom of QcSp PPA #1 and 2. **Response: The PPA area boundaries have been refined, and new top and bottom depth surface grid files have been created.**

279. GIS file QCSP_wells contains the following errors:

a. The file is incomplete and does not contain all wells used for Queen City and Sparta formation stratigraphic picks. Please provide all well control. **Response: All well control point locations for the stratigraphic picks are now in the GIS file.**

b. The field [API] contains incorrect API numbers for each well encountered. All API numbers end with the digit zero; it appears that some type of rounding error occurred when data was placed in this field. Please ensure the field entries are correct. **Response: API numbers have been lengthened from the 10-digit form to the 14-digit form.**

c. The fields [Lat_NAD27] and [Long_NAD27] are irrelevant since all well control and GIS files should be using North American Datum (NAD) 83. Please rename the fields and populate with latitude and longitude coordinates in NAD83. **Response: The fields have been renamed and populated with NAD83 coordinates.**

d. The file contains inaccurate well locations. For example, BRACS Well 9631 (API number 4231102371) was assigned a well id by BEG as 75242. The correct location this well according to the geophysical well log header is approximately 6 miles south southeast of the location provided in the BRACS Excel files and this GIS point file. Please double check well locations; these inaccuracies have caused errors in additional datasets. **Response: The inaccurate well locations have been fixed.**

280. GIS file CW_wells contains the following errors:

a. The file should contain stratigraphic top and bottom picks for each formation (Carrizo-Wilcox, Middle Wilcox, Lower Wilcox) similar to the field design of file QCSP_Wells. **Response: All well control point locations for the stratigraphic picks are now in the GIS file.**

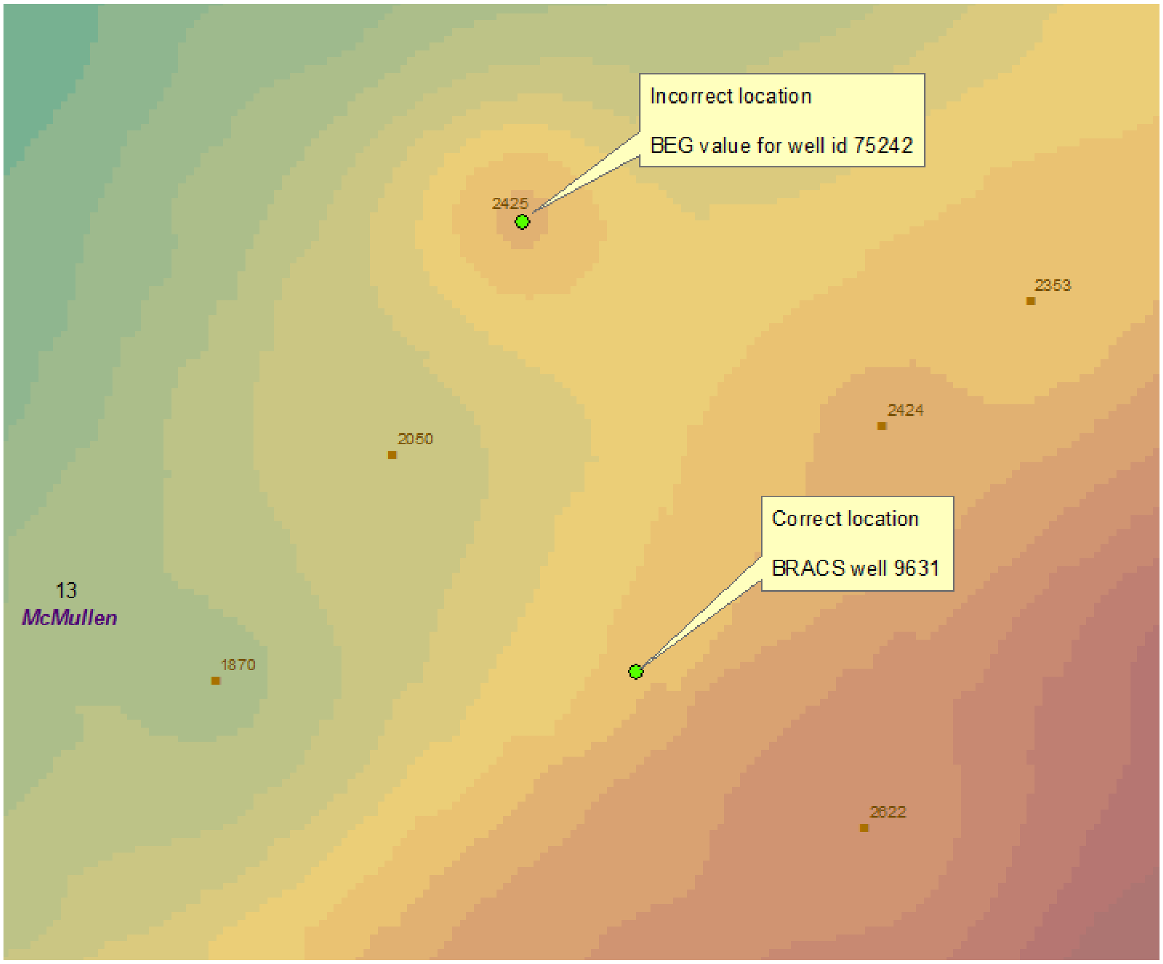
b. The field [API] contains incorrect API numbers for each well encountered. Please ensure the field entries are correct. **Response: API numbers have been lengthened from the 10-digit form to the 14-digit form.**

