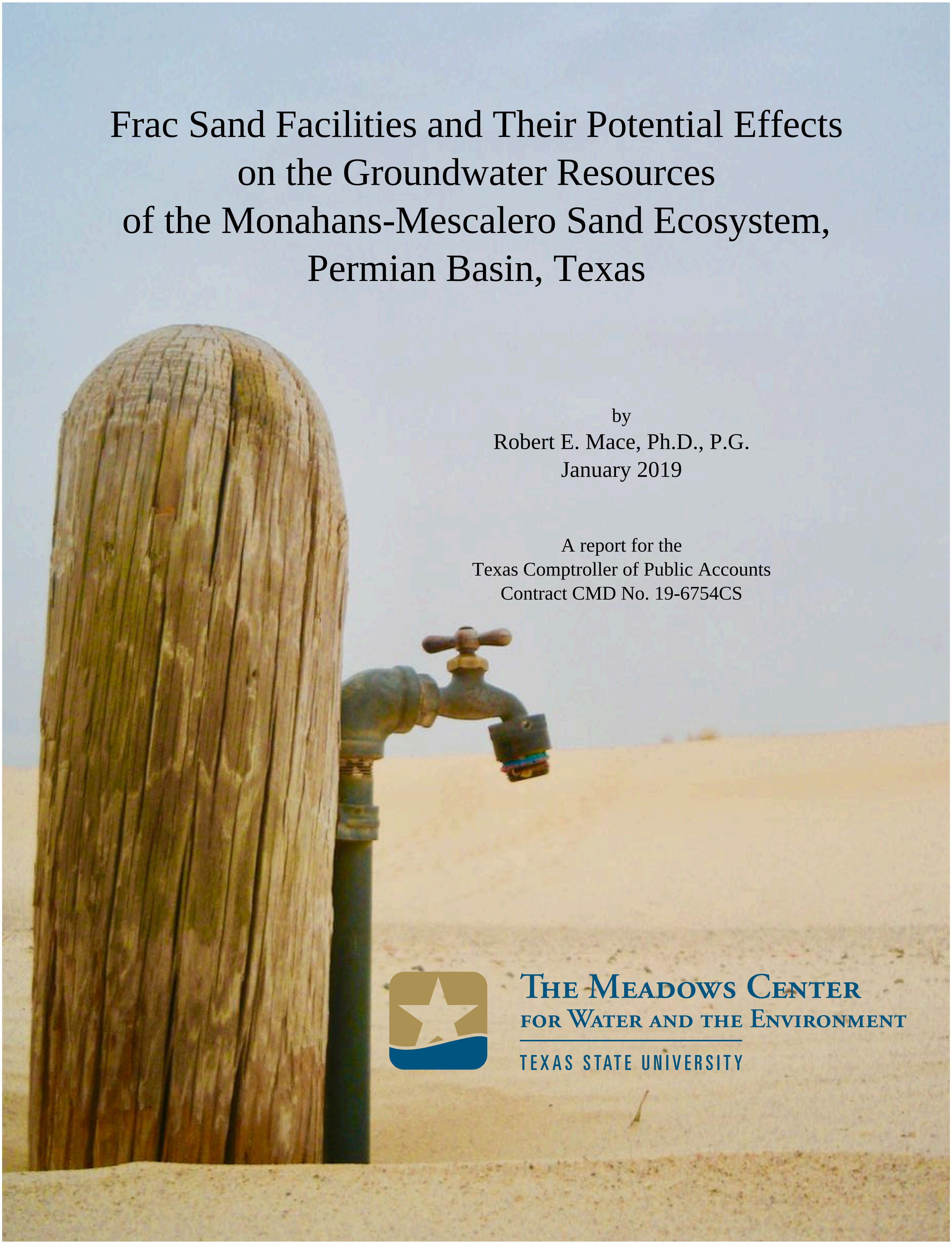

Frac Sand Facilities and Their Potential Effects on the Groundwater Resources of the Monahans-Mescalero Sand Ecosystem, Permian Basin, Texas

by
Robert E. Mace, Ph.D., P.G.
January 2019

A report for the
Texas Comptroller of Public Accounts
Contract CMD No. 19-6754CS

The Meadows Center
for Water and the Environment
Texas State University

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THE MEADOWS CENTER
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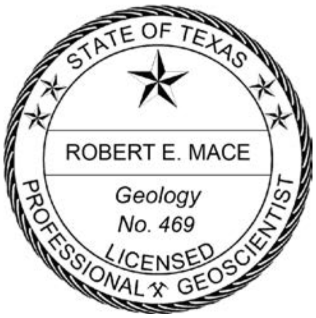

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Executive Summary

Hydraulic fracturing (fracking) a well requires sand and water—water to overpressure the formation to its breaking point and sand to prop the resulting array of fractures open once the pressure is released. Before 2017, except for several frac sand facilities located in Texas, almost all frac sand for the Permian Basin was sourced from the upper Midwest. After the downturn in oil prices in 2015, engineers in the Permian Basin began experimenting with local sands to reduce costs. Finding them usable and saving $45 per ton, frac sand facilities—which include mining and processing—began appearing in and along the Monahans-Mescalero Sand Ecosystem, home to the Dunes Sagebrush lizard, a species proposed for listing under the Endangered Species Act.

Frac sand facilities may impact the environment through air quality, land damage, surface-water and groundwater contamination, and groundwater depletion, all of which may affect habitat. The purpose of this study was to investigate the potential effects of frac sand facilities on the groundwater resources in the Monahans-Mescalero Sand Ecosystem in Andrews, Crane, Ector, Gaines, Ward, and Winkler counties in West Texas.

Since the first frac sand facility registered with the state in the study area in April 2017, a total of 17 frac sand facilities (one of which is idled) had registered with the Texas Commission on Environmental Quality by the end of 2018. All of the 16 active frac sand facilities are clustered along the Monahans-Mescalero Sand Ecosystem in a 20-mile by 40-mile area. Disturbed acres reported by operators in annual state registration paperwork for frac sand facilities in the study area—the projected acreage of excavation for the coming year in addition to the previous acres excavated—range from 5 to 300 acres for a total of 2,927 acres. These frac sand facilities have an annual capacity of 56.8 million tons.

Frac sand facilities generally need water for mining and transport, sand processing, dust control, and on-site potable needs. Water used to wash mined sand is commonly recycled, and the water use efficiency is generally high since many operators use closed-loop systems. There is no public data on how much water frac sand facilities in the Permian Basin consume. Facilities in the upper Midwest that are 90 percent efficient are reported to consume 130 to 260 gallons of water per ton of sand produced. Limited local information suggests that frac sand facilities in the study area consume between 60 and 250 gallons of water per ton—the exact amount will vary depending on how sand is transported, how clean the sand is, and the water efficiency of a facility.

Water for frac sand production in the Permian Basin is primarily sourced on-site from the Pecos Valley and the Dockum aquifers, although one site completed wells into the upper Permian and some sites use or appear to use off-site water from local and regional water providers. Perched aquifers form in the dune area where caliche slows the downward movement of water through the ground. These perched aquifers will be unaffected by

pumping from deeper aquifers but may be locally impacted by pumping from pools or shallow quarries and by removing contributing dunes.

I identified 230 production wells for the 16 facilities with production wells drilled at their locations. These wells range from 80 to 1,199 feet deep with 103 completed in the Pecos Valley Aquifer, 71 completed in the Dockum Aquifer, 32 completed in both the Pecos Valley and Dockum aquifers, and, at one facility, 14 completed in the Pecos Valley and Dockum aquifers and the upper part of the Permian. The number of wells at individual facilities ranged from 4 to 30. Nine—possibly 10—facilities have wells completed in both the Pecos Valley and Dockum aquifers. The relatively large number of wells drilled at many of these facilities suggests that the aquifers in this area are not highly productive, a conclusion supported by the thin saturated thickness of the Pecos Valley Aquifer and the low hydraulic conductivity of the Dockum Aquifer. Facility operators have to drill and string together wells until they meet their water needs.

Every pumped well affects an aquifer, whether through water levels, discharge to surface-water bodies, or land subsidence. It's too soon to see possible impacts from pumping beneath frac sand facilities with available state-collected data since the frac sand facilities are new, and the state measures water levels annually during the winter months. Furthermore, the wells the state measures are not in the best locations to assess effects of frac sand facility pumping. Also, pumping by the oil and gas industry and various municipalities may make it difficult to see the effects of frac sand facilities without purpose-built monitoring. Current estimated frac sand facility water use (10,000 to 40,000 acre-feet per year, based on 60 to 250 gallons of water consumed per ton of produced sand) rivals or exceeds that of water used in the four counties (Crane, Ector, Ward, and Winkler) with active frac sand facilities (23,500 acre-feet per year).

With a lack of site-specific water use and hydraulic properties, I modeled two hypothetical situations for a typical frac sand facility for a typical Pecos Valley Aquifer source and a typical Dockum Aquifer source consuming 70 gallons of water per ton of produced sand.

For a well field of 12 wells in the Pecos Valley Aquifer, the distance to the 5-foot water-level decline is 550 feet after 1 year of pumping and 4,000 feet after 10 years of pumping. A well in the interior of the well field would have 25 feet of water-level decline after 1 year of pumping and 47 feet of decline after 10 years of pumping. Given that the saturated thickness of the typical Pecos Valley Aquifer in the study area is 70 feet, this suggests that long-term pumping of the aquifer in the area may be a challenge requiring additional wells over time or the use of alternative water supplies.

For a well field of 7 wells in the Dockum Aquifer, the distance to the 5-foot water-level decline contour is about 40,000 feet (7.5 miles) after 1 year of pumping and 130,000 feet (24.6 miles) after 10 years of pumping. A well in the interior of the well field would have 272 feet of water-level decline after 1 year of pumping and 360 feet of decline after 10 years of pumping. Pumping the Dockum Aquifer results in larger and broader declines because, in large part, it’s a confined aquifer whereas the Pecos Valley Aquifer is unconfined. For the Dockum Aquifer, these simulations suggest that pumping might completely deplete artesian pressure at the well field after 10 years.

Wells in well fields can interfere with each other, but well fields can also interfere with each other. For the Pecos Valley Aquifer, facilities with well fields within two miles of each other are likely to produce water-level declines that interfere with each other in as soon as a year and more as time goes on. This interference may further lower well yields resulting in the need for more wells over time. For the Dockum Aquifer, well fields within 50 miles of each other may interfere with each other. Again, this interference may lower well yields resulting in the need for more wells. Pumping effects over the long term will likely remain relatively local in the Pecos Valley Aquifer—a common attribute of unconfined aquifers—and will likely be regional in the Dockum Aquifer—a common attribute of confined aquifers.

Recent sand demand growth is due to an increase in the amount of sand used per foot of frac, longer laterals, and increasing frac stages. The amount of sand per unit distance of frac is expected to increase with improving technology and increasing number of frac stages per hole. Since local sands currently provide almost 40 percent of the Permian Basin’s sand needs, local sand production will likely continue—and continue to grow—for the foreseeable future.

The Rule of Capture rules in the four counties with active frac sand facilities, meaning that landowners can drill as many wells as they want and pump as much as they want without permits or regulation. Outside of the Llano Estacado Underground Water Conservation District in Gaines County—where there are no active frac sand facilities—there is no regulatory authority for groundwater use in the rest of study area beyond state requirements to submit a driller’s report with the Texas Department of Licensing and Regulation. Groundwater conservation districts could be formed in the study area at any time through petitioning the Texas Commission on Environmental Quality, legislative action, the Priority Groundwater Management Area process, or annexation to a neighboring district.

The Pecos Valley and Dockum aquifers are witnessing a great deal of new well drilling and pumping by existing users such as local municipalities and the oil and gas industry and new users such as non-local water suppliers east of the study area and frac sand facilities. At this point, given all the new interest in the area’s groundwater resources and the uncertainty in pumping rates, it’s unclear what the effects of increased pumping might be, but water levels will surely decline over time. How much they decline and how much they affect groundwater resources—and the people and species that rely on them—remains to be seen.

I recommend following ongoing activity in the area by all pumpers and, if possible, expanding water-level monitoring to gain a better understanding of how additional pumping is affecting the aquifers. This study suffered from a lack of site-specific information on water use and produced sand tonnage. If the state wishes to have a better understanding of potential effects from pumping at these facilities, then requiring the reporting of this information would be useful. Finally, well completions across different aquifers should be discouraged. Even when pumping at these wells stop, aquifers with higher water-level elevations—such as the Pecos Valley Aquifer—will continue to drain into deeper, depleted formations, thus affecting the water resources for remaining users as long as the well connection exists.

"Other than water, there is very little in the world more boring than sand."
–Jennifer Presley, Executive Editor, E&P Magazine

1. Introduction

There are many aspects to successfully hydraulic fracturing (or fracking) a well, but there are no raw ingredients more critical than sand and water. Water is needed to overpressure the formation to its breaking point and carry sand into the resulting array of fractures, and sand is necessary to prop those fractures open once the overpressure is released[1]. Water and sand work together to create passageways for oil and gas to flow to a producing well.

Ever since the shale revolution started with fracking the Barnett Shale in and near Fort Worth, Texans have expressed concern about the potential effects on water resources, including quantity (for example, Bene and others 2007) and quality (for example, Rawlins 2014). Although the volume of water used for fracking in Texas amounts to about 150,000 acre-feet per year, it constitutes no more than 1 percent of total water use in the state (TWDB 2017 p57). However, since the water demand for fracking is focused where shale is productive, fracking water use as a percentage of local demand can be much more significant.

The ideal sand used for fracking (frac sand) is uniform in size and shape (WDNR 2012) and can withstand lithostatic pressure, temperature, and dissolution (Bleiwas 2015). Traditionally, frac sand has sourced from the upper Midwest with sand called Northern White or Ottawa White (Benson and Wilson 2015). However, transportation costs, generally by rail and truck, can double to triple the price of sand produced at a facility[2] in

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[1] Sand serves as a proppant. There are alternative proppants on the market such as ceramics, but, due to cost, sand is generally the proppant of choice.

[2] Commonly referred to as 'frac sand mines,' I've chosen to refer to them in the report as 'frac sand facilities' because these operations generally include on-site processing plants in addition to mining.

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the upper Midwest by the time it is delivered to the Permian Basin (based on numbers provided by Bleiwas 2015 for ~2013, Zdunczyk 2016, McEwan 2017).

These transportation costs initially led to the search for more local sources such as Brown Sand or Brady Sand mined from the Hickory Sandstone Member near Brady, Texas (Benson and Wilson 2015), even though these local sands may not be as ideal as sands from the upper Midwest (Bleiwas 2015). After a downturn in oil prices in 2015, engineers in the Permian Basin began experimenting with even more local sand from the Monahans-Mescalero Sand Dunes and found them passable (McEwen 2017; Mentz 2018, Zdunczyk 2018). By reducing transportation costs through local sources, estimated cost savings can be $45 per ton of sand (Zdunczyk 2018). Triepke (2018a) estimated that twenty local frac sand facilities could save the oil and gas industry in the Permian Basin $3.5 billion.

As with any mining and processing activity, frac sand facilities have their potential environmental impacts, including air quality, land damage, surface-water and groundwater contamination, and groundwater depletion (Orr and Krumenacher 2015) as well as noise and traffic (Maslowski 2012 as cited in Benson and Wilson 2015) and wildlife.

The purpose of this study was to investigate the potential effects of frac sand facilities on groundwater resources in the Monahans-Mescalero Sand Ecosystem area, home to the Dunes Sagebrush lizard (Zdunczyk 2018), a species proposed for listing under the Endangered Species Act. I did this by (1) describing the physiography, hydrogeology, groundwater management, and frac sand production in the area; (2) estimating water usage; and (3) modeling potential effects that groundwater production may have—short-term and long-term—on water levels in the area.

Regulation of groundwater use and water-level and aquifer property information in the area is limited; therefore, information on water use and its effects are limited, restricting my ability to assess and project impacts. Furthermore, the development of frac sand facilities in the area is a rapidly changing with new production expected. Nonetheless, this analysis can be used to provide a glimpse into what is currently happening in the area concerning facility development and water resources and what that might mean for water levels in the area.

I’ve used operator and facility names based on the names used to register frac sand facilities with the state. The frac sand business is undergoing consolidation and change, so there have been some acquisitions since facilities have been registered (and those acquisitions continue). I’ve noted the acquisitions I’m aware of in the footnotes of Table 5.1.

2. Study Area

The study area includes Andrews, Crane, Ector, Gaines, Ward, and Winkler counties in West Texas (Figure 2.1). These counties are part of the Southern High Plains physiographic province characterized by its flatness, playa lakes, and local dune fields (Wermund 1996). Land-surface elevation ranges from about 2,300 feet above sea level in Crane County near Girvin, Texas, to about 3,700 feet in the northwest corner of Gaines County.

Average annual precipitation is about 15 inches (TWDB 2012 p149) and is unimodal with most precipitation falling between May and October (TWDB 2012 p147). Average annual gross lake evaporation is about 70 to 75 inches per year (TWDB 2012 p149). Average annual temperature is about 58 to 60 degrees Fahrenheit (TWDB 2012 p149).

The study area is split northwest to southeast between the Rio Grande and Colorado river basins (Figure 2.2). All six counties of the study area include parts of the Monahans-Mescalero Sand Ecosystem (Figure 2.3). Havard Shin Oak, Havard Shin Oak-Mesquite, and Mesquite-Lotebush brush exist in the dune area (TPWD 1984).

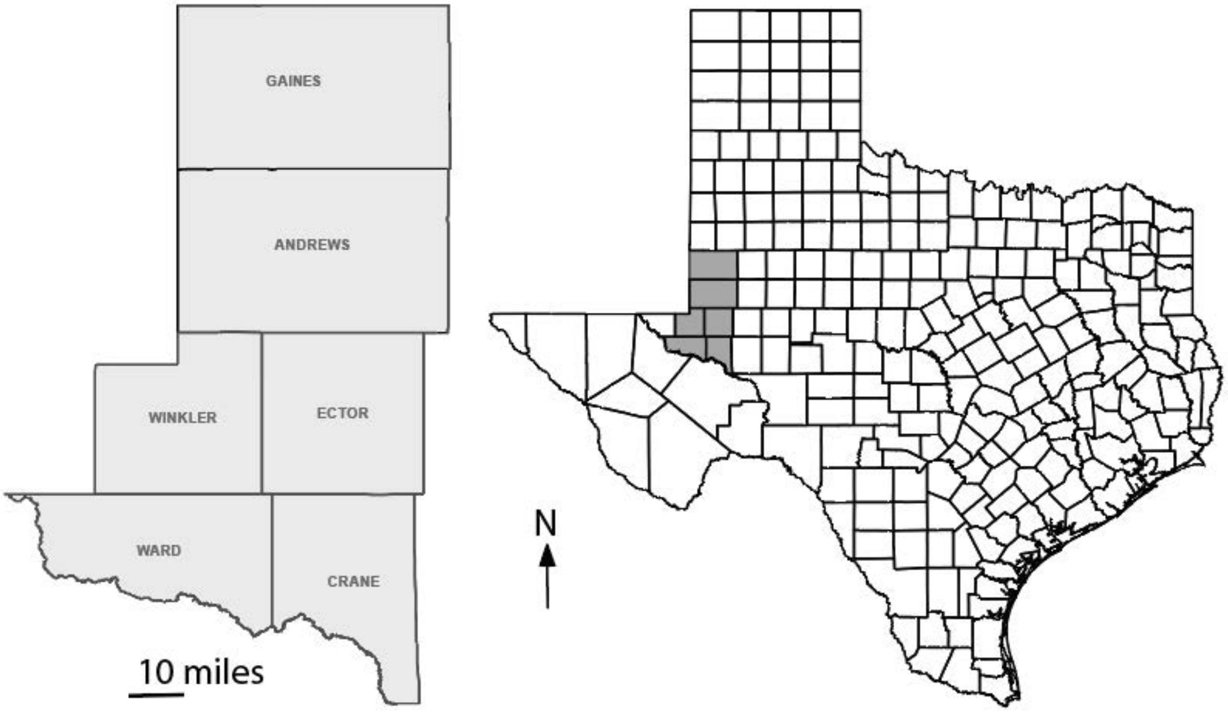

Figure 2.1: Study area located in Andrews, Crane, Ector, Loving, Ward, and Winkler counties.