c. The fields [Lat_NAD27] and [Long_NAD27] are irrelevant since all well control and GIS files should be using North American Datum (NAD) 83. Please rename the fields and populate with latitude and longitude coordinates in NAD83. **Response: The fields have been renamed and populated with NAD83 coordinates.**

d. The file contains inaccurate well locations. For example, BRACS Well 9631 (API number 4231102371) was assigned a well id by BEG as 75242. The correct location this well according to the geophysical well log header is approximately 6 miles south southeast of the location provided in the BRACS Excel files and this GIS point file. Please double check well locations; these inaccuracies have caused errors in additional datasets. **Response: Well log and API mismatch corrected, updated API equals 42311013090000. Location also updated. Well log data and interpretations not changed.**

281. GIS files for the geologic formation raster files contain the following errors:

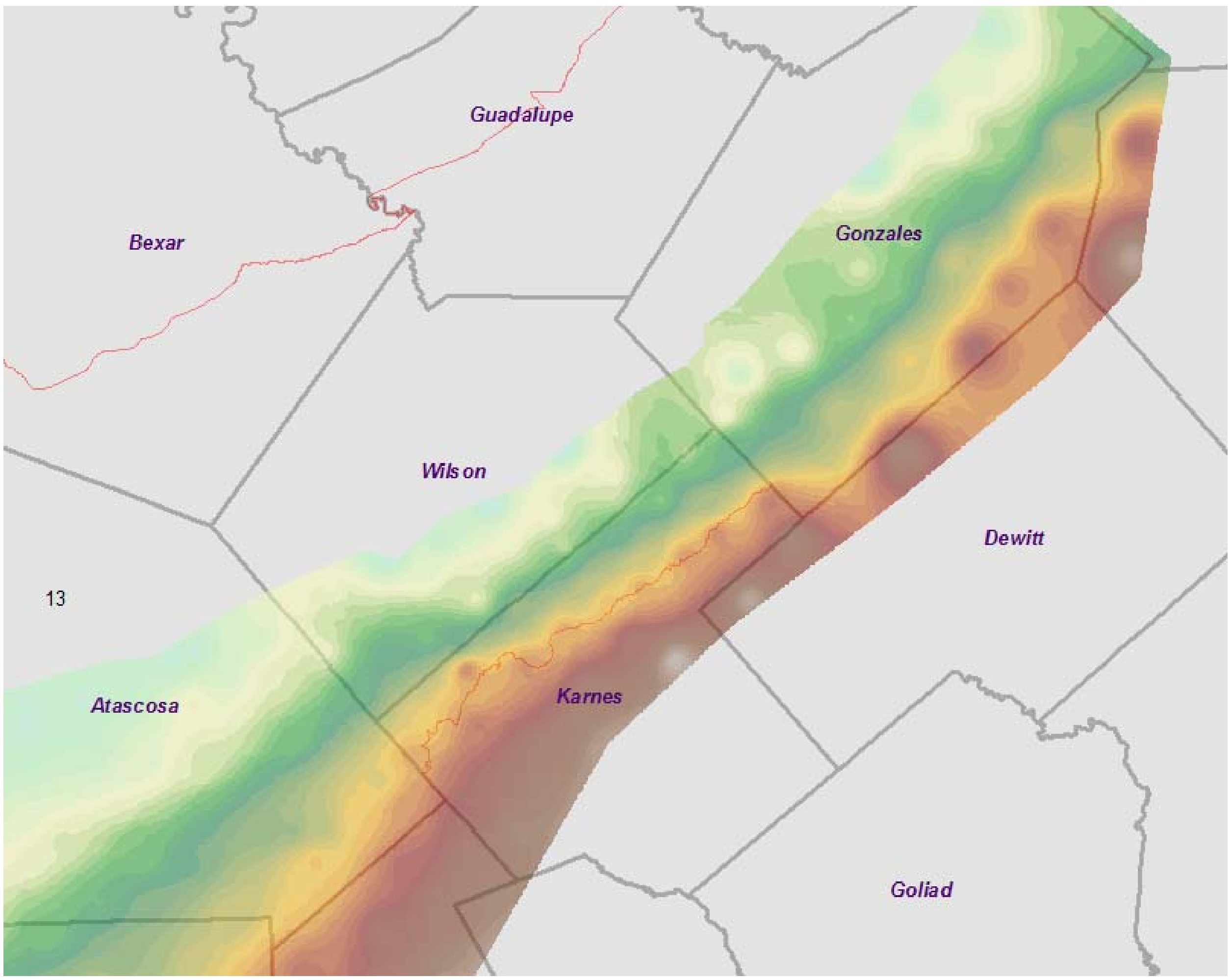
a. Incorrect well locations led to posting of formation top and bottom stratigraphic picks and sand picks in the wrong locations that led to incorrect top and bottom stratigraphic surfaces and sand maps. The figure below showing the Sparta Formation bottom depth surface and well control illustrates this point:



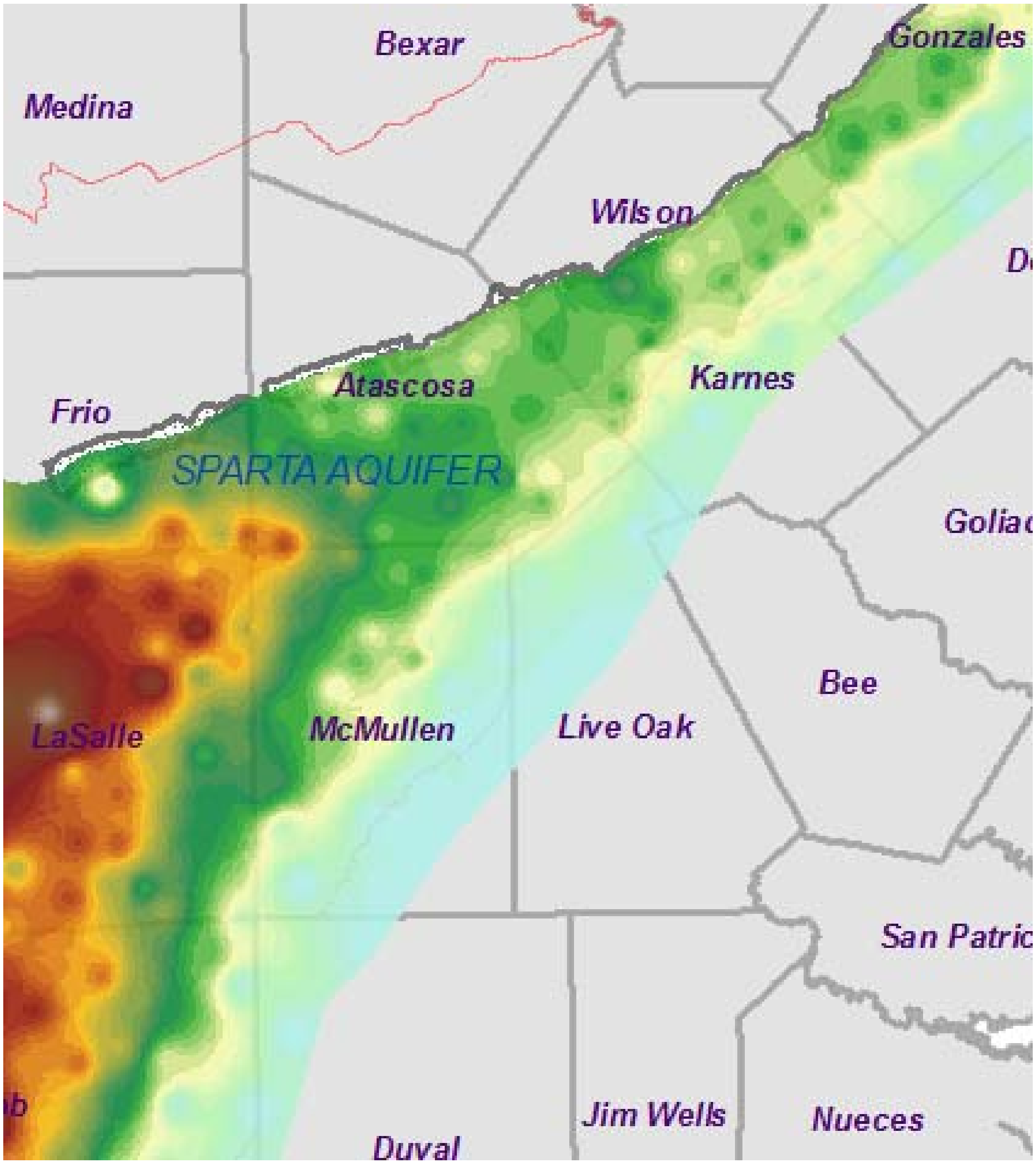
The incorrect location of this well permitted the posting of the Sparta Formation bottom depth 6 miles to the north.

Please review the formation and sand surfaces, correct well location errors, and correct the surfaces. **Response: See reply to comment in part b below.**