Figure 2.2: The basin boundary between the Colorado River and Rio Grande splits the study area primarily through Andrews and Ector counties (modified from TWDB 2018a).

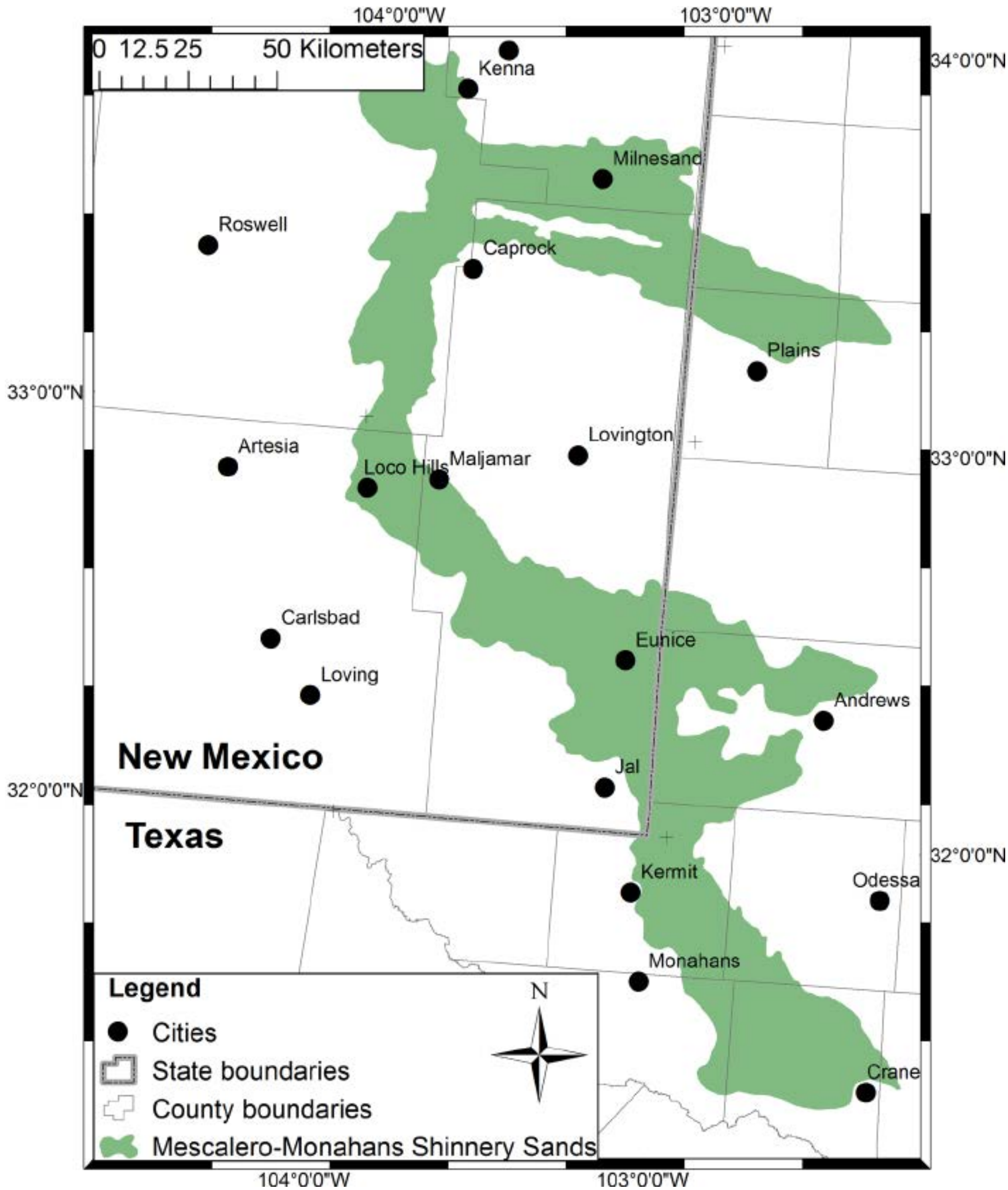

Figure 2.3: Approximate extent of the Monahans-Mescalero Sand Ecosystem in Texas and New Mexico (from Leavitt and Fitzgerald 2013).

3. Hydrogeology

The study area has three major aquifers— Edwards-Trinity (Plateau), Ogallala, and Pecos Valley—and four minor aquifers— Capitan Reef Complex, Dockum, Edwards-Trinity (High Plains), and Rustler—as defined by the Texas Water Development Board (Figure 3.1; George and others 2011).

The Ogallala Aquifer consists of sand, gravel, clay, and silt deposited during the Tertiary (Ashworth and Hopkins 1995) and underlies all of Gaines County, most of Andrews County, the northeast corner of Ector County, and a small part of northeastern Winkler County (Figure 3.1a). The Ogallala Aquifer in Gaines County is the source of about 86 percent (~330,000 acre-feet) of all the pumping in the study area with about 96 percent of that pumping used for irrigation (Table 3.1). Users pump lesser amounts of Ogallala water in Andrews (~20,000 acre-feet constituting about 93 percent of all groundwater use in the county) and Ector (165 acre-feet) counties (Table 3.1).

The Pecos Valley Aquifer consists of alluvial and windblown sediments in the Pecos River Valley (George and others 2011) and underlies all of Ward County, most of Crane and Winkler counties, and parts of Andrews and Ector counties (Figure 3.1a). The Pecos Valley Aquifer is the primary source of groundwater in Crane (~84 percent) and Ward (~88 percent) counties with lesser amounts pumped in Andrews County (Table 3.1).

The Edwards-Trinity (Plateau) Aquifer consists of the limestone and dolomites of the Edwards Group and the sandstones of the Trinity Group (George and others 2011) and underlies most of Ector County and parts of Andrews, Crane, and Winkler counties (Figure 3.1a). In parts of Andrews and Ector counties, the Ogallala Aquifer overlays the Edwards-Trinity (Plateau) Aquifer (Figure 3.1a). The aquifer is the primary source of groundwater in Ector County (~83 percent) but also provides minor amounts of groundwater for Andres and Winkler counties (Table 3.1).

The Edwards-Trinity (High Plains) Aquifer underlies parts of the Ogallala Aquifer and consists of the limestones and sandstones of the Edwards and Trinity groups (George and others 2011). In the study area, the aquifer underlies the northern two-thirds of Gaines County (Figure 3.1b) providing about 10,000 acre-feet in 2016, mostly for irrigation (Table 3.1).

The Dockum Aquifer consists of gravel, sandstone, siltstone, mudstone, shale, and conglomerate with the highest yields from the middle and base of the aquifer, generally from the Santa Rosa Formation (George and others 2011). The lower, productive part of the Dockum is often referred to locally and on well logs as the Santa Rosa Aquifer. The Dockum underlies most of the study area including all or almost all of Andrews, Ector, and Winkler counties and most of Crane, Gaines, and Ward counties (Figure 3.1b). Most (~83 percent) of the pumping from the Dockum Aquifer occurred in Winkler County with most of that (~98 percent) for municipal use (Table 3.1).

The Rustler Aquifer consists of carbonates and evaporites and appears in the subsurface in the far western part of Ward County (Figure 3.1b) where it provided two acre-feet for municipal and livestock needs (Table 3.1).

The Capitan Reef Complex Aquifer consists of cavernous dolomite and limestone (George and others 2011) and occurs in the study area in Ward and Winkler counties (Figure 3.1b). There is no reported water use from this aquifer in the study area (Table 3.1).

The two aquifers locally used for frac sand production in the study area are the Pecos Valley and Dockum aquifers (see Section 6.3); therefore, I will only present hydrologic information on these two aquifers.

3.1 Hydraulic Properties of the Pecos Valley Aquifer

The Pecos Valley Aquifer fills two troughs, the Monument Draw Trough that runs through Winkler, Ward, and Pecos counties and the Pecos Trough in Reeves County and far western Ward County (Figures 3.2 and 3.3). The Monument Draw Trough is of interest since it exists in the study area. In the deepest parts of the Monument Draw Trough, the thickness of the sediments that make up the Pecos Valley Aquifer in the study area are much thicker—upwards of 1,000 to 1,500 feet thick—than on the flanks of the trough—including the Monahans-Mescalero Sand Ecosystem—where thicknesses are commonly less than 200 feet (Figure 3.4).

Depths to the water table, as measured between 2000 and 2009, range from about 17 feet in southeastern Ward County near the Pecos River to 165 feet in west-central Winkler County in the Monument Draw Trough (Figure 3.5). For the Monahans-Mescalero Sand Ecosystem—located in eastern Winkler and Ward counties and Crane County—depth to water is shallower at 12 to 75 feet (Figure 3.5). The saturated thickness of the Pecos Valley Aquifer—the distance between the water table and the base of the aquifer—ranges from almost nothing to more than 1,000 feet with most of the study area at less than 100 feet (Figure 3.6). For most of the Monahans-Mescalero Sand Ecosystem in the study area, the saturated thickness is less than 100 feet with small areas of no saturated thickness and areas with more than 100 feet of saturated thickness (Figure 3.6).

Hydraulic conductivity—a measure of how easily water flows through porous media—ranges from about 4 to 27 feet per day for the Pecos Valley Aquifer (Figure 3.7) with higher values in the Ward, Winkler, and Andrews counties where the dune sands overlie the aquifer (compare Figure 3.7 to Figure 2.3). Anaya and Jones (2009) were not able to locate storativity values—a measure of how much water is released from or added to storage per unit surface area in the aquifer for a unit change in water level—for the Pecos Valley Aquifer but noted that specific yield values (storativity for unconfined aquifers) for sand and gravel alluvium commonly range from 0.1 to 0.25 (based on Fetter 1988, Domenico and Schwartz 1990, Anderson and Woessner 1992). In their groundwater model, Anaya and Jones (2009 p84) used 0.20 for the specific yield for the Pecos Valley Alluvium.

3.2 Hydraulic Properties of the Dockum Aquifer

The Dockum Aquifer sits immediately below the Pecos Valley Aquifer in the study area (Figures 3.9, 3.10, and 3.11 with Figure 3.8 for spatial reference). Elevation of the bottom of the Dockum Group ranges from under 1,200 feet above sea level in Andrews and Gaines counties to just over 2,400 feet in Winkler County with a ridge in Ward and Winkler counties (Figure 3.12). Thickness of the lower portion of the Dockum Group (which includes the sandstones and conglomerates of the Santa Rosa Formation and the mudstones and siltstones of the Tecovas Formation; Ewing and others 2008 p3-2), ranges from under 200 feet in western Winkler County to more than 1,200 feet thick in parts of Andrews, Ector, and Gaines counties (Figure 3.13). Water-level elevations for 1997 range from about 2,400 feet above sea level in southeastern Crane and southern Gaines County to 2,800 feet in northwestern Winkler County (Figure 3.14).

Measured hydraulic conductivity of sands in the Dockum Aquifer ranges from 0.3 to more than 300 feet per day (Figure 3.15). Kriged values range from less than 5 to more than 30 feet per day (Figure 3.16). Because sand fractions for much of the study are less than 50 percent of the thickness of the lower portion of the Dockum Group (Figure 3.17), calibrated hydraulic conductivity values (Figure 3.18) better reflect the aquifer.

Bradley and Kalaswad (2003 p. 2) reported storativities for the Dockum Aquifer in Winkler County of 2.4×10^{-4} and 2.5×10^{-4}, indicative of confined conditions. Ewing and others (2008) noted that storativities in the Dockum ranged from 1×10^{-4} to 5×10^{-4}, again indicative of confined conditions. Ewing and others (2008) indicated that there were no measurements of specific yield for the Dockum Aquifer and used 0.15 in their model.

3.3 Shallow Groundwater in the Monahans-Mescalero Sand Dunes

There have been historical and contemporary reports of long-term standing water among the Monahans-Mescalero Sand Dunes. Brune (1981) noted that Antonio de Espejo found Jumanos hunting white-tailed deer in the sand hills in 1583 and that two Christianized Indians were held captive at a ranch at the springs of the sand hills in 1763. Many Indian artifacts have been found among the dunes, indicative of attracting humans to the area (Justice and Leffler 2016).

In 1848, Captain R.B. Marcy of the Corps of Topographical Engineers found a Comanche in Santa Fe willing to take him across the dreaded Llano Estacado along a southern route paralleling the present-day border between Texas and New Mexico. Marcy's entourage encountered the dunes in modern-day Ward County (Mace 2006):

> *"These hills, or mounds, present a most singular and anomalous feature in the geology of the prairies. They extend (so far as we have explored) at least fifty miles in nearly a north and south direction, and from five to ten miles east and west; they are white drift-sand thrown up with much uniformity into a multitude of conical hills, destitute of soil, trees, or herbage. In following up the trail from our road into the midst of this ocean of sand, we suddenly came upon several large,*

deep pools of pure water the very last place on earth where one would ever think of looking for it. We are told by our guide that water can always be found here in the dryest [sic] season, and, judging from the rushes and other water plants growing in the ponds, I have no doubt that such is the case."

More recently, Machenberg (1982, 1984) mentions "interdunal ponds" at Monahans Sandhills State Park and includes photographs of them. Machenberg (1982) notes that unvegetated dunes immediately absorb rainfall (there is no surface drainage in the dune field) and can store large amounts of rainfall and that the surficial sand is a locally important aquifer. She also notes that perched water tables form where the caliche is sufficiently thick.

The Atlas Sand Company's north facility (Atlas North near Kermit) has a shallow dugout ("no more than 10-15 ft. deep") that they used as a source of water for construction (Triepke 2018b; Figure 3.19). The high water content in the sand onsite caused Atlas Sand to modify construction techniques (Triepke 2018b). High Roller Sand's Kermit Plant also has shallow water (described as pooling in a shallow quarry; Triepke 2018c).

A perched aquifer is a "[l]ocally saturated zone overlying a low-permeability unit in the otherwise unsaturated zone" (Porges and Hammer 2001). Perched aquifers generally form when the downward movement of water encounters a lower-permeable layer allowing water to accumulate into a saturated zone before developing enough hydraulic head to push water through the perching layer at the same rate the water is moving downward or flowing over the lateral limits of the perching layer.

As discussed, Machenberg (1984 p. 19) suggests that a perched aquifer is the source for the interdunal ponds. A generalized cross-section in her guidebook shows that pond sediments and caliche may act as local perching layers. Machenberg (1984 p. 25–26) noted that ponds form after heavy rains but disappear after a couple of months; however, she said that there are a few permanent pools fed by a perched aquifer in the northwest corner of the state park (I was not able to identify any bodies of water in the park via Google maps).

In addition to shallow water pooling in a shallow quarry, High Roller Sand's Kermit Plant also had deeper wells where the water table is reached at 40 feet (Triepke 2018c) suggesting that the shallow water at the surface is hydraulically separate from the deeper aquifer and thus perched. Machenberg (1984) also noted shallow wells in the area used for livestock. I found shallow stock wells to the west of the park reported depths to water of 13 feet in 1957 and 1967 (Well 45-18-701; although well is reported to be 10 feet deep), 5 feet in 1957 (Well 45-18-702; well is 10 feet deep), 9.9 feet deep in 1949 and 9.6 feet deep in 1967 (Well 45-17-907; well is 10 feet deep) (TWDB 2018b).

If these pools source from perched aquifers—as they appear to be—then pumping from the Pecos Valley Aquifer beneath would have no impact on them. However, pumping or potential pumping from the pools, as described by Triepke (2018b, c) as well as removing contributing dunes would likely impact these perched aquifers.

Table 3.1: Groundwater pumping in acre-feet in the study area in 2016 as reported by TWDB (2018c).

County	Aquifer	Municipal	Manu.	Mining	Electric	Irrigation	Livestock	Total
Andrews	Dockum	-	-	8	-	-	2	10
	Edwards-Trinity (Plateau)	-	-	-	-	-	2	2
	Ogallala	3,009	-	114	-	16,536	156	19,815
	other	-	-	-	-	-	2	2
	Pecos Valley	110	-	-	-	-	28	138
	unknown	-	-	1,358	-	-	-	1,358
	total:							21,325
Crane	Dockum	154	-	-	-	-	21	175
	Pecos Valley	1,014	-	-	-	-	41	1,055
	unknown	-	-	29	-	-	-	29
	total:							1,259
Ector	Dockum	61	4	-	-	-	2	67
	Edwards-Trinity (Plateau)	2,198	14	12	14	131	84	2,453
	Ogallala	108	-	-	-	53	4	165
	Pecos Valley	-	-	-	-	-	-	-
	Trinity	4	6	-	-	-	-	10
	unknown	-	-	501	-	-	-	501
	total:							2,950
Gaines	Dockum	17	-	-	-	-	-	17
	Edwards-Trinity (High Plains)	123	-	-	-	9,797	37	9,957
	Ogallala	8,800	189	4,623	-	315,676	92	329,380
	unknown	-	-	501	-	-	-	501
	total:							339,855
Ward	Dockum	6	-	-	-	21	8	35
	other	-	-	-	-	43	-	43
	Pecos Valley	5,273	-	-	16	1,650	50	6,989
	Rustler	1	-	-	-	-	1	2
	unknown	-	-	879	-	-	-	879
	total:							7,948
Winkler	Dockum	1,438	29	-	-	-	6	1,473
	Edwards-Trinity (Plateau)	-	-	549	-	-	-	549
	total:							11,388
Grand total:								384,725

manu. = manufacturing; other = an aquifer that is not recognized as a major or minor aquifer by the state; unknown = unknown aquifer. The Trinity Aquifer is listed under Ector County; however, the Trinity Aquifer as defined by George and others (2011) does not exist in this part of Texas, although Trinity rocks are part of the Edwards-Trinity (Plateau) and Edwards-Trinity (High Plains) aquifers. The Mining category includes water pumped for oil and gas as well as for frac sand facilities; however, for the study area, these pumping estimates do not include frac sand facilities because the estimates pre-date frac sand activities.