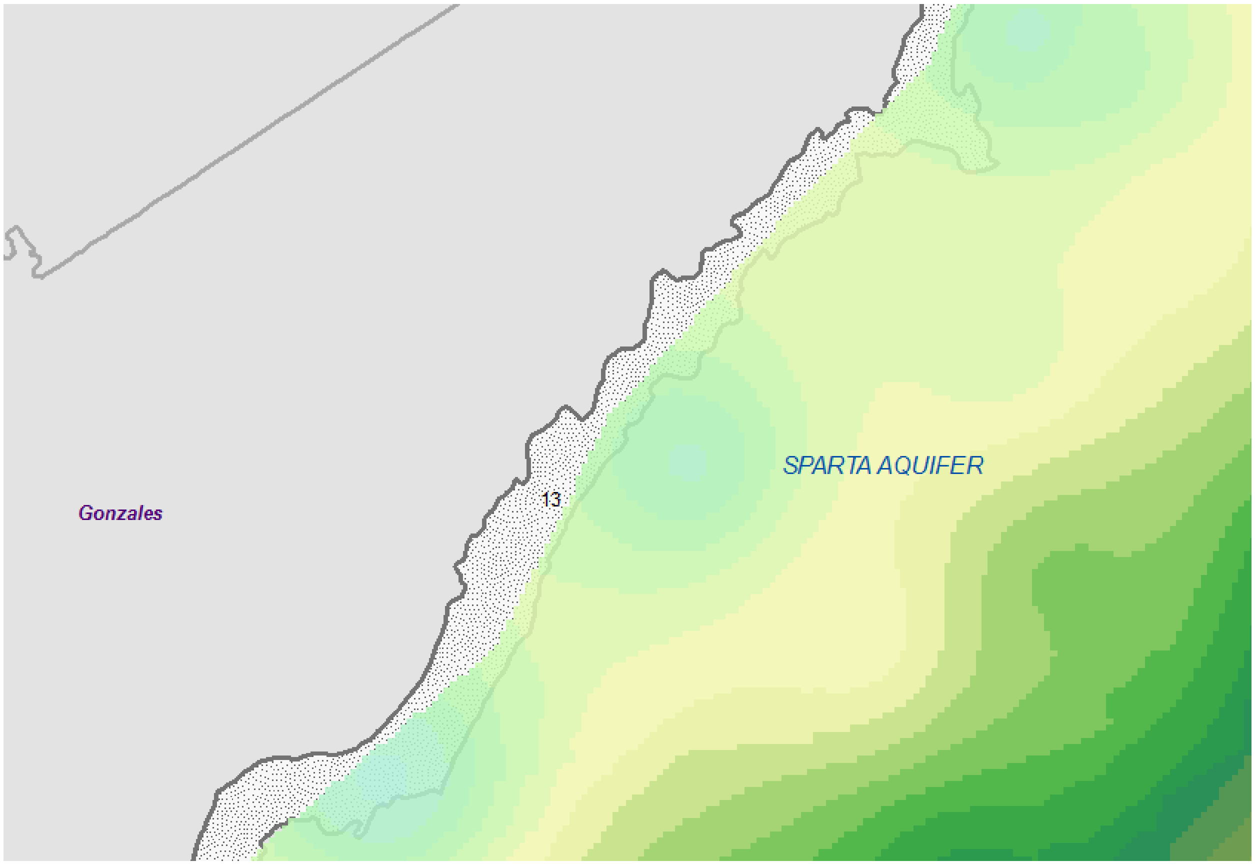
b. The inverse distance weighted surface interpolation technique used to create the formation and sand surfaces created a tremendous number of artifacts in the surfaces that are not geological in nature and lead to erroneous results. Please review the use of this technique and, if necessary use a surface interpolation tool that creates a more geological surface. The following figure using the Sparta Formation bottom depth illustrates this point: **Response: All GIS surface elevation grid files and thickness grid files have been re-generated using ordinary kriging methods.**



This figure of the Sparta Formation net sand thickness illustrates the same point:



c. The formation top and bottom depth rasters and sand rasters do not extend to the updip limit of the formation outcrop. The following figure of the Sparta Formation bottom depth illustrates this point:



The Sparta Formation outcrop is symbolized with black stippled bounded by black lines and the Sparta Formation bottom depth is in a color range. **Response: The clipping boundaries for most of the formation surfaces are now clipped at the southeastern-most outcrop boundaries, which represent the formation intersections with the ground surface. The outcrop areas are not included in most surface files because there is generally no well log information in those areas. The single exception is the base elevation grid file for the Queen City, for which there are several (28) well log locations defining the base depth of the formation in that outcrop area. Because well log information was not available in either the Sparta or Carrizo-Wilcox outcrop areas, the base elevation grid files for those units do not include the outcrop area.**

d. The formation top depth raster should include values of zero for the depth within the outcrop zone since the formation is at the ground surface. **Response: Conceptually, this is incorrect. The formation top surface elevation/depth is represented by the southeastern-most outcrop boundary, which forms a single line of intersection representing the formation top intersection with the ground surface and is not a planar feature. All areas within the outcrop represent locations within the**

formation that are intermediate to the top and the base depths. It seems inappropriate to mix conceptual values in the same grid file.