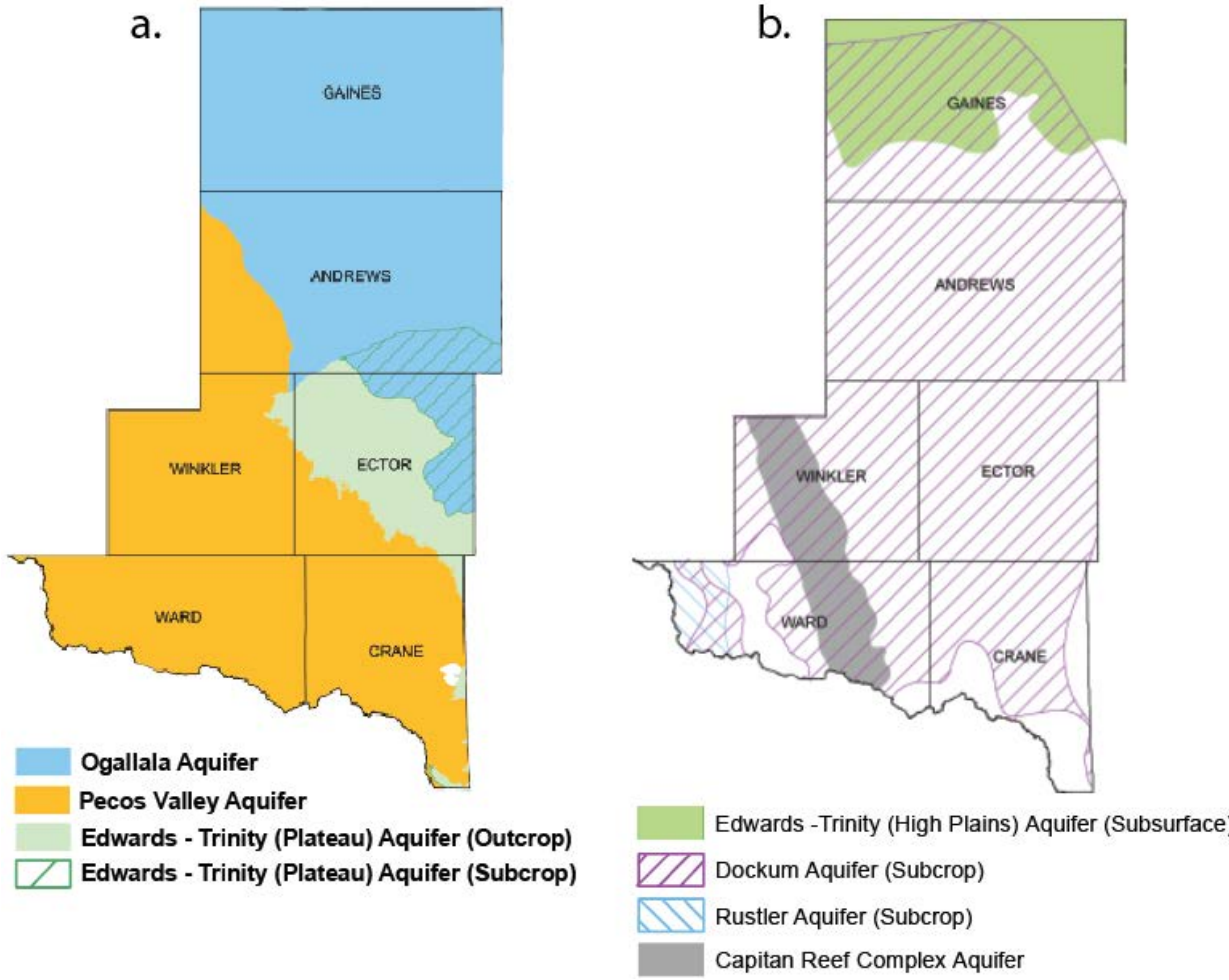

Figure 3.1: Major and minor aquifers in the study area (modified from TWDB 2018a).

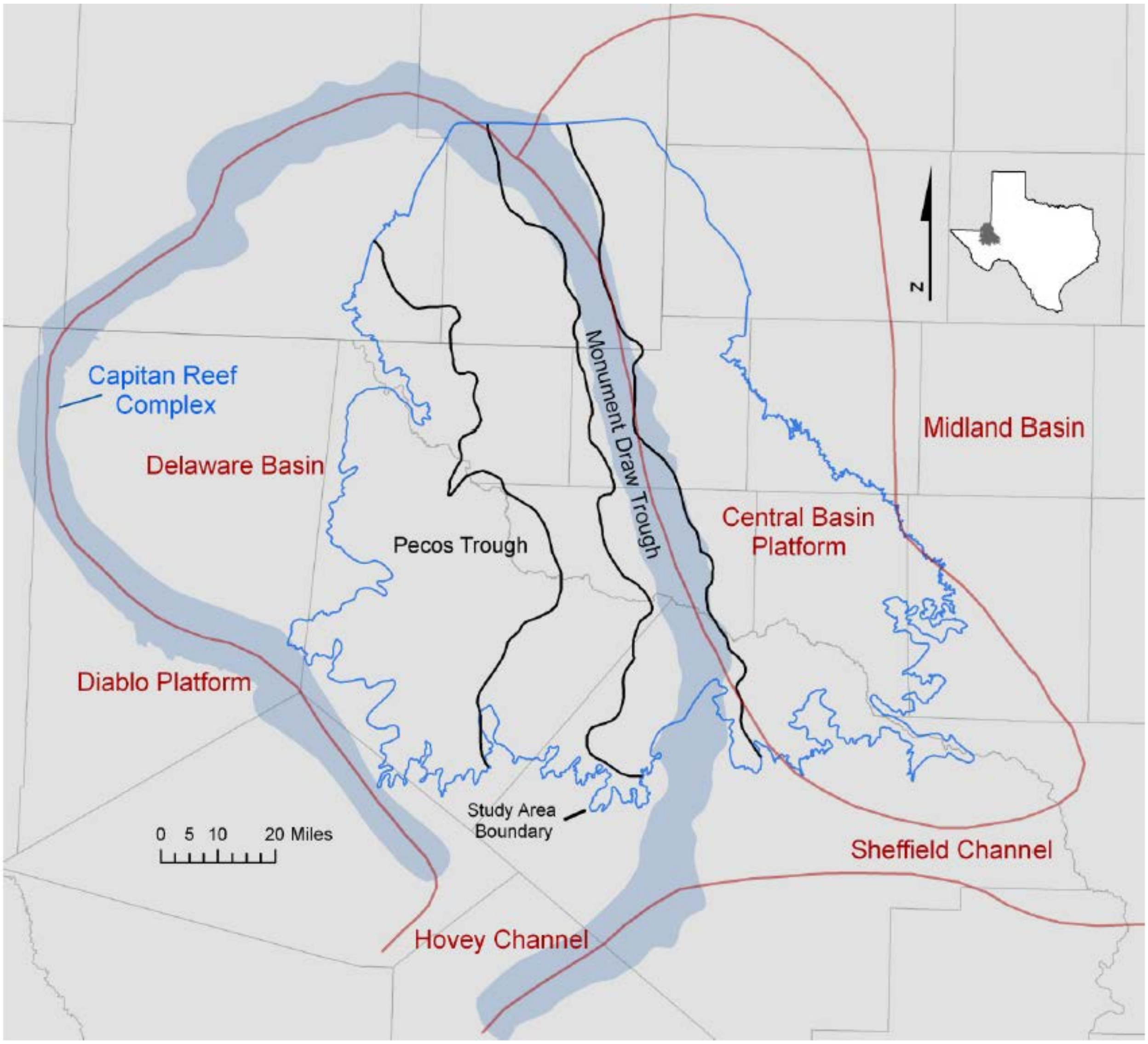

Figure 3.2: Major geologic features in the Pecos Valley Aquifer area (noted as 'Study Area Boundary' on the graphic; from Meyer and others 2012).

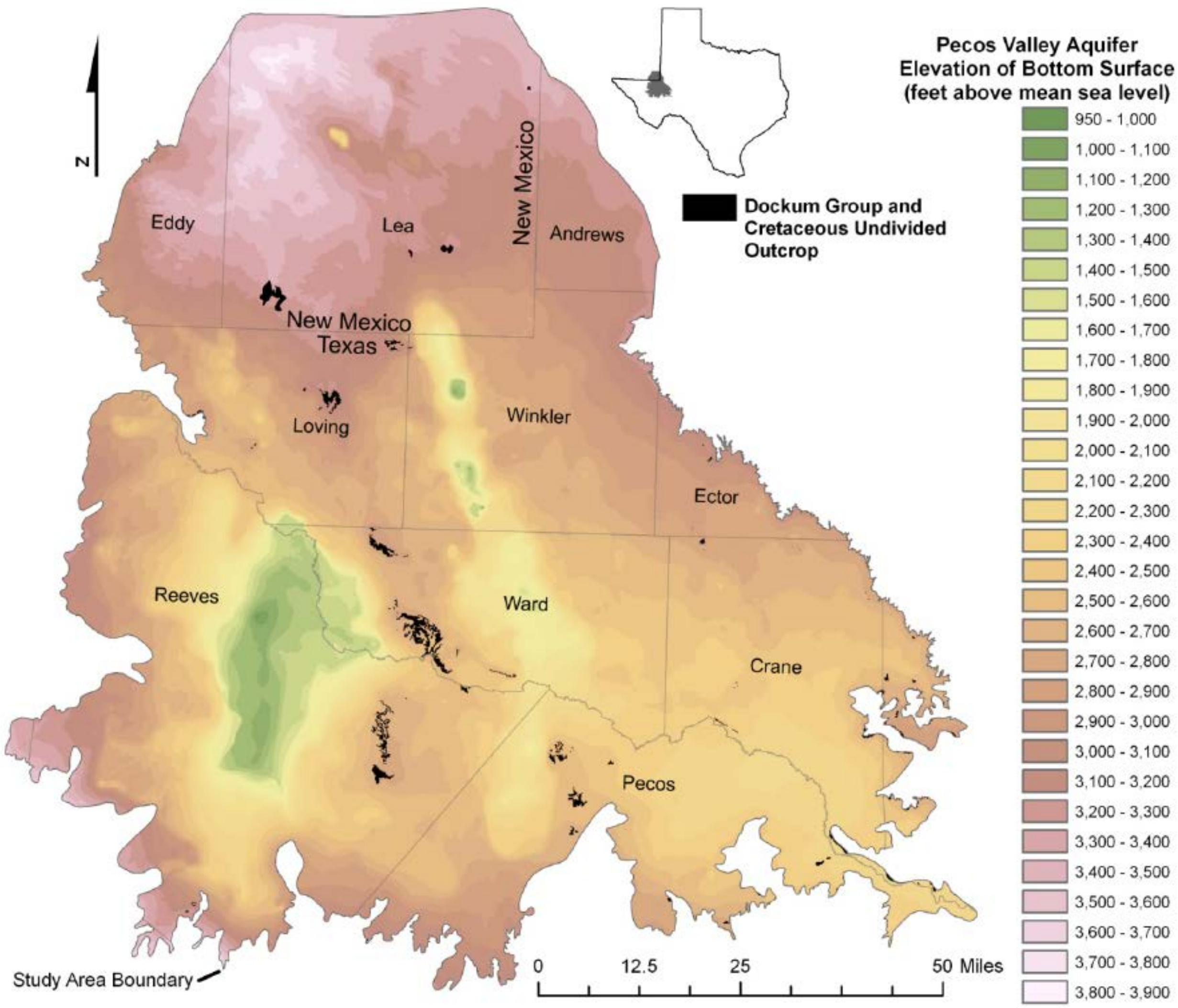

Figure 3.3: Elevation of the bottom of the Pecos Valley Aquifer (from Meyer and others 2012).

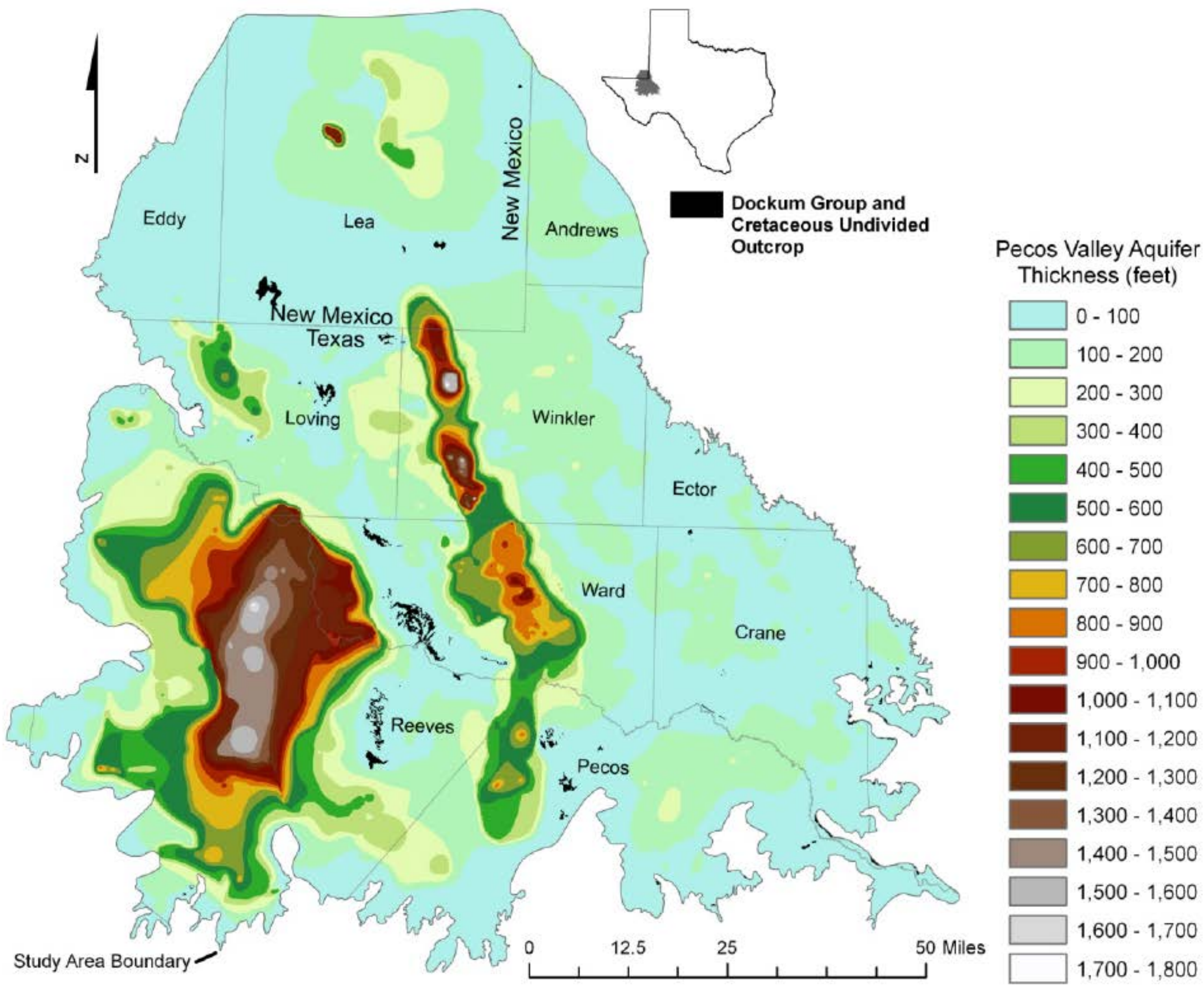

Figure 3.4: Thickness of the sediments that make up the Pecos Valley Aquifer (from Meyer and others 2012).

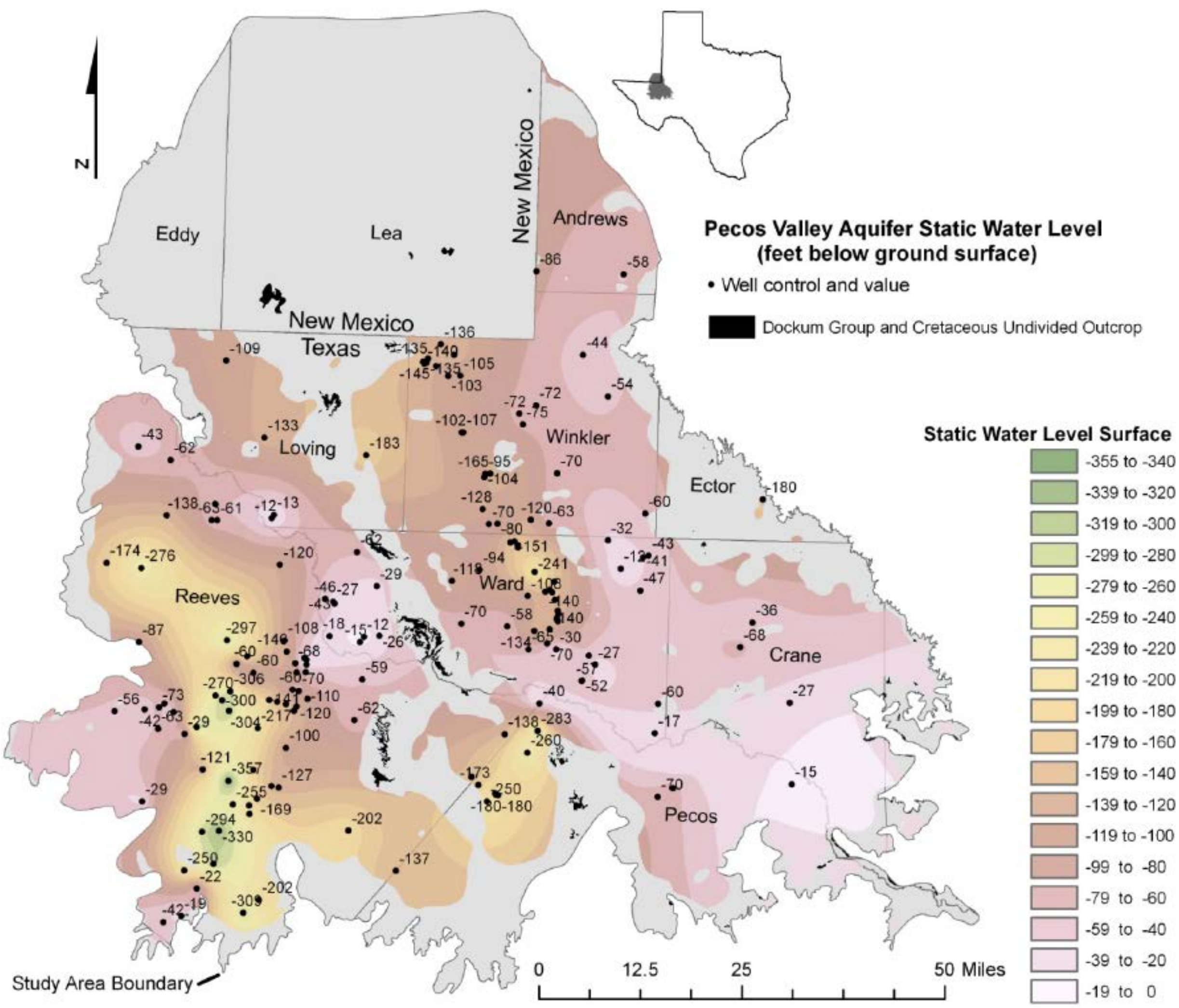

Figure 3.5: Depth to the water table in the Pecos Valley Aquifer as measured between 2000 and 2009 (from Meyer and others 2012).

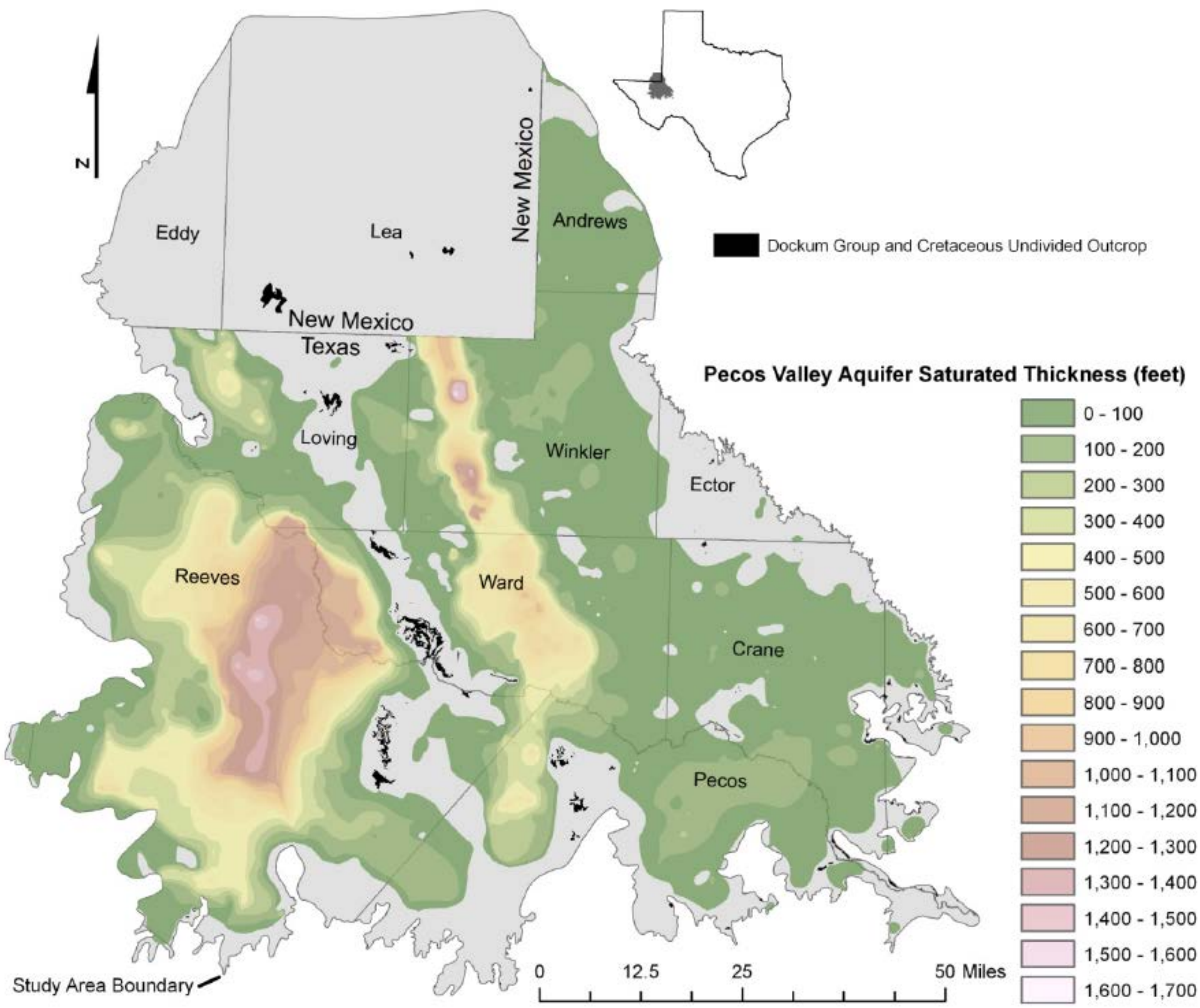

Figure 3.6: Saturated thickness of the Pecos Valley Alluvium (from Meyer and others 2012 for water levels measured between 2000 and 2009).

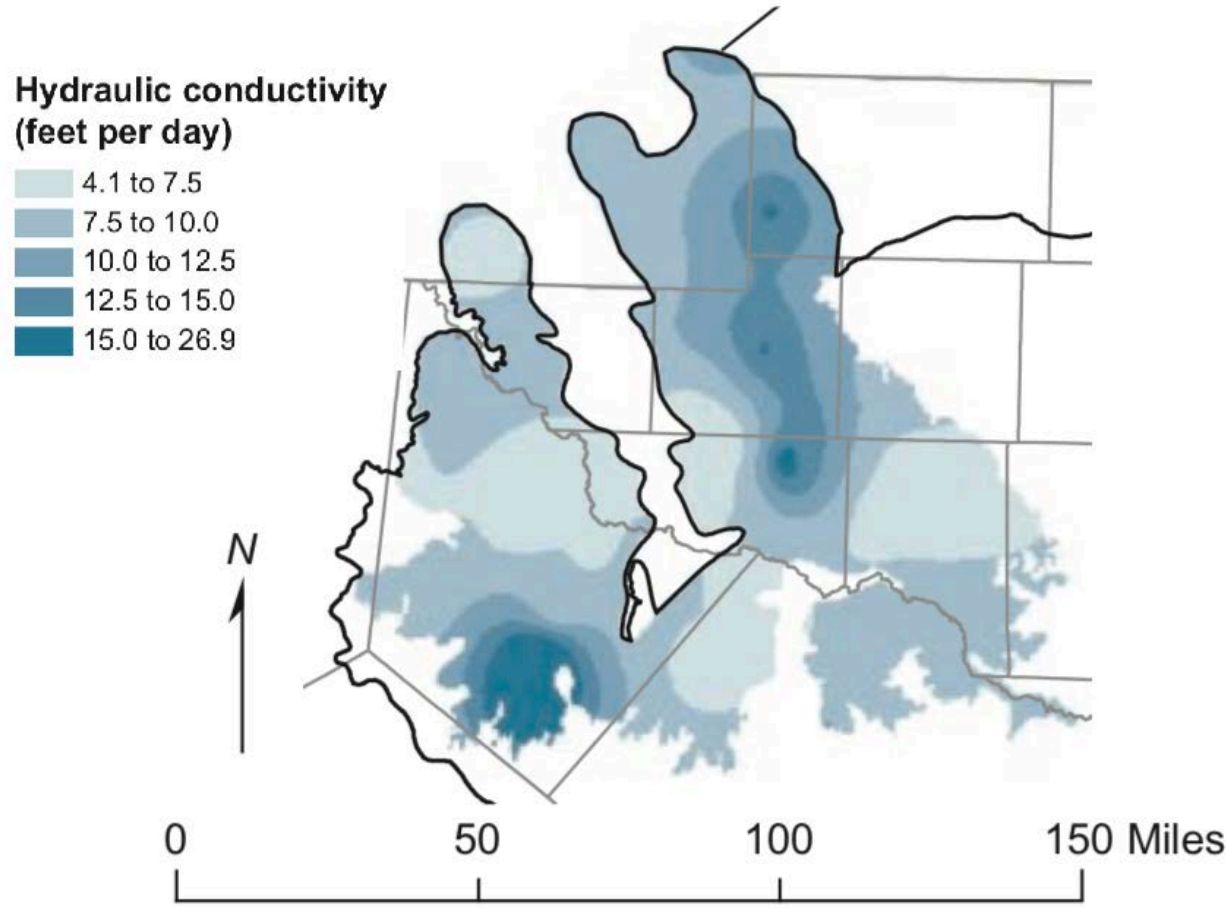

Figure 3.7: Hydraulic conductivity in the Pecos Valley Aquifer (modified from Anaya and Jones 2009).

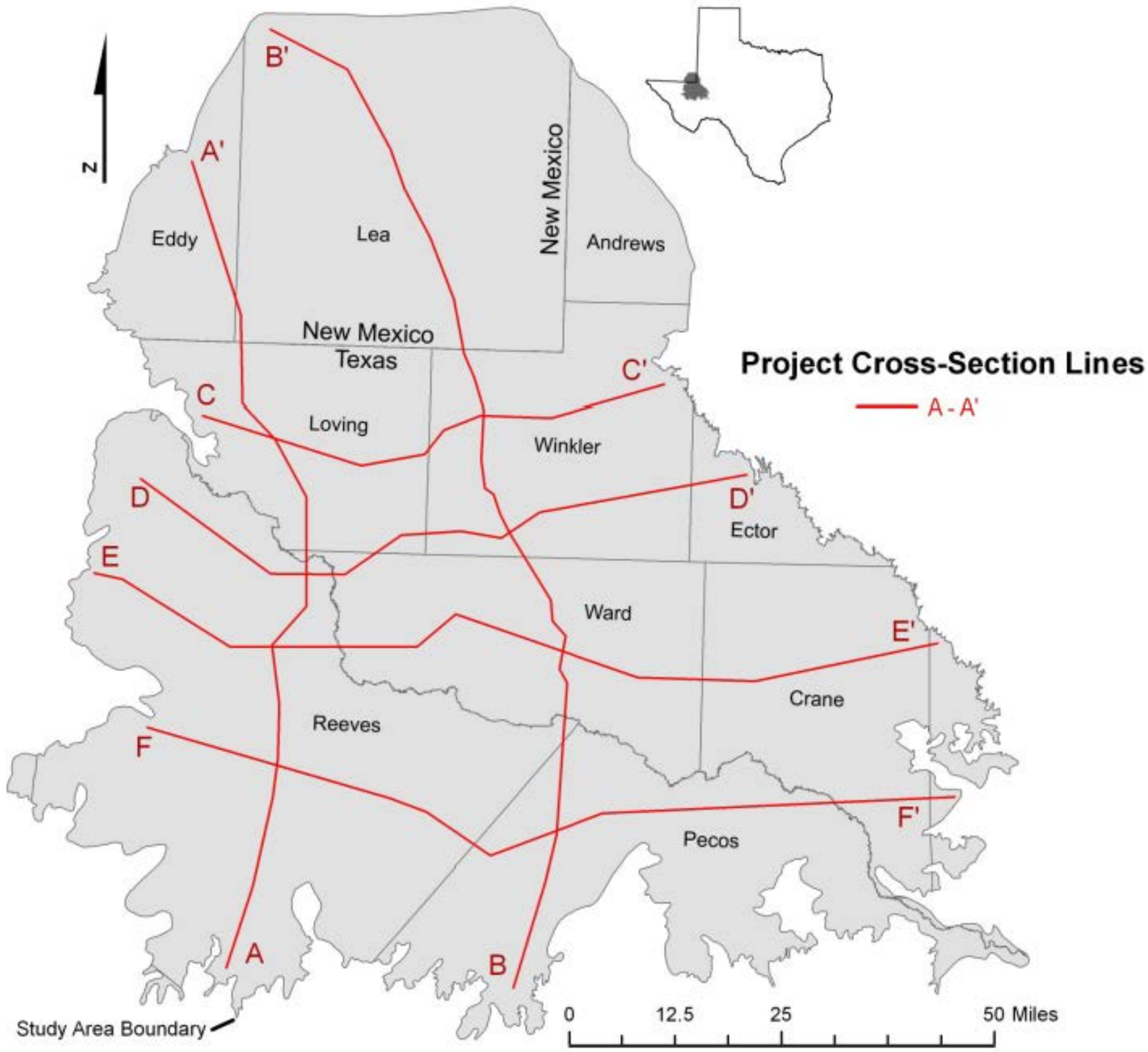

Figure 3.8: Location of geologic cross-sections (from Meyer and others 2012). I only show cross-sections C–C', D–D', and E–E' in this report.

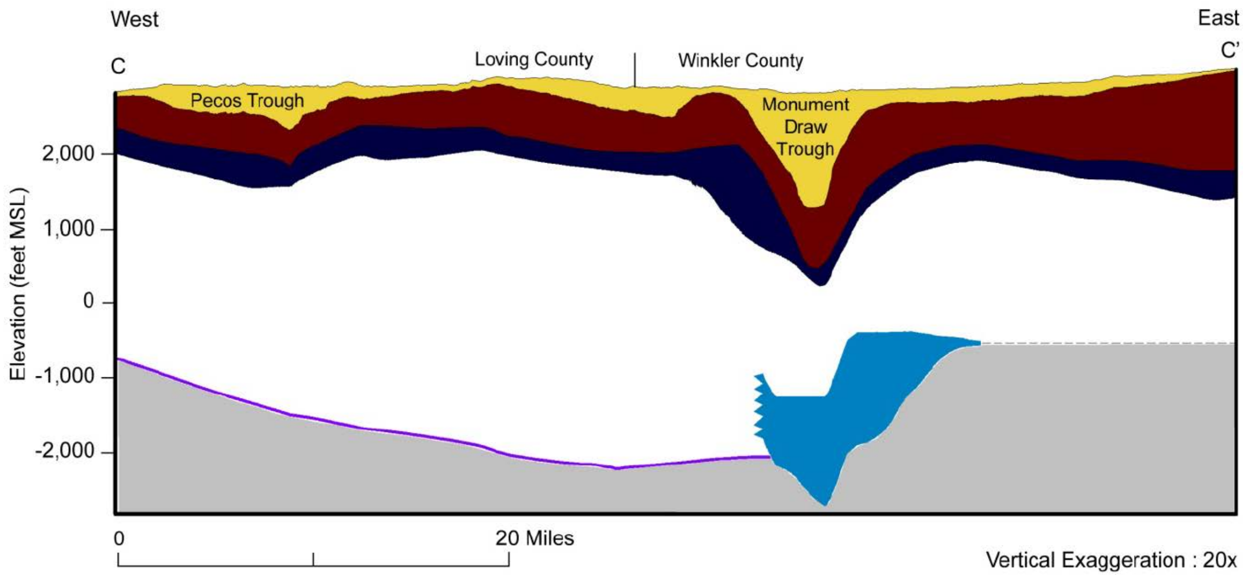

Figure 3.9: Cross-section C–C' from Figure 3.8 through Loving and Winkler counties (from Meyer and others 2012). Yellow is the Pecos Valley Aquifer, and reddish-brown immediately below the Pecos Valley Aquifer is the Dockum Aquifer. Shown beneath the Dockum Aquifer are various Permian formations including the Capitan Reef Complex in blue.

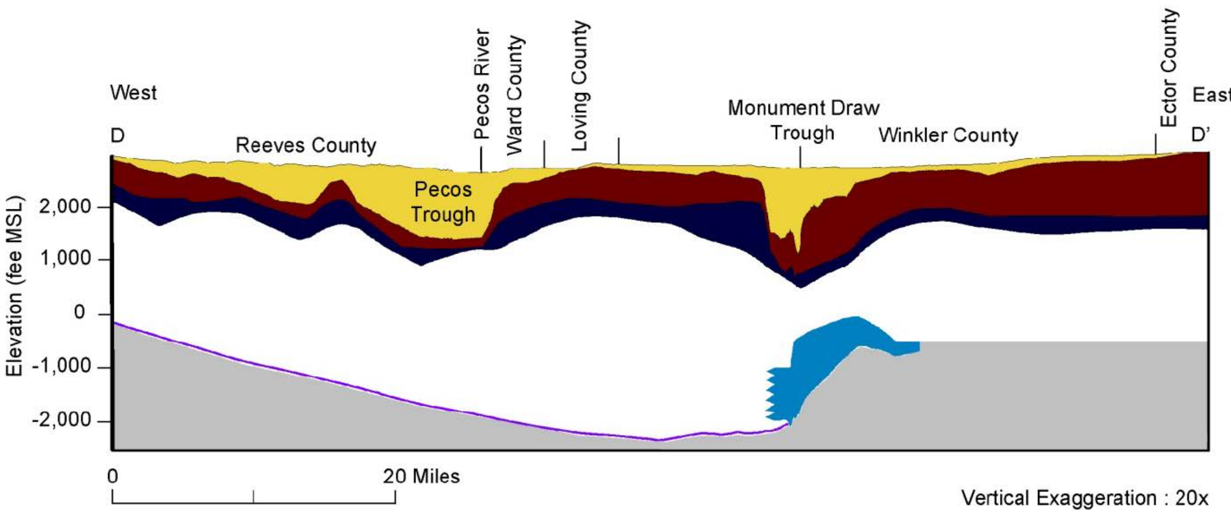

Figure 3.10: Cross-section D–D' from Figure 3.8 through Reeves, Ward, Loving, and Winkler counties (from Meyer and others 2012). Yellow is the Pecos Valley Aquifer, and reddish-brown immediately below the Pecos Valley Aquifer is the Dockum Aquifer. Shown beneath the Dockum Aquifer are various Permian formations including the Capitan Reef Complex in blue.

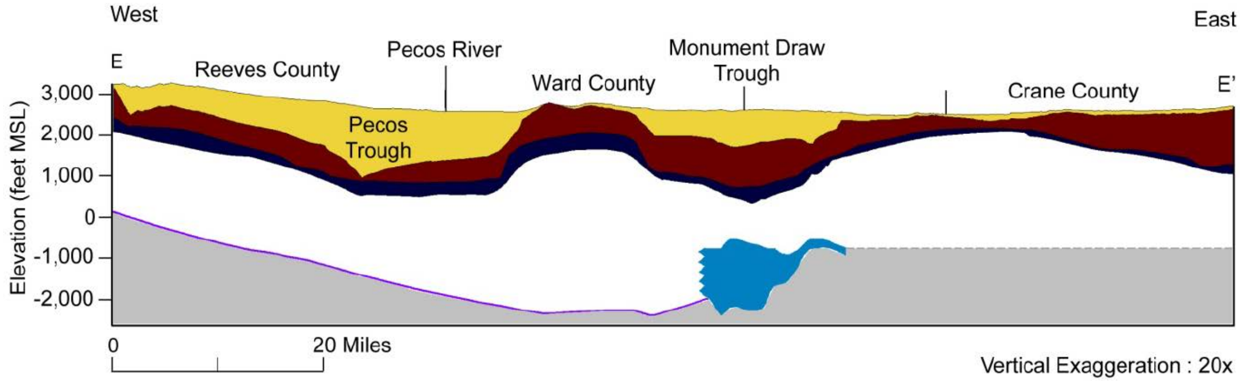

Figure 3.11: Cross-section E–E' from Figure 3.8 through Reeves, Ward, and Crane counties (from Meyer and others 2012). Yellow is the Pecos Valley Aquifer, and reddish-brown immediately below the Pecos Valley Aquifer is the Dockum Aquifer. Shown beneath the Dockum Aquifer are various Permian formations including the Capitan Reef Complex in blue.

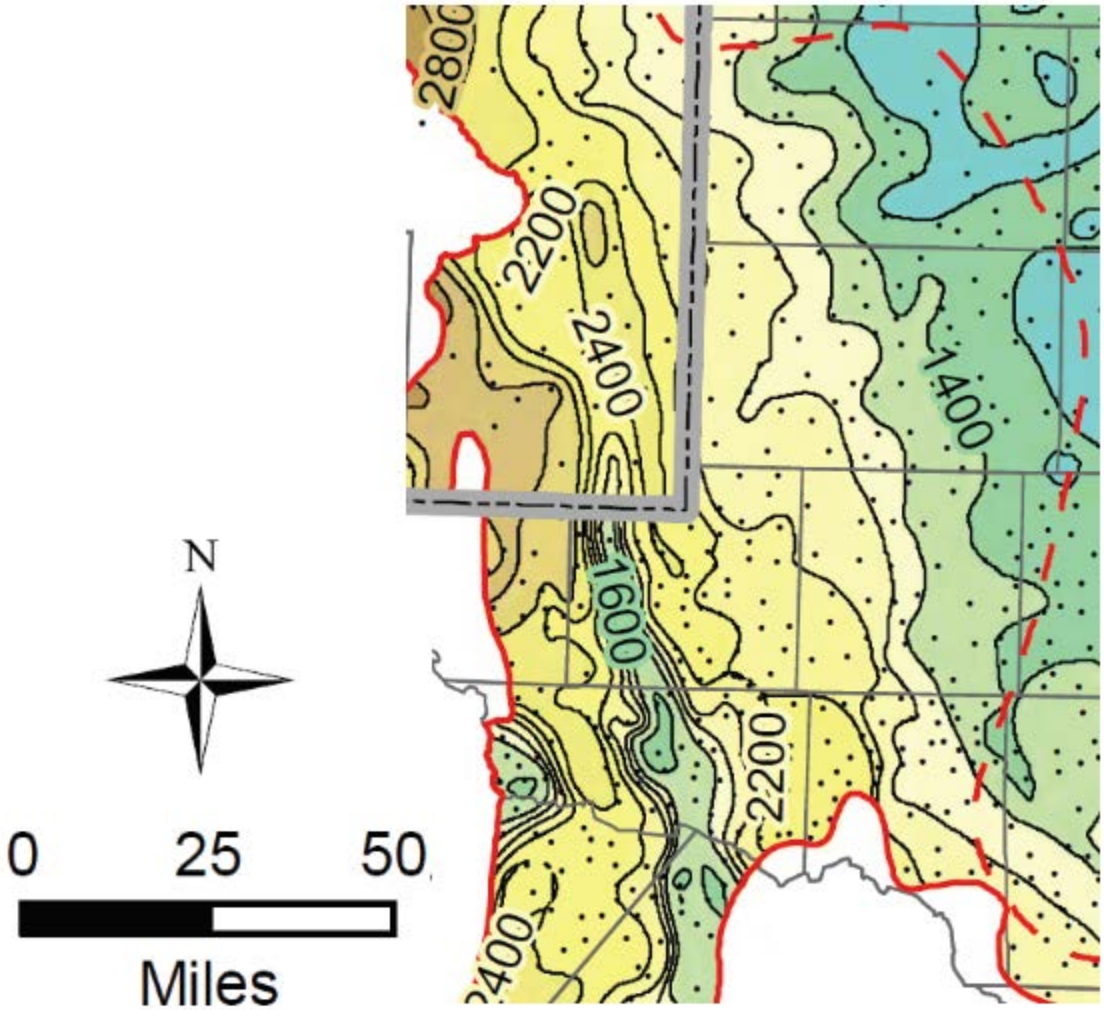

Figure 3.12: Bottom elevation of the Dockum Group in feet above mean sea level (modified from Ewing and others 2008).