282. Please provide a GIS file with a record for each fault evaluated in the study. Contract amendment 7, paragraph 2, indicates that faults will be mapped. **Response: We did not map individual faults because fault intersections in well bores are rare and do not provide adequate information for mapping regional groundwater salinity patterns, or for documenting fault control on salinity changes. Documented regional fault zones from the literature are more useful for this task. See discussions in sections 4.1.2.3 and 4.1.2.5.**

BRACS Database Excel Files

282. Excel file tblWell_location.xlsx contains the following errors:

a. This table is required to have one record per well. The table provided contains 1,483 records and 240 of these have two records per well. The two records in many cases have different attributes and it appears many are in a NAD 83 and NAD 27 horizontal datum. Please rebuild this table and insert correct records. **Response: Done**

b. Please note that all well records should have location coordinates in NAD 83 format. Refer to contract Attachment II, Exhibit C, Attachment 4, Well Locations, 10 b. **Response: Done**

c. The table is missing a record for well 77010, API 4231101843 used on QCSP_CS4 cross section. Please provide this well information in all relevant tables. **Response: Done**

d. The field [Kelly bushing height] contains completely inaccurate data. A date value represents 423 of the 1483 records and the remainder of the records are null. Please provide accurate Kelly bushing heights in units of feet above ground surface. **Response: Done**

e. Twenty-one records contain missing county name values. Please provide this information. **Response: Done**

f. Twenty-three records have no latitude or longitude values. Please provide this information. **Response: Done**

g. Sixteen records have the latitude and longitude in the wrong fields. Please correct this information. **Response: Done**

283. Excel file tblBracs_ForeignKey.xlsx contains the following errors:

a. The table is missing records for wells with a BRACS well id 76039 – 76045. Please provide all foreign key records that are associated with all wells used in this study. **Response: these well ids not used in study**

284. Excel file tblWell_Geology.xlsx contains the following errors: **Response: Done**

a. There is incomplete lithology description for a significant number wells. For example, BRACS Well ID 4654 (API 4247934319) contains only three lithology records (sand), two of which in the Sparta (30 feet total) and one for the Queen City (26 feet total). However, the GIS raster indicates Sparta Formation net sand thickness is 96 feet and Queen City Formation net sand thickness is 910 feet. Review of the geophysical well log indicates that the Sparta Formation contains 106 feet of net sand in 6 sand units. The Queen City Formation contains 914 feet of net sand in 49 sand units. An analysis of the geology table indicates that 127 wells out of 312 wells only have one sand record in the Queen City Formation. An additional 93 wells out of the 312 wells have only two sand records in the Queen City Formation. The Queen City Formation across the study area consists of multiple sand units. Please provide the complete lithology analysis (all units, sand and clay) for every well used for lithology assessment in each of the study area formations.

b. Lithology data written to the field [lithologic_name] that was obtained from geophysical well log analysis should be written to the field [simplified_lithologic_name].

c. The hydrochemical records provided contain numerous errors with respect to salinity zone top and bottom depths and render the data useless. The salinity zones should stack on top of one another, yet (1) there may be gaps between zones, (2) there may be overlap between zones, (3) zones are duplicated, and (4) zones from the Queen City-Sparta and Carrizo-Wilcox formations overlap with one another. The following tables illustrate this problem for well 75200 (API 4228330123).

Table 1. Well 75200 showing the salinity zone top and bottom depths.

Strat. Name	Salinity Zone	Depth top	Depth Bottom
Queen City – Sparta	Slightly Saline	499	2290
Queen City – Sparta	Moderately Saline	543	1600
Queen City – Sparta	Fresh	741	2360

Queen City – Sparta	Very Saline	891	1392
Queen City – Sparta	Very Saline	891	1392
Carrizo-Wilcox	Slightly Saline	2275	3396
Carrizo-Wilcox	Fresh	2397	3101
Carrizo-Wilcox	Moderately Saline	3417	3596
Carrizo-Wilcox	Very Saline	3640	5037

Table 2. Well 75200 showing the stratigraphic top and bottom depths for each formation.