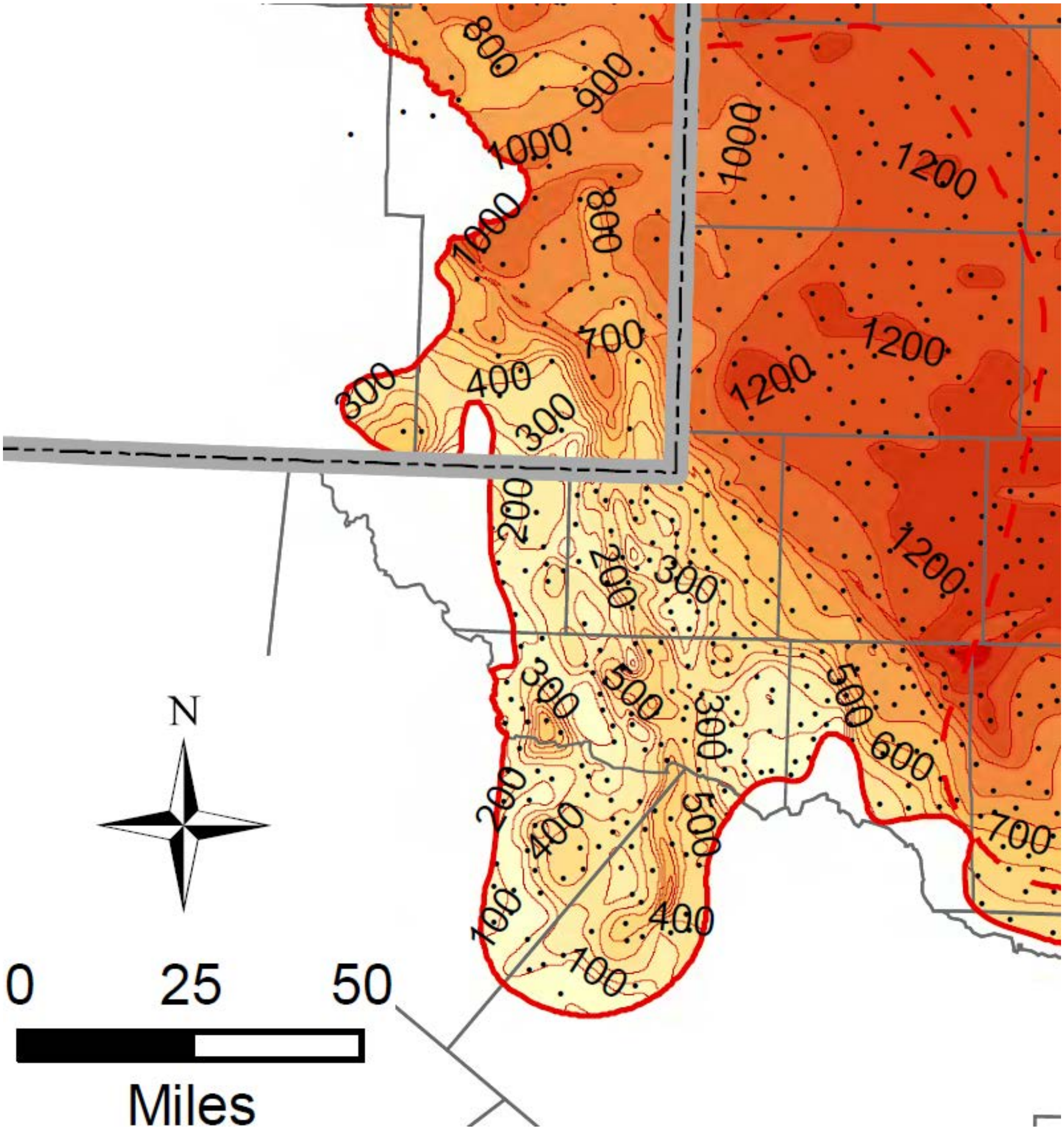

Figure 3.13: Thickness of the lower portion of the Dockum Group (modified from Ewing and others 2008).

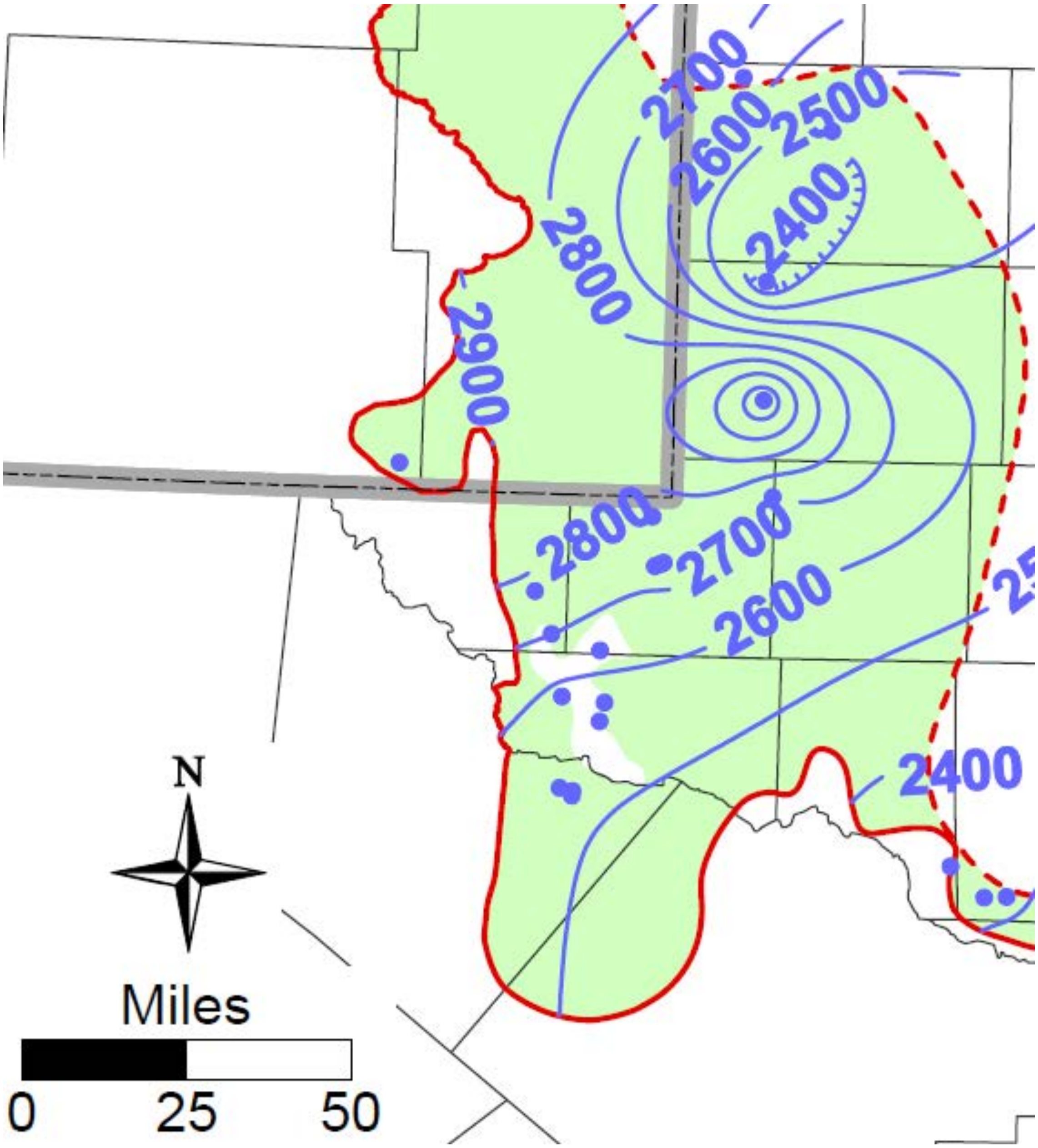

Figure 3.14: Estimated water-level elevations for the lower portion of the Dockum Group in 1997 (modified from Ewing and others 2008).

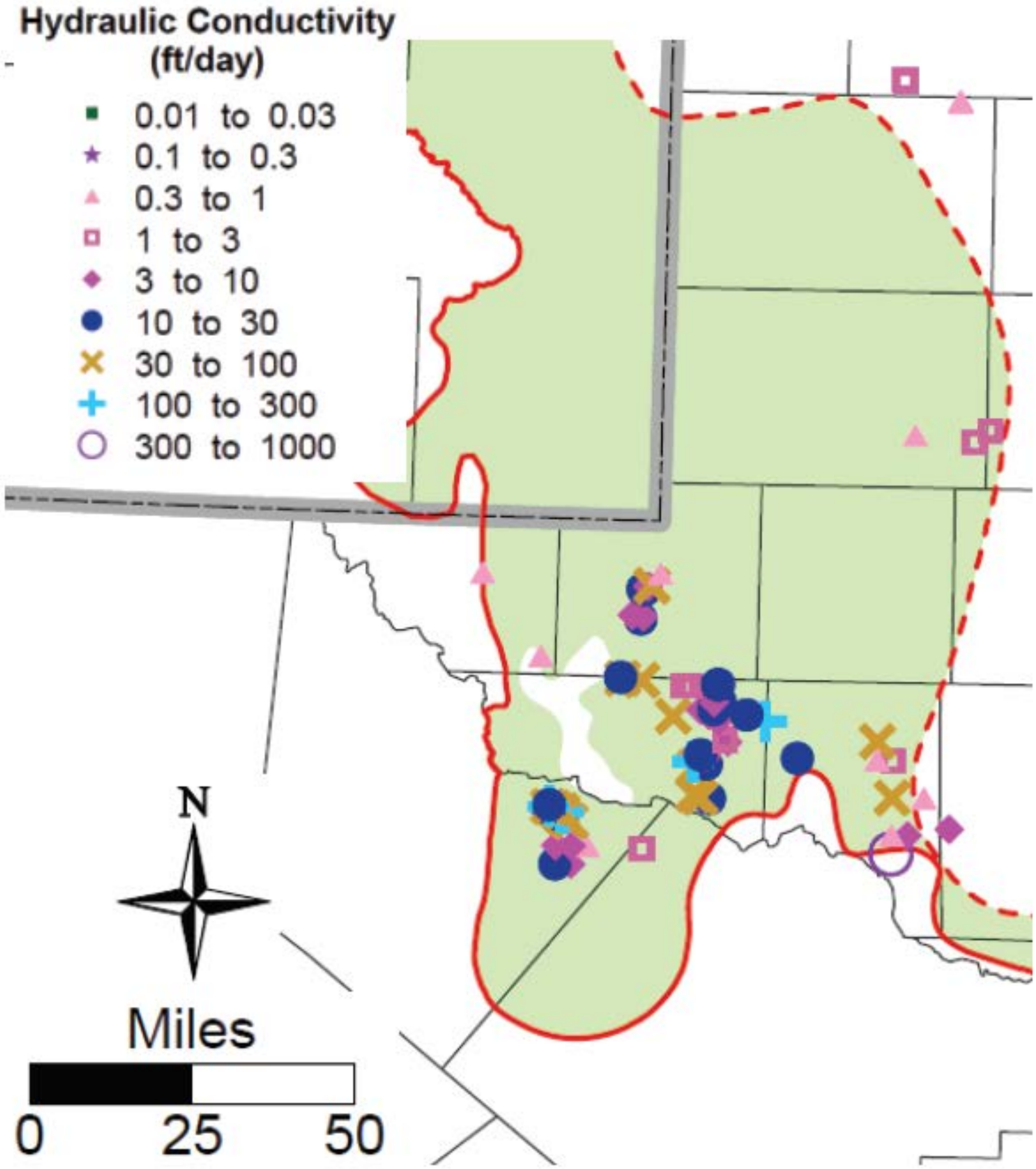

Figure 3.15: Sand hydraulic conductivity for the lower portion of the Dockum Group (modified from Ewing and others 2008).

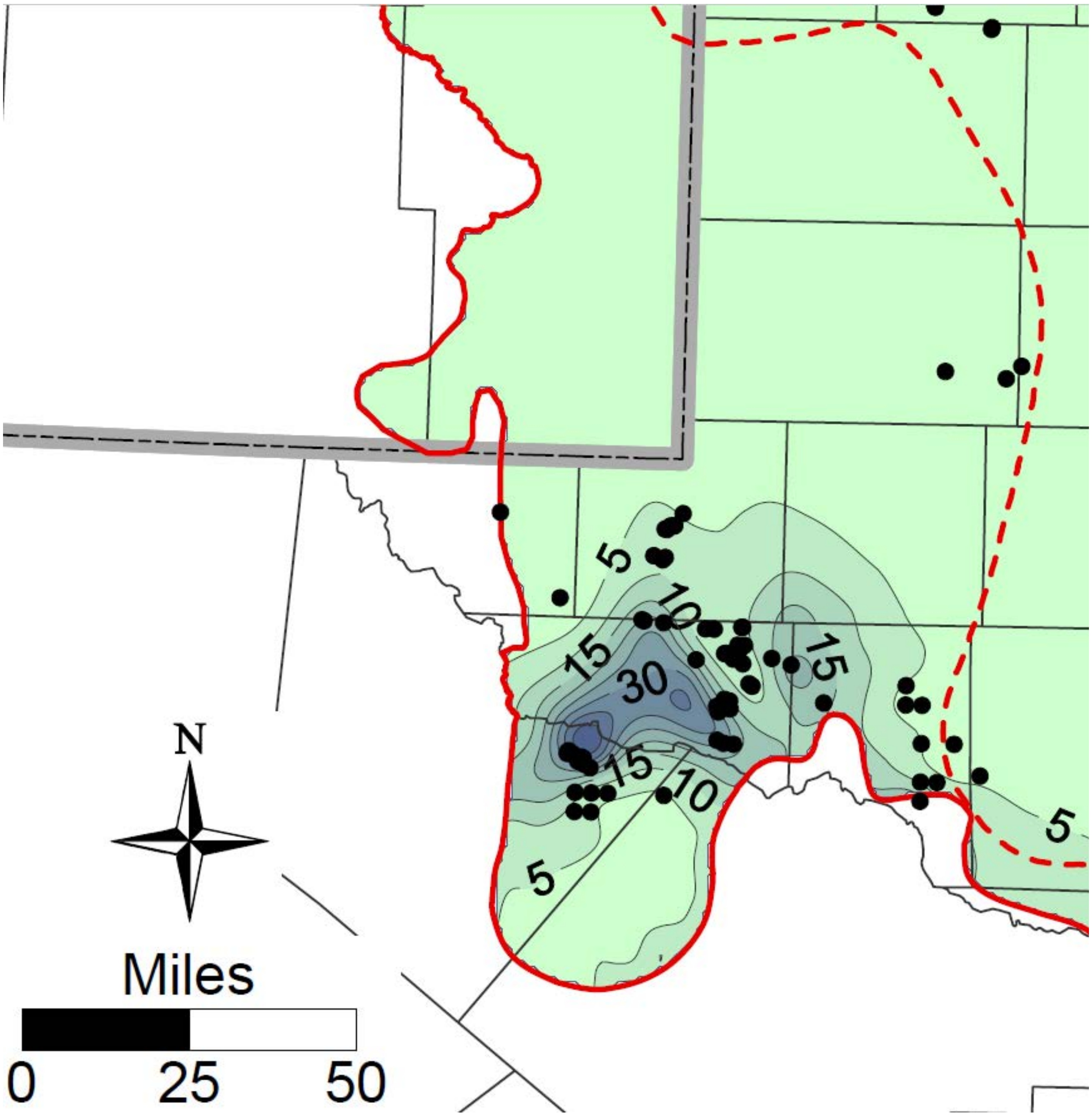

Figure 3.16: Kriged map of sand hydraulic conductivity for the lower portion of the Dockum Group (modified from Ewing and others 2008).

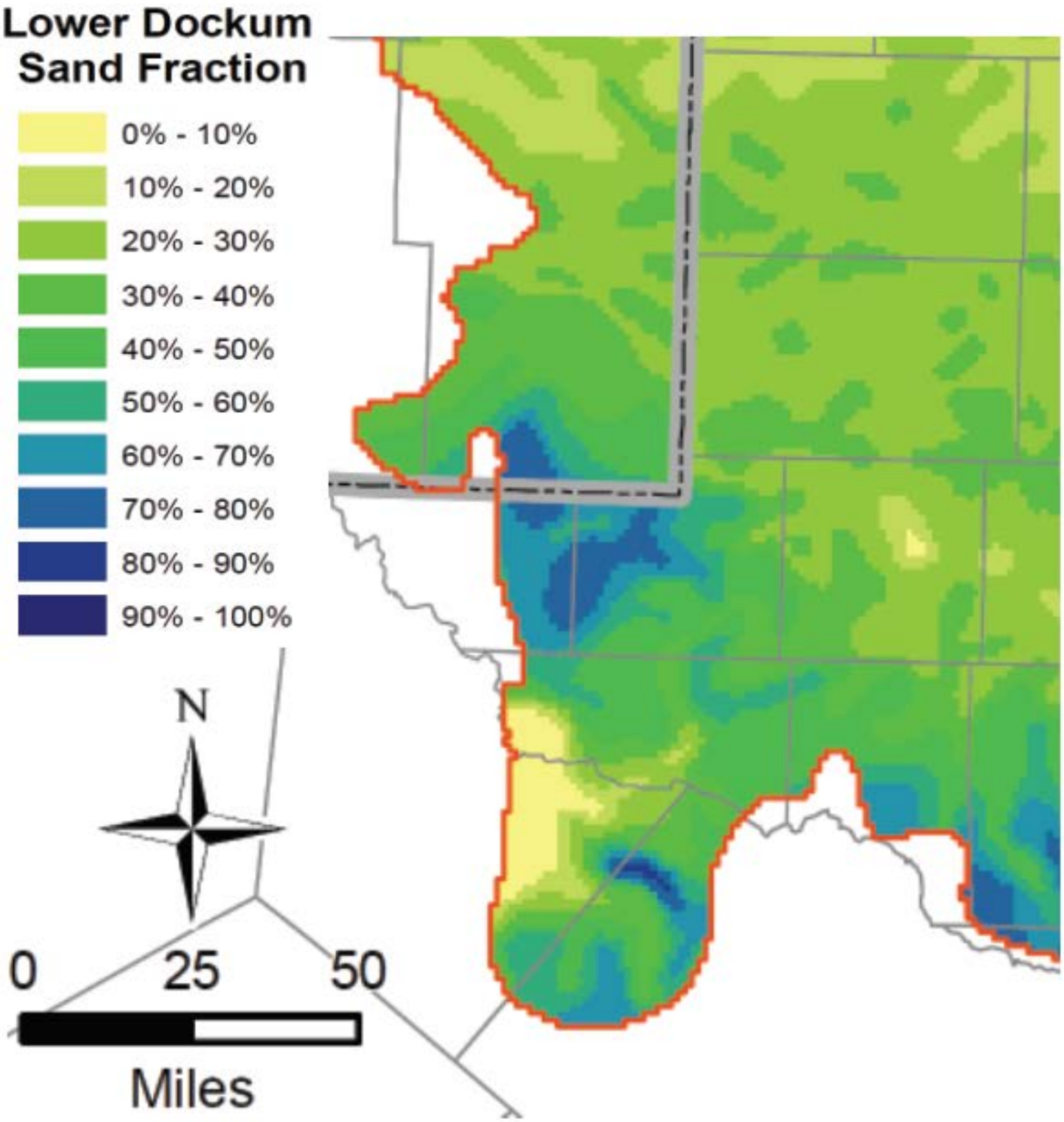

Figure 3.17: Sand fraction for the lower portion of the Dockum Group (modified from Ewing and others 2008).

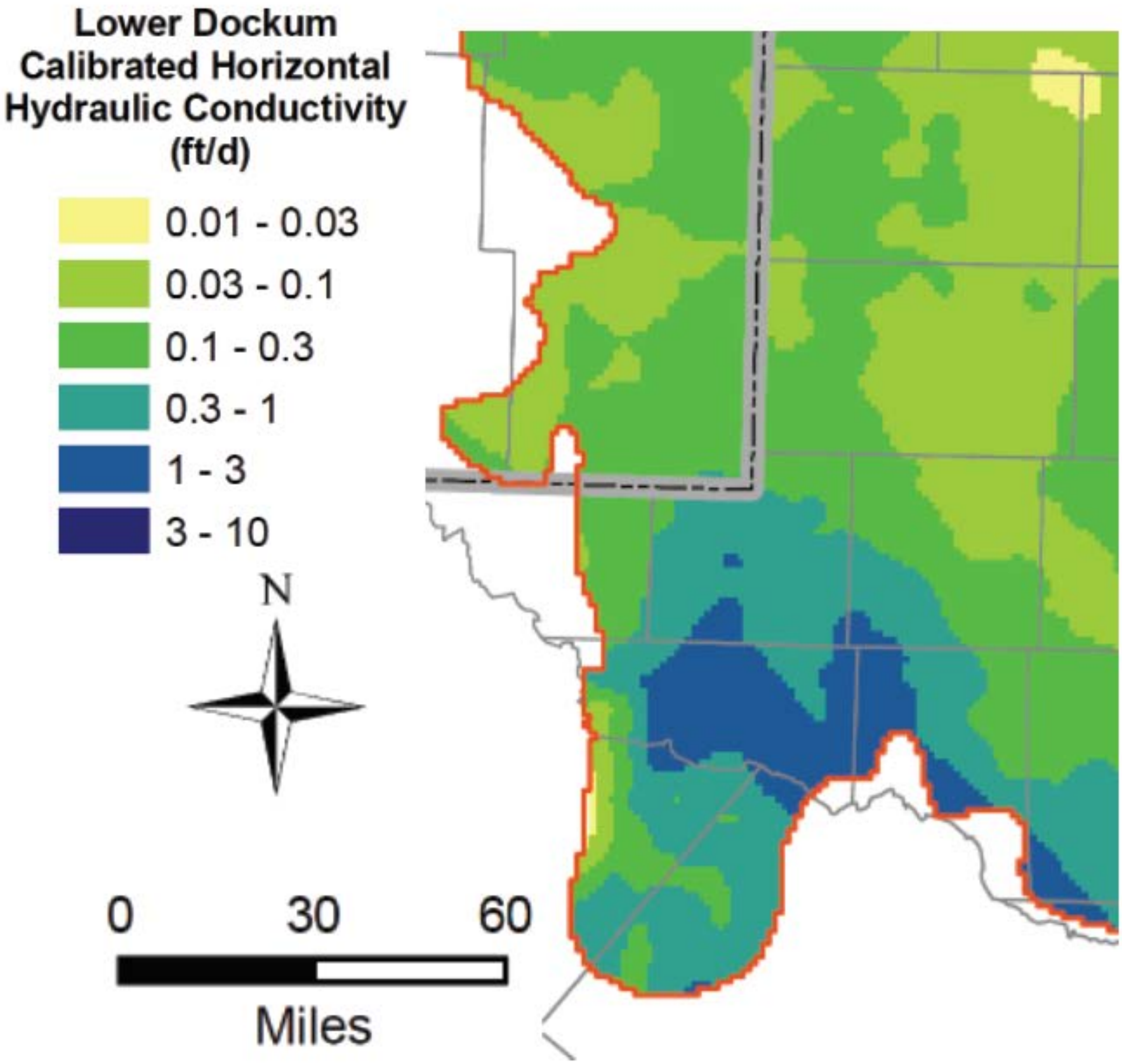

Figure 3.18: Calibrated horizontal hydraulic conductivity for the lower portion of the Dockum Group (modified from Ewing and others 2008).

Figure 3.19: Aerial photograph of the shallow water-producing feature at the Atlas North frac sand production facility (Google Maps, accessed December 30, 2018). The pond is about 50 feet across.

4. Groundwater Management

As a state, Texas falls under the Rule of Capture, or Absolute Ownership, Doctrine (see, for example, Potter 2004; Mace 2016) where the landowner owns the groundwater and can pump as much as she wants from anywhere on her property with no legal recourse for her neighbors. However, the courts have modified the Rule of Capture in Texas by forbidding waste, intentionally damaging a neighbor, and damaging neighbors through groundwater-pumping induced land subsidence. The Rule of Capture is further modified, often substantially, through the creation of local groundwater conservation districts where landowners may have to adhere to well spacing and production requirements, depending on the authority and rules of the district.

The study area has one groundwater conservation district: the Llano Estacado Underground Water Conservation District in Gaines County (Figure 4.1a). This district requires well registration, a production limit of 10 gallons per minute per contiguous acre not to exceed 16.13 acre-feet per acre per year, and setbacks from property lines and other wells (LEUWCD 2018). There is no regulatory authority for groundwater use in the rest of the study area beyond state requirements to submit a driller's report with the Texas Department of Licensing and Regulation.

Additional groundwater conservation districts could be created in the study area at any time. Districts can be created by (1) petitioning the Texas Commission on Environmental Quality, (2) legislative action (generally followed by a local confirmation election), (3) the Priority Groundwater Management Area process, and (4) annexation to a neighboring district. The petition process requires the signature of 50 landowners to bring district creation to a local vote. A district formed in this manner has the standard powers described in Chapter 36 of the Texas Water Code.

The legislature has created most districts, and the resulting enabling legislation may modify the powers in Chapter 36. The Priority Groundwater Management Area process is the way the state, through the Texas Commission on Environmental Quality, can create a district. This creation process is accomplished through first studying the area, something that is instigated by the Texas Commission of Environmental Quality and the Texas Water Development Board, and then determining whether an area is experiencing or expecting to experience groundwater issues over the next 50 years. The Commission developed two past assessments in the study area that included Ward and Winkler counties (Williamson 1990, Mills 2005) and concluded that designation as a priority groundwater management area was not warranted at that time.

In addition, groundwater conservation districts are required to meet and approve desired future conditions for the relevant groundwater resources in their groundwater management area every five years (with 2016 being the most recent year; Table 4.1). The study area includes three groundwater management areas: 2, 3, and 7 (Figure 4.1b). Andrews and Gaines counties are in Groundwater Management Area 2; Crane, Ward, and Winkler counties are in Groundwater Management Area 3; and Ector County is in

Groundwater Management Area 7. A desired future condition—the management goal for a particular aquifer through the state water planning period of 50 years—is then used by the Texas Water Development Board to estimate the modeled available groundwater—the amount of water that can be pumped to achieve the desired future conditions (Table 4.2). The desired future conditions and modeled available groundwater numbers are then used by districts to manage resources within their district boundaries, and by regional water planning groups for planning purposes.

Districts may (and arguably should) define desired future conditions for aquifers or parts of aquifers without districts even though there is no regulatory body to enforce those limits. State law requires regional water planning groups to use modeled available groundwater numbers in their planning exercises regardless of the existence of a district. Although planning groups do not have regulatory authority, modeled available groundwater numbers may disallow the use of state funds or state financing for a groundwater project, although alternative (such as private) funding could still be used to implement the groundwater project. The study area includes two regional water planning areas, F and O (Figure 4.2). Gaines County is in Region O with the rest of the study area in Region F.

Modeled available groundwater totals 439,586 acre-feet per year for the study area with Gaines County, because of the prolific Ogallala Aquifer, at nearly 300,000 acre-feet per year, Ward and Winkler counties at just over 50,000 acre-feet per year, Andrews County at just over 25,000 acre-feet per year, and Ector County at about 5,500 acre-feet per year (Table 4.2). Except in a few minor cases, modeled available groundwater is above pumping estimates for 2016 (Table 4.2; pumping estimates do not include water used for fracking).

State law requires the Texas Water Development Board to provide estimates of total estimated recoverable storage to groundwater conservation districts to consider in the development of desired future conditions and their groundwater management plans. The Board provides this number as a range of 25 to 75 percent of the estimated drainable porosity of an aquifer and without consideration of economics, saltwater intrusion, and environmental impacts. Total estimated recoverable storage values are much larger than modeled available groundwater and pumping estimates (totaling about 718 million acre-feet in the study area) in part because they are not annual values (they are a total value) and in part because they do not consider the economic, hydrologic, and environmental aspects of completely emptying an aquifer.

If groundwater conservation districts were formed in any of the five counties in the study area without a district, they would inherit the existing desired future conditions and modeled available groundwater and would be required to manage toward the desired future condition. Any new districts would participate in a subsequent five-year revision of the relevant desired future conditions.

Table 4.1: Desired future conditions for the relevant aquifers in the counties of the study area (information from TWDB 2018d)

County; Aquifer: desired future condition

Andrews; Ogallala and Edwards-Trinity (High Plains): *average drawdown between 23 and 27 feet for all of Groundwater Management Area 2*

Andrews; Dockum: *average drawdown of 27 feet for all of Groundwater Management Area 2*

Crane; Edwards-Trinity (Plateau) and Pecos Valley: *total net drawdown not to exceed 58 feet in 2070 as compared with aquifer levels in 2010*

Crane; Dockum: *total net drawdown not to exceed 0 feet in 2070 as compared with aquifer levels in 2012*

Ector; Edwards-Trinity (Plateau), Pecos Valley, and Trinity: *average drawdown not to exceed 4 feet*

Gaines; Ogallala and Edwards-Trinity (High Plains): *average drawdown between 23 and 27 feet for all of Groundwater Management Area 2*

Gaines; Dockum: *average drawdown of 27 feet for all of Groundwater Management Area 2*

Ward; Edwards-Trinity (Plateau) and Pecos Valley: *total net drawdown not to exceed 63 feet in 2070 as compared with aquifer levels in 2010*

Ward; Dockum: *total net drawdown not to exceed 30 feet in 2070 as compared with aquifer levels in 2012*

Ward; Rustler: *total net drawdown not to exceed 30 feet in 2070 as compared with aquifer levels in 2009*

Ward; Capitan Reef Complex: *total net drawdown not to exceed 2 feet in 2070 as compared with aquifer levels in 2006*

Winkler; Edwards-Trinity (Plateau) and Pecos Valley: *total net drawdown not to exceed 161 feet in 2070 as compared with aquifer levels in 2010*

Winkler; Dockum: *total net drawdown not to exceed 22 feet in 2070 as compared with aquifer levels in 2012*

Winkler; Rustler: *total net drawdown not to exceed 31 feet in 2070 as compared with aquifer levels in 2009*

Winkler; Capitan Reef Complex: *total net drawdown not to exceed 2 feet in 2070 as compared with 2006 aquifer levels*

Table 4.2: Modeled available groundwater, total estimated recoverable storage, and 2016 groundwater production for the relevant aquifers in the counties of the study area.

County	Aquifer	Modeled available groundwater in 2020 (acre-feet/year)	Total estimated recoverable storage (acre-feet)	Pumping in 2016[a] (acre-feet)
Andrews	Pecos Valley Alluvium	-	-	138
	Ogallala and Edwards-Trinity (High Plains)[b]	24,937	5,400,000	19,815
	Edwards-Trinity (Plateau)	-	32,000	2
	Dockum	1,319	220,000,000	10
	unknown	-	-	1,358
Crane	Edwards-Trinity (Plateau) and Pecos Valley[c]	4,991	13,027,000	1,055
	Dockum	94	30,000,000	175
	unknown	-	-	29
Ector	Ogallala	-	840,000	165
	Edwards-Trinity (Plateau), Pecos Valley, and Trinity[d]	5,542	6,120,000	2,463
	Dockum	-	100,000,000	67
	unknown	-	-	265
Gaines	Ogallala and Edwards-Trinity (High Plains)[e]	294,251	14,100,000	339,337
	Dockum	0	200,000,000	17
	unknown	-	-	501
Ward	Edwards-Trinity (Plateau) and Pecos Valley[f]	49,976	34,000,000	6,989
	Dockum	2,150	18,000,000	35
	Rustler	0	980,000	2
	Capitan Reed Complex	103	5,900,000	0
	other	-	-	4
	unknown	-	-	879
Winkler	Ogallala	-	9,600	-
	Edwards-Trinity (Plateau) and Pecos Valley[g]	49,949	21,003,300	9,366
	Dockum	6,000	42,000,000	1,473
	Capitan Reef Complex	274	6,100,000	-
	Unknown	-	-	549

Table 4.2: Continued.

[a] Does not include water used for fracking

[b] 5,400,000 acre-feet for the Ogallala and 0 acre-feet for the Edwards-Trinity (High Plains) for total estimated recoverable storage and 19,815 for the Ogallala and 0 for the Edwards-Trinity (High Plains) for pumping

[c] 13,000,000 for the Pecos Valley and 27,000 for the Edwards-Trinity (Plateau) for total estimated recoverable storage and 1,055 for the Pecos Valley and 0 for the Edwards-Trinity (Plateau) for pumping

[d] 220,000 acre-feet for the Edwards-Trinity (Plateau), 0 acre-feet for the Trinity, and 5,900,000 acre-feet for the Pecos Valley for total estimated recoverable storage and 2,453 acre-feet for the Edwards-Trinity (Plateau), 10 acre-feet for the Trinity, and 0 acre-feet for the Pecos Valley for pumping

[e] 11,000,000 acre-feet for the Ogallala and 3,100,000 acre-feet for the Edwards-Trinity (High Plains) for total estimated recoverable storage and 329,380 acre-feet for the Ogallala and 9,957 acre-feet for the Edwards-Trinity (High Plains) for pumping

[f] 34,000,000 acre-feet for the Ogallala and 0 acre-feet for the Edwards-Trinity (High Plains) for total estimated recoverable storage and 6,989 for the Pecos Valley and 0 for the Edwards-Trinity (Plateau) for pumping

[g] 21,000,000 acre-feet for the Ogallala and 3,300 acre-feet for the Edwards-Trinity (High Plains) for total estimated recoverable storage and 9,364 for the Pecos Valley and 2 for the Edwards-Trinity (Plateau) for pumping

Data for modeled available groundwater are from TWDB (2018d), numbers for total estimated recoverable storage are from Jones and others (2013a, b) and Kohlrenken and others (2013), and numbers for pumping are from TWDB (2018c).

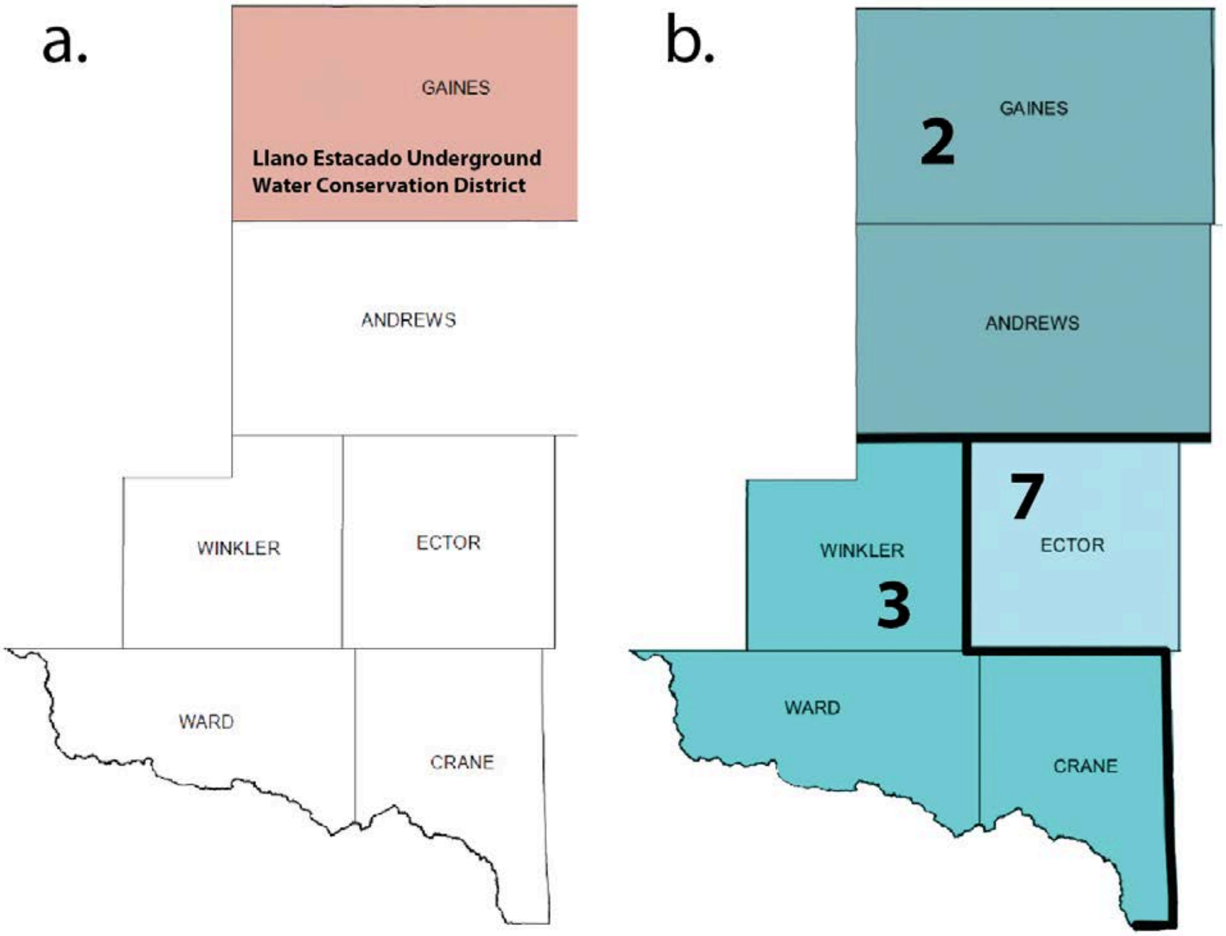

Figure 4.1: Location of (a) the groundwater conservation district (Llano Estacado Underground Water Conservation District) and (b) groundwater management areas (2, 3, and 7) in the study area (modified from TWDB 2018a).