Stratigraphic Name	Depth top	Depth Bottom
Sparta Formation	496	786
Weches Formation	786	800
Queen City Formation	800	2361
Reklaw Formation	2361	2397
Carrizo-Upper Wilcox Subgroup	2397	3694
Middle Wilcox Subgroup	3694	4282
Lower Wilcox Subgroup	4282	5073

Review of the digital geophysical well log for well 75200 shows that the zones provided in the table are incorrect.

Please review and append new hydrochemical records for each well evaluated in the study. The salinity zones should be organized by individual aquifer (not grouped between aquifers, for example, Queen City – Sparta or Carrizo-Wilcox). **Response: Errors and repeats corrected. Salinity zones are interbedded, not stacked. More saline sands commonly overlie less saline sands. In some cases QC freshwater sands are completely below (top and base) QC brackish water sands. Stacked salinity zones increasing downward are not common here. These hydrochemical depths are better thought of as "deepest occurrence", which is how they are described in the report.**

d. Contract amendment 7, paragraph 2, indicates that fault picks will be made during this project. This information needs to be provided in the geology table with the field [geologic_pick] = "fault". Please refer to the BRACS Data Dictionary for information on the other required fault fields. **Response: No fault picks were made. The rare occurrence of a near vertical fault intersecting a vertical well does not provide much information about regional faulting patterns. Published fault maps were used instead.**

286. Excel file tblGeophysicalLog_Suite.xlsx contains the following errors:

a. The majority of the tools listed in this table are "electric". These records do not list each of the geophysical tools on the geophysical log. Please provide a record for each tool on the log with its corresponding start and end depths. Refer to contract Attachment II, Exhibit C, Attachment 4, Geophysical Well Log Data. **Response: Not done**

b. The geophysical log header table has 895 records. The geophysical well log suite table has 796 records. Each geophysical well log header record must have at least one corresponding record in the suite table. **Response: Done**

287. Excel file tblBracs_Ro_TDS_Main.xlsx contains the following errors:

a. Bracs Well ID 37235 and 77001 both have zero values for the fields [depth_top] and [depth_bottom]. These fields record the depth of the geologic unit that was assessed and are required fields. **Response: Done**

Aquifer Test Data

288. All aquifer test data used for the Wilcox, Carrizo, Queen City, and Sparta aquifers must be submitted to TWDB. Page 283, section 6.2.5.1 describes some of this data. This data needs to have one record per well provided in the well location table, corresponding records in the foreign key table, well report records in the well data table, aquifer test results provided in the aquifer test table, and copies of every digital well report. Please refer to the BRACS Data Dictionary for a list of each field of information that is required for the aquifer tests. This information was to be assembled under Task 6 of the contract amendment with all well control provided in Task 9 of the contract, deliverables, part 3. **Response: All of the hydraulic conductivity values used for the Carrizo-Wilcox models were assembled from Deeds and others (2003). No new aquifer information was gathered. Most of the hydraulic conductivity values for the Queen City and Sparta models were from Deeds and others (2003). Additional hydraulic conductivity values were calculated from specific capacity tests obtained from the TWDB electronic database of Submitted Drillers Logs. We have included those values in the TWDB database.**

Digital Geophysical Well Logs

289. If digital depth calibration files were created, purchased, or otherwise obtained for raster geophysical well logs in this study then they need to be provided as a deliverable. Please provide an Excel table with one record per well that lists the following attributes: 1) BRACS well id, 2) BRACS GL number, 3) digital file name for the tif or las digital log file, and 4) the digital file name for the depth calibration file. We consider the depth calibration files an integral deliverable used in the study. Please refer to contract amendment, Attachment II, Exhibit C, Attachment 4, section 1c: All well reports, geophysical well logs, a***nd other well information used in a project*** shall be provided to TWDB (italics added for emphasis). **Response: Done**

290. Please provide a copy of the digital geophysical well log(s) for well 77010, API 4231101843 used on the QCSP_CS4 cross section (Figure 4-57). **Response: Done, and located in folder with the depth calibration files**