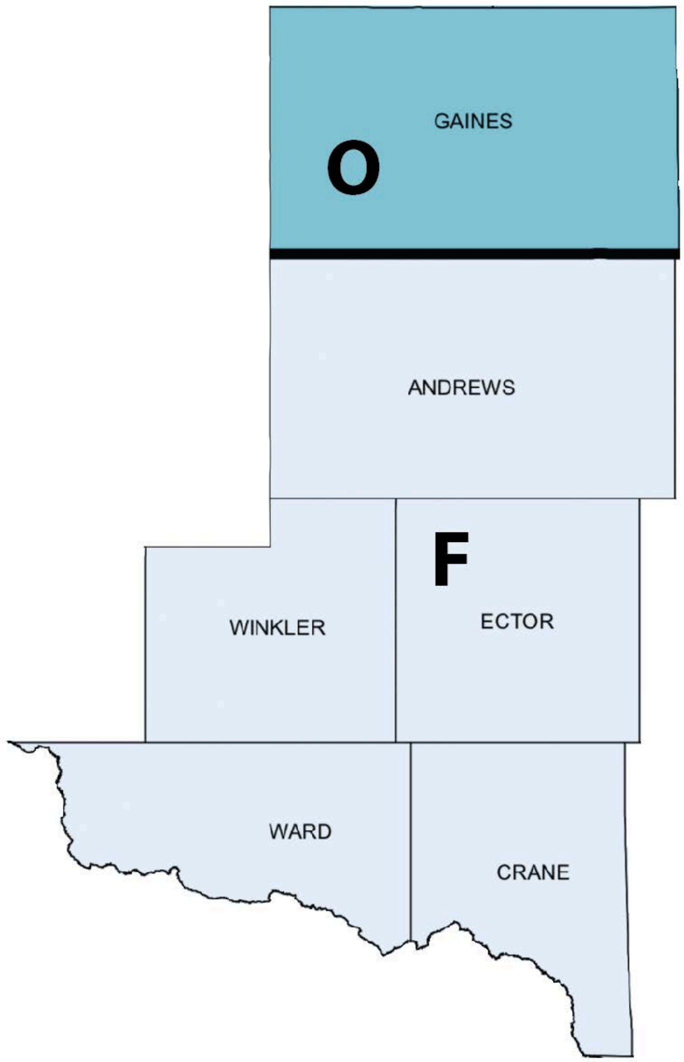

Figure 4.2: Location of regional water planning areas in the study area (modified from TWDB 2018a).

5. Frac Sand Facilities

In Texas, the state considers frac sand facilities as aggregate production operations, which must be registered with the water quality program at the Texas Commission on Environmental Quality (30 Texas Administrative Code 342.25[a]) with an annual renewal[3].

Depending on the number of disturbed acres—the projected acreage of excavation for the coming year in addition to the previous acres excavated—and method of registration, costs to register and renew range from $300 to $950 I used an online database of these registrations to identify frac sand facilities in the study area (TCEQ 2018).

As of December 26, 2018, 17 frac sand facilities had registered with the Texas Commission on Environmental Quality, one of which is idle (Table 5.1; Figure 5.1). Based on water well drilling in the area (see next section), another frac sand facility (in addition to the 17) may be under development by Smart Sand (Triepke 2018d).

Mississippi Sands LLC operated the Seagraves Sand Plant in Gaines County but canceled its registration on May 21, 2017. U.S. Silica bought Mississippi Sands LLC in August 2017 and noted that the plant was idled but could be put back into operation (USSHI 2017). U.S. Silica's website lists the Seagraves Sand Plant as one of its assets, but the facility is not currently registered.

The first frac sand facility in the study area to be registered was the Hi-Crush facility in Winkler County on April 4th, 2017. Since then, 16 additional frac sand facilities have been registered with all the actively registered facilities clustered along the dunes between south-east of Monahans and north-east of Kermit in a 20-mile by 40-mile area (Figure 5.1). Disturbed acres reported by operators in annual state registration paperwork for frac sand facilities in the study area range from 5 to 300 acres for a total of 2,927 acres for the 17 frac sand facilities (Table 5.1). The total acreage of property purchased by individual operators is much greater than what is currently reported as disturbed, and the disturbed acres here only represent excavated or soon-to-be-excavated acres.

Based on operator-reported or press reports of annual production amounts, the 17 facilities have 56.8 million tons of annual capacity (Table 5.1). Not including the idled plant, the 16 frac sand facilities average to about 3.6 million tons of annual capacity per facility.

More frac sand facilities—in addition to Smart Sand—may be in development. Triepke (2018e) identified more than 30 potential facilities for the area. Current frac sand capacity is meeting about 40 percent of total demand and is expected to grow to 50 percent by 2023 (Rock Products 2018).

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[3] There is also a requirement to obtain air permits from the Texas Commission on Environmental Quality, generally for bulk sand handling; boilers, heaters, and other combustion devices; and wet sand and gravel production.

Table 5.1: Registered frac sand facilities in the study area as of January 21, 2019.

County	Operator/Facility name	Initial permit	Disturbed[a] acres	Registration #	Tonnage[b]
Crane	(1) Unimin Corporation[c]/Covia Crane Facility	5/9/2018	228	AP0002685	3
	(2) U.S. Silica/Crane County Plant	12/1/2017	188	AP0002546	4
Ector	(3) Preferred Sands of Monahans	10/23/2017	100	AP0002853	3.3
Gaines	(4) U.S. Silica/Seagraves Sand Plant	5/23/2017	33	idled	0.5
Ward	(5) Wisconsin Proppants/E Ranch Facility	5/24/2018	213	AP0002697	3
	(6) Black Mountain Sand/Sealy Smith Facility	9/21/2018	150	AP0002792	1
Winkler	(7) Hi-Crush Permian Sand/Hi-Crush	4/4/2017	70	AP0002202	3
	(8) Black Mountain Sand/Vest Facility	12/11/2017	348	AP0002552	6
	(9) High Roller Sand Operating[d]/Kermit Plant	12/21/2017	134	AP0002560	4
	(10) Lonestar Prospects[e]/West Texas Sand Plant	1/19/2018	250	AP0002587	3
	(11) FML Sand[c]/FML Kermit	3/26/2018 10/16/2018	250 300	AP0002645 AP0002849	3
	(12) Black Mountain Sand/El Dorado Facility	4/27/2018	247	AP0002673	6
	(13) Alpine Silica/Alpine Silica	5/4/2018	60	AP0002679	3
	(14) Badger Mining Corporation/Kermit Plant	5/4/2018	125	AP0002680	3
	(15) Atlas Sand Company/Atlas North	6/8/2018	83	AP0002721	4
	(16) Atlas Sand Company/Atlas South	8/29/2018	88	AP0002804	4
	(17) Hi-Crush Permian Sand/Kermit Plant North	12/14/2018	60	AP0002879	3
	(18) Smart Sand[f]	-	-	-	-

[a] The Texas Commission on Environmental Quality requires operators to report projected acreage of excavation for the year. Acreage is added annually and reported as the cumulative size of the excavation. Additional surface disturbances, including facilities and supporting infrastructure, are not included in the calculation.

[b] Registrations do not report annual tonnage capacity; I found these numbers from facility sites, press releases, or media reports.

[c] Unimin and FML Sand merged to form Covia.

[d] Now owned by Wisconsin Proppants

[e] Lonestar Prospects is a subsidiary of Vista Proppants.

[f] Smart Sand has not registered with the state but is drilling water wells in the area; I include this as a potential future frac sand facility.

- Appendix A shows aerial images and well maps for the facilities; Appendix B lists out the individual wells.

Figure 5.1: Location of actively registered frac sand facilities in the study area (base map from Google Maps). Not shown is U.S. Silica's idled Seagraves Sand Plant located near the town of Seagraves in Gaines County.

6. Water Use Associated with Frac Sand Facilities

In this section, I describe how water is generally used and reused at frac sand facilities, estimate how much water frac sand facilities consume in the study area, discuss sources of water for frac sand facilities in the study area, and project how much water facilities might consume in the future.

6.1 How Water Is Used in Mining and Processing

The production of frac sand may require water for mining and transport, sorting, dust control, and on-site potable water needs. Depending on the type of mining, water may be used or encountered (WDNR 2012) for hydraulic mining and slurry transporting sand (Orr and Krumenacher 2015) or for dewatering if mining encounters a shallow water table. Mining in the study area, at least at present, does not appear to require much if any water for the extraction or transporting of sand.

Frac sand needs to have uniform shape and size; to achieve the desired shape and size, mined sand is washed, dried, sorted, and stored (WDNR 2012). Washing removes the fine particles and may be accomplished through spraying water on sand on a vibrating screen or through an up-flow clarifier where the sand is fully immersed in wash-water where the sand falls to the bottom (WDNR 2012) while the fines are carried away by the up-flow (MEQB 2013, Orr and Krumenacher 2015). The washed sand may then be drained with a dewatering screen before subsequent processing (Kelley 2012). The wash-water may be treated with flocculants to remove the fines and then used again (MEQB 2013). The slurry of fines may then be plate pressed to recycle as much of the water it holds as possible (for example, Triepke 2017a, Triepke 2018f). Wet fines are then generally used for partial reclamation of the mine.

Washed sand is then taken to a surge pile where water adhering to the grains of the sand either evaporate out of the pile or drain down out of the pile (WDNR 2012). One operator, Hi-Crush (2018) delivers sand to the surge pile with less than 12 percent moisture. Water that drains downward out of the pile may be collected and reused (for example, Triepke 2017a). A drainage system beneath these piles can reduce moisture content to 2 to 4 percent (Hi-Crush 2018). Sand from the surge pile is then collected, dried, and screened into specific particle sizes (WDNR 2012).

Water may also be used on the site to meet potable needs and for dust control (WDNR 2012). Dust control is a significant environmental concern because breathing silica dust can cause silicosis; spraying water at the mine and plant is effective in mitigating airborne particles (Orr and Krumenacher 2015, Zdunczyk 2016, Mathews 2017). Mathews (2017) estimated that operators would need about 57 inches of water per year under average conditions to stay even with evaporation for dust control. Mathews (2017) also noted several alternatives to using water, such as greater paved areas, road cleaning, dust control chemicals, limited exposure, minimizing wind exposure, and using stabilized berms.

6.2 Water Consumption

It's important to note the difference between water *use* and water *consumption*. Water use is the total amount of water needed to achieve a certain task. For example, if I need 100 gallons of water to accomplish process X, then my water use is 100 gallons. Consumption refers to the amount of water lost during the process, perhaps from evaporation, leaks, or incorporation into a product. If in the previous example I'm 90 percent efficient, my water consumption is only 10 gallons. That means that, at the end of process X, I have 90 gallons of water I can recycle and reuse. To repeat process X, I need 10 more gallons of water, often referred to as *make-up water*, to add to the 90 gallons of recycled water to meet my use need of 100 gallons. In the case of frac sand production facilities, it's this make-up water and where it's coming from that's important in understanding the effects of frac sand production on water resources.

Unfortunately, *use* and *consume* are employed interchangeably making it difficult to determine what is use and what is consumption. Furthermore, it can be challenging to identify what processes are included in use and efficiency estimates. For example, are reported use and efficiency numbers for the sand processing or for the entire operation, including for mining, dust control, and on-site potable water needs? In addition, reported amounts do not include water sales that may be occurring.

Facilities commonly recycle water used to wash mined sand (Orr and Krumenacher 2015). WDNR (2016) notes that, for Wisconsin frac sand facilities, water use efficiency is generally high since many operators use closed-loop systems where evaporation and incorporation are the only processes in which water is lost during processing. Furthermore, newer plants are more efficient and therefore require less water than older plants (WDNR 2016).

Closed-loop systems that recycle 90 percent of their water can consume as little as 6.6 million gallons per year as compared to open-loop systems that can use as much as 730 million gallons per year (Orr and Krumenacher 2015; values not normalized to sand production). Facilities that recycle can consume between 6.6 million and 91 million gallons per day (Orr and Krumenacher 2015; values not normalized to sand production).

An average industrial sand facility in Wisconsin can withdraw 657 million gallons per year from aquifers or streams and rivers (WDNR 2016); however, this number is for a range of facility sizes and efficiencies and isn't normalized to sand production (and the use of the word "can" suggests permitted amounts, not actual produced amounts). Orr and Krumenacher (2015) noted that facilities might need 250 to 500 gallons per minute of make-up water per million tons of sand production (130 to 260 gallons of water consumed per ton of sand produced) for closed-loop systems that recycle 90 percent of their water.

There are no published numbers for water consumption that I was able to find for frac sand facilities in Texas; however, I was able to access limited information and compare it to Orr and Krumenacher's (2015) numbers. I list the estimates below from largest to smallest. Note that only one of the numbers (U.S. Silica) was explicitly normalized to tons of sand produced. For many of the other estimates, I assumed that reported (or contracted) water use is associated with plant capacity, which may not be accurate, especially if a facility is ramping up production. I first present the data in the units they were reported in and then end each paragraph with a summary in gallons per ton of sand (gallons of water consumed per ton of sand produced).

- Preferred Sands of Monahans has a take-or-pay contract (regardless of how much of the water they use, the wholesaler charges them for the full amount) with the Colorado River Municipal Water District for 2,000 gallons per minute of supply for 4.2 million tons per year of possible production (Triepke 2018f) resulting in a high-end water consumption of 250 gallons per ton of sand.
- Based on estimated well yields reported in water well drillers reports, Atlas Sand South may be able to produce 1,870 gallons per minute for its 4-million-tons-of-sand-per-year plant, which results in a high-end water consumption of 246 gallons per ton of sand.
- For a frac sand facility in Cooke County, Texas, the operator, EOG, estimated their consumptive water use at 370 gallons per minute (Osbourne 2013) to produce 1 million tons of sand a year (Russell 2011). That amounts to a possible water consumption of 194 gallons per ton of sand.
- Triepke (2018a) estimated that the addition of 20 potential frac sand facilities with 56 million tons per year of production would add about 10 billion gallons of annual freshwater demand to the Permian Basin. That amounts to an average water consumption per facility of about 180 gallons per ton of sand.
- A local driller noted that frac sand companies were generally seeking 400 to 600 gallons per minute (210 million to 315 million gallons per year) of supply (Doug Shields, Water Texas Water Well Service, personal communication). If this range applies for an average frac sand operation that produces 3.6 million tons per year, that amounts to a possible water consumption of about 60 to 90 gallons per ton of sand.
- U.S. Silica reported that their water consumption is 70 gallons per ton of sand (Wes Penn, U.S. Silica, personal communication).

Atlas Sand, which can produce 4 million tons of sand per year, claimed that their total consumption was 500 barrels per day (Hunter Wallace, Atlas Sand, personal communication). That results in the consumption of 1.9 gallons per ton of sand. This number appears to be much too low. At a minimum, the water lost to capillary forces before sand is dried is about 11 gallons of water per ton[4], and this doesn't account for water lost through the fines and other processes.

Based on these estimates, reported or inferred consumptive water use ranges from 60 to 250 gallons of water consumed per ton of sand in the Permian Basin as compared with Orr and Krumenacher's (2015) 130 to 260 gallons per ton.

6.3 Sources of Water

With its dry climate and lack of available surface-water resources, frac sand operations in the study area almost exclusively (if not exclusively) use groundwater for frac sand facility operations. Local aquifers provide most of the water for frac sand production in the Permian Basin (Campbell 2018; this study), municipal and private suppliers are also sources or future sources of water. For example, Preferred Sands of Monahans signed a 30-year contract with the Colorado River Municipal Water District to meet its water needs of up to 2,000 gallons per minute (Triepke 2018f). U.S. Silica uses a combination of wells on site for 20 percent of its supply and groundwater piped from 40 miles away (Wes Penn, U.S. Silica, personal communication). RRIG Water Solutions is converting a crude oil pipeline that runs next to the sand dunes to a water-supply pipeline with the source of water from southeast Winkler County (probably in the Monument Draw Trough of the Pecos Valley Aquifer) and hopes to sell to the oil and gas industry, including frac sand facilities (Triepke 2017b).

To help assess water sources for frac sand facilities in the study area, I used the Texas Water Development Board's Groundwater Data Viewer (TWDB 2018b) to inspect submitted drillers reports. Water well drillers in Texas are required to submit a report to the Texas Department of Licensing and Regulation after completing a well. Drillers reports include information on location, borehole size and depth, lithology, and casing. The reports also request information on water quality, water level, and well tests; however, drillers generally do not collect or report data in these categories.

Drillers may submit reports electronically or in paper form. Forms submitted electronically are instantly available online; however, Texas Water Development Board staff enter paper forms and may take more than a year for entry. For example, for Lonestar Prospects' West Texas Sand Plant, four well reports submitted in paper form in October 2017 weren't entered into the database until late December 2018. Therefore, if a driller submitted paper forms for the wells they drilled, the wells will not be reflected in this study.

I identified a total of 230 production wells for the 16 sites that had production wells drilled at their locations. There may be more wells than reported since there may be a delay in data entry (for example, two wells drilled at the West Texas Sand Plant in

[4] Sand at 70 mesh (0.21 millimeters) would have a porosity of about 40 percent that, once drained, would retain 7 percent of water by volume (Johnson 1966). For a sand with a dry bulk density of 1.5 grams per cubic centimeter, this amounts to the loss of 11.2 gallons of water per ton of sand.

October 2017 and another two wells drilled in February 2018 didn't appear in the database until December 2018). Drillers identified most production wells as industrial; however, drillers marked a few as irrigation wells (perhaps because they are intended for dust suppression). Since I did not see any agricultural irrigation associated with these wells from aerial photography, I included irrigation wells as production wells for the facilities. Several facilities also had test and monitor wells; however, I did not include these wells in the analysis. Test wells were generally plugged after boring, and monitor wells generally had small diameters consistent with monitoring. Two sites did not have any wells in the state database, suggesting an off-site source of water.

Based on the depth of wells, which ranged from 80 to 1,199 feet deep (Table 6.1), and geologic structure (Figures 3.3 and 3.12), supply wells at the facilities are completed in the Pecos Valley Aquifer (103 wells), the Dockum Aquifer (71 wells), both the Pecos Valley and Dockum aquifers (32 wells), and, at one facility, the Pecos Valley and Dockum aquifers and the upper part of the Permian (14 wells). The drillers for 10 wells did not report completion information, but, given their depths, are either completed in the Dockum Aquifer or both aquifers.

Seven facilities have wells completed in both aquifers either explicitly (screened in both) or non-explicitly (screened in the Dockum but with the borehole annulus packed with gravel or sand across both formations). Completing a well in both formations allows an operator to produce from both aquifers with the same well, increasing well yield and decreasing costs. However, the shallower Pecos Valley Aquifer, where water-level elevations are generally at a higher elevation than the underlying Dockum Aquifer, will drain into the well whether its pumping or not.

The number of wells at individual facilities ranged from 4 to 29 (Table 6.1). For facilities solely reliant on the Pecos Valley Aquifer, the number of wells per facility ranges from 8 to 14, whereas for facilities reliant exclusively on the Dockum Aquifer, the number of wells per facility ranges from 4 to 27 (Table 6.1). Nine—possibly 10—facilities have wells completed in both aquifers.

My results corroborate Campbell (2018) who found facilities consist of 10 to 15 wells pumping water from the top two aquifers and where wells can be screened in both the Pecos Valley Aquifer and the Dockum Aquifer. Campbell (2018) notes that well installation costs vary from about $100,000 per well for the shallow wells to about $250,000 per well for the deeper wells.

The relatively large number of wells drilled at these facilities suggests that the aquifers in this area are not highly productive, a conclusion supported by the thin saturated thickness of the Pecos Valley Aquifer and the low hydraulic conductivities of the Dockum Aquifer. Facility operators have to drill and string together wells until they meet their water needs, presumably with several additional back-up wells to provide supplies when other wells are down for servicing.

6.4 Well and Aquifer Descriptions for the Facilities

Below I provide a facility-by-facility description of wells and local hydrologic conditions. For the shallow (<200 feet), unconfined Pecos Valley Aquifer, if drillers did not report water levels, I inferred the depth to water (and hence the saturated thickness) from the upper bound of the screen in the well, which is usually set 10 to 20 feet below the water table. Wells drilled through the Pecos Valley Aquifer were also drilled about 10 feet into the underlying bedrock; however, drillers placed well screen only in the aquifer. For the Dockum, I've assumed that the top and bottom of the screen are completed in the Santa Rose, the productive part of the Dockum, and the top of the screen represents the bottom of an overlying confining layer. These assumptions are not ideal; however, lacking good on-site or near-site information, they are a rough approximation of site conditions.

6.4.1 Covia Crane Facility

Based on structural data (Anaya and Jones 2009) and the drillers' reports, the Pecos Valley Alluvium is shallow at this facility, with the 11 wells here (ranging in depth from 123 to 153 feet) fully penetrating the aquifer. Based on the setting of well screens, the water table is probably about 50 to 60 feet below land surface, resulting in a saturated thickness of about 70 feet. Six wells across the road to the south for the City of Crane have specific capacity measurements. Using the Theis non-equilibrium method (Mace 2001; assuming a storativity of 0.2), these specific capacities result in transmissivities ranging from 109 to 675 ft^2 per day. Assuming screen thickness is aquifer thickness, hydraulic conductivities ranging from 1.6 to 11.3 feet per day with a geometric mean of 4.4 feet per day. Production wells are about 900 feet apart.

6.4.2 Crane County Plant

None of the wells drilled in the area list U.S. Silica as the owner. Instead, the wells are listed in Barr Engineering's name; therefore, I assumed that all the wells drilled by Barr Engineering in the vicinity of the Crane County Plant were drilled for the facility. Wells at this facility are completed in the Pecos Valley Aquifer, the Dockum Aquifer, or both aquifers. Wells drilled into the Dockum either went deep into the formation (485 to 705 feet) or shallower into the formation (190 to 320 feet). Those wells drilled shallower into the Dockum were all dual completed with the Pecos Valley Aquifer. Except for one well, the deeper Dockum wells were solely completed in the deeper Dockum.

Based on structural data (Anaya and Jones 2009) and the drillers' reports, the Pecos Valley Alluvium is shallow at this facility, with wells about 150 feet deep. Based on screen setting and area wells, depth to water in the Pecos Valley Aquifer is about 50 feet.

6.4.3 Preferred Sands of Monahans

None of the wells drilled in the area list Preferred Sands as the owner. Instead, the wells are listed in Hydro Logics name; therefore, I assumed that all the wells drilled by Hydro Logics in the vicinity of the Monahans facility were drilled for the facility. The wells drilled at this facility may be intended for two separate facilities on the property since Preferred Sands was thinking about opening a second facility at the site (Triepke 2018e). Furthermore, Preferred Sands has a take-or-pay contract with the Colorado River Authority for 2,000 gallons per minute for the site (Triepke 2018e; the source of this water is from the deep Monument Draw of the Pecos Valley Aquifer in Ward County).

All but one of the wells drilled here are over 1,000 feet deep, extending below the Dockum Aquifer and into the underlying Permian rocks. The top of the Rustler Formation is about 400 feet below the top of the Permian here (Ewing and others 2012 p. 4-25), so some of these wells may be partially completed in the Rustler; however, the designated Rustler Aquifer is 30 miles to the west and southwest, suggesting that water quality here would be poor. Campbell (2018) notes that a few facilities had completed wells in the Rustler Aquifer with mixed results. Although screened at depth, wells at this site were sand or gravel packed from surface or near surface to depth thereby hydraulically connecting the entire borehole and pulling water from the Pecos Valley Aquifer, the Dockum Aquifer, and perhaps the Permian, including the Rustler. Screen length ranges from 270 to 579 feet long and averages about 400 feet. There are no reported water levels or aquifer tests at this facility.

6.4.4 E Ranch Facility

Based on structural data (Anaya and Jones 2009) and the drillers' reports, the Pecos Valley Alluvium is shallow here, with the 120-to-155-feet-deep wells at the facility fully penetrating the aquifer. The well driller at this site reported depth to water, which ranged from 50 to 63 feet below land surface in 10 of the 11 wells with an average of 60 feet (one of the wells appears to have entered well depth for depth to water, so I left its water-level depth out of this analysis). Based on well depths, reported lithology, and depths to water, the saturated thickness of the aquifer here is about 80 feet.

Wells in the area have reported yields ranging from 50 to 141 gallons per minute. One well at the state park has a reported specific capacity. Using the Theis non-equilibrium method (Mace 2001; assuming a time of pumping of 8 hours), this specific capacity results in a transmissivity of 171 ft^2 per day and a hydraulic conductivity of 2.9 feet per day. Production wells are about 1,000 feet apart.

An agenda for September 26, 2017, for the City of Monahans suggests that the city is selling the facility water. The city is probably also selling water to the Sealy Smith facility.

6.4.5 Hi-Crush

Based on the depths of the wells (~900 feet) and structure in the area (Bradley and Kalaswad 2003 p. 18), these well are completed in the lower part of the Dockum Aquifer. Screen lengths suggest that the productive part of the Dockum Aquifer is about 200 feet thick. Production wells are about 1,700 feet apart. Four of the wells list irrigation as their proposed use; the driller did not report completion information for these wells.

6.4.6 Vest

The Vest site has 13 production wells, 10 of them shallow (<165 feet deep) and 3 deep (720 to 769 feet deep). Comparison of well depth and structure suggests that the shallow wells are completed in the Pecos Valley Aquifer and the deeper wells in the Dockum Aquifer. Based on depth to water in nearby wells, the saturated thickness of the Pecos Valley Aquifer at the location is about 90 feet. Average screen length in the Dockum wells is about 280 feet. Production wells in the Pecos Valley Aquifer are about 1,000 feet apart while wells in the Dockum Aquifer are about 1,600 feet apart.

6.4.7 Kermit Plant

This facility has 29 wells, 28 relatively shallow (<=200 feet deep) and one deep (910 feet deep). The shallow wells are completed in the Pecos Valley Alluvium and part of the upper Dockum with about 60 feet of saturated thickness (based on nearby wells with water levels and screen lengths). A nearby well with a water quality analysis has a total dissolved solids concentration of 758 milligrams per liter. Well yields reported for 12 of the shallow wells range from 90 to 200 gallons per minute with an average of about 170. The deeper well is completed in the Dockum with 320 feet of the well screened to the formation. Production wells are about 1,000 feet apart.

6.4.8 West Texas Sand Plant

This facility has 28 wells, all at about 580 feet deep, which places them into the Dockum Aquifer. Screen length averages about 170 feet. Water levels are about 190 feet below land surface. Assuming that the top of the screened interval is the top of the confined aquifer, there are about 200 feet of hydraulic head above the top of the aquifer. Well yields, reported for 25 of the wells, range from 35 to 95 gallons per minute (average of 60). Twenty-five of the production wells have specific capacity measurements showing about 230 feet of drawdown after about one day of pumping resulting in specific capacities ranging from 0.15 to 0.41 gallons per minute per foot of drawdown and averaging 0.26. Using the Theis non-equilibrium method (Mace 2001), these specific capacities result in transmissivities of 33 to 97 ft^2 per day and, assuming screen thickness is aquifer thickness, hydraulic conductivities of 0.17 to 1.08 feet per day. Spacing between production wells ranges from about 1,000 to 5,200 feet apart.

6.4.9 FML Kermit

This facility has 7 wells, all about 930 feet deep, which places them in the Dockum. The wells average about 310 feet of screen. No information is available in the area on water levels or aquifer properties. Spacing between production wells ranges from about 1,000 to 2,200 feet.

6.4.10 El Dorado Facility

This facility has 12 wells, 9 in the Pecos Valley Aquifer (average depth of 165 feet) and 3 in the Dockum Aquifer (average depth of 715 feet). Water levels in nearby wells are about 50 to 70 feet below land surface suggesting a saturated thickness of about 70 to 90 feet in the Pecos Valley Aquifer here. Screen length for the Dockum wells is about 350 feet. Production wells in the Pecos Valley Aquifer are about 1,000 feet apart while wells in the Dockum Aquifer are about 3,600 feet apart.

6.4.11 Alpine Silica

This facility has 8 wells with an average depth of 890 feet placing them in the Dockum. Screen length ranges from 200 to 490 feet with an average length of about 300 feet. None of the wells nor any nearby wells have information on water levels or aquifer properties in this area. Spacing between production wells ranges from about 400 to 2,000 feet.

6.4.12 BMC-Kermit Plant

This facility has 4 wells that average about 500 feet deep placing them in the Dockum. Screen lengths are all about 200 feet. A nearby well in the Dockum (SWN 46-08-417) reports a yield of 40 gallons per minute, static water levels about 200 feet below land surface in 1995, and total dissolved solids concentration of 397 milligrams per liter. One of the wells at the facility had a drawdown of 250 feet after pumping 100 gallons per minute resulting in a specific capacity of 0.4 gallons per minute per foot. Using the Theis non-equilibrium method (Mace 2001; assuming a pumping time of 8 hours), this specific capacity results in a transmissivity of 93 ft^2 per day. Assuming screen thickness is aquifer thickness, this well location has a hydraulic conductivity of 0.47 feet per day. Spacing between production wells ranges from about 900 to 1,600 feet.

6.4.13 Atlas North

This facility has 14 wells that average 160 feet deep placing them in the Pecos Valley Aquifer. Screen lengths are about 104 feet long. The driller estimated yields of about 100 gallons per minute for five of the wells. Spacing between production wells ranges from about 400 to 800 feet.

6.4.14 Atlas South

This facility has 22 wells, 19 shallow ones (<=120 feet deep) in the Pecos Valley Aquifer and 3 deep (>300 feet deep) wells in the Dockum. Saturated thickness for Pecos Valley Aquifer is probably about 75 feet; average screen length for the Dockum is about 180 feet. The driller estimated the yields of the Dockum wells to be about 30 to 35 gallons per minute. For the Pecos Valley Alluvium, driller-estimated wells yields range from 10 to 165 gallons per minute averaging about 100 gallons per minute. Spacing between most production wells for the Pecos Valley Aquifer range from about 300 to 500 feet apart while spacing for the wells in the Dockum Aquifer range from about 800 to 1,800 feet.

6.4.15 Kermit Plant North

This facility has 12 wells with depths ranging from 900 to 944 feet deep. Four of the wells source water from the Dockum Aquifer, and two of the wells are gravel or sand packed across the Pecos Valley and Dockum aquifers. The driller did not report screened intervals on five of the wells, but, for the 7 wells with reports, screen length averages 206 feet. The wells are about 2,600 and 3,800 feet from each other.

6.4.16 Smart Sand

This facility has 6 wells that average about 400 feet deep, placing them in the Dockum Aquifer. The average screen length for these wells is about 190 feet. The wells are about 1,500 feet from each other.

6.5 The Future of Sand Production

The amount of sand per unit distance of frac is expected to increase with improving technology and growing number of frac stages per hole (Bleiwas 2015). Recent sand demand growth is due to an increase in the amount of sand used per foot of frac, longer laterals, and increasing frac stages (Rock Products 2018). The amount of sand used per foot of frac increased 8 to 10 times between 2008 and 2015, and the number of frac stages increased from 2 to 33 in the Midland Basin and from 4 to 16 in the Delaware Basin over the same period (Scanlon and others 2017). Fracking used to require 1 million pounds of sand; now it needs 8 to 12 million pounds (Kuhar 2016).

The share of locally produced sand is expected to soon grow to 40 percent (Presley 2018) and grow to 50 percent by 2023 (Rock Products 2018). Because of local sand production, Texas is now the second leading state in order of tonnage after Wisconsin (USGS 2018). Local frac sand production in the Permian and other basins is affecting, and even closing, more distant facilities. For example, Pioneer announced in November that it would close its frac sand plant near Brady (Blum 2018a), and more than 12 million tons per year of capacity in the upper Midwest has been idled with another 10 to 15 million tons more possibly idling over the next year (Presley 2018). Some of the idling is due to pipeline constraints, which has decreased the amount of fracking in the Permian Basin (Presley 2018). For example, Hi-Crush idled a plant in Wisconsin is "…because of weakening demand triggered by oil pipeline constraints in West Texas' Permian Basin" (Blum 2018b).

More oil and gas companies are seeking to self-source their sand, and more frac sand facilities are seeking to own storage and transportation assets to control costs (Rock Products 2018; Triepke 2018g). Transportation costs for in-basin sands still account for 65 percent of sand cost (Rock Products 2018).

The Permian Basin is a multi-layered target for fracking. The Permian Basin holds up to 10 stacked reservoirs with the Wolfcamp Shale in the Midland Basin (a subset of the Permian Basin) holding an estimated 20 billion barrels of technically recoverable oil by itself (Scanlon and others 2017). Local sand mining will likely continue—and continue to grow—for the foreseeable future.

Table 6.1: Number of production wells drilled at the facilities.

County	Facility name	Latitude, Longitude	# Wells	Depth (feet)	Aquifer
Crane	(1) Covia Crane Facility	31.480, -102.704	8	123–153	Pecos Valley
	(2) Crane County Plant[a]	31.602, -102.690	2	150	Pecos Valley
			8	485–705	Dockum
			16	190–320	both (upper)[b]
			1	550	both (lower)[b]
Ector	(3) Preferred Sands of Monahans[c]	31.658, -102.775	14	581–1,199	both+Permian
Gaines	(4) Seagraves Sand Plant	32.924, -102.568	0	-	-
Ward	(5) E Ranch Facility	31.610, -102.792	13	120–155	Pecos Valley
	(6) Sealy Smith Facility	31.618, -102.897	0	-	-
Winkler	(7) Hi-Crush	31.965, -102.973	5	910–944	Dockum
			2	910–940	both
			4	900	unknown
	(8) Vest Facility	31.861, -102.915	10	129–161	Pecos Valley
			1	721	Dockum
			2	720–769	both
	(9) Kermit Plant	31.996, -103.036	28	80–230	Pecos Valley
			1	910	Dockum
	(10) West Texas Sand Plant	31.764, -102.869	26	520–640	Dockum
			1	600	unknown
	(11) FML Kermit	31.932, -102.983	9	917–938	Dockum
	(12) El Dorado Facility	31.840, -102.966	9	120–185	Pecos Valley
			3	702–725	Dockum
	(13) Alpine Silica	32.055, -103.049	9	840–906	Dockum
	(14) BMC-Kermit Plant	31.962, -103.108	4	496–515	Dockum
	(15) Atlas North	31.967, -103.009	14	140–240	Pecos Valley
	(16) Atlas South	31.659, -102.877	19	100–120	Pecos Valley
			3	330–380	both
	(17) Kermit Plant North	31.967, -102.972	5	200–220	Dockum
			2	200–210	both
			5	900	unknown
	(18) Smart Sand	31.770, -103.035	6	360–512	both

[a] Listed owner of wells drilled in area is Barr Engineering; assumed these wells were all drilled for Unimin.
[b] ‘upper’ refers to wells completed in the shallower part of the Dockum on-site and ‘lower’ refers to the lower part. All other references to Dockum in this table refer to the lower part.
[c] Listed owner of wells drilled in area is Hydro Logics; assumed these wells were all drilled for Preferred Sands.

7. Potential impacts from groundwater production

Any well that is pumped impacts an aquifer. Locally, a cone of depression is formed around a pumping well where water levels are drawn down around the well. With everything else the same except for storativity, a measure of how much water is released from storage per unit aquifer of the aquifer per unit decline in water level, the cone of depression around a well in an unconfined (or water table) aquifer is not as deep nor as wide as one in a confined aquifer (Figure 7.1). If multiple wells are pumping the same aquifer and they are close enough together, the cones of depression will interfere with each other. In this case, multiple cones of depression are additive resulting in more drawdown at a location than if there was one cone of depression. For example, if pumping Well A causes 5 feet of water-level decline at Point X and pumping Well B causes 4 feet of water-level decline at Point X, when both wells are pumping, the water-level decline at Point X will be 9 feet.

Over time, cones of depression generally become broader, affecting a wider area, although the rate of growth decreases with time. If an aquifer hosts many pumping wells, over time there may be region-wide water-level declines; in other words, declines observed across the aquifer. If the amount of water pumped exceeds the amount of water that effectively recharges the aquifer, regional water-level declines may be seen year after year as water is removed from storage. Lowered water levels may cause higher energy costs to raise water to the land surface and, in unconfined aquifers, lead to declining well yields as the saturated thickness thins. If water levels continue to decline, economically usable amounts of water may not be able to be produced from the aquifer for certain users. For confined aquifers, declining water levels may convert the aquifer, at least locally, from a confined aquifer to an unconfined one. Declining water levels in confined aquifers may also lead to declining well yields over time.

If an aquifer is hydraulically connected to the land surface at a river, stream, spring, or pond, declining water levels may decrease flow to those surface-water bodies and possibly dry them up when there's no surface-water runoff. Declining water levels may also cause land subsidence.

MEQB (2013), writing about the effects of frac sand facilities in Minnesota, noted that the cumulative effects on water quantity of multiple silica sand mines in proximity are not well understood and recommended requiring monitoring wells at frac sand facilities to measure water levels, flow directions, and water quality. Rock Products (2018), quoting IHS Markit, noted that regional Texas sands have challenges related to water availability. Campbell (2018), referring to the Permian Basin, indicated that "…increasing stresses on the aquifer will provide the 'opportunity' to test the sustainability of the supply and the success of the collective efforts to plan and provide for future demand."

It's too soon to see possible impacts from pumping beneath frac sand facilities with available data collection. Since there are no groundwater districts in the area measuring water levels, the only available data is collected by the Texas Water Development Board and entered into their on-line database (TWDB 2018b). In areas without groundwater conservation districts or districts that don't measure water levels, the Texas Water Development Board measures water levels annually during the winter months when irrigation and other seasonal uses are at a minimum. Since most of the frac sand facilities went into operation during 2018, many of those measurements hadn't been made yet at the time the work for this report was completed. However, even with the Board's measurements, the monitor wells may not be in the right place to accurately assess effects.

7.1 Comparison to other water uses

Other pumping may make it difficult to tease out the effects of frac sand facilities without purpose-built monitoring. With at least 53.8 million tons per year of production capacity possibly needing between 60 and 250 gallons of water per ton of sand production, frac sand facilities may be pumping between 10,000 and 40,000 acre-feet per year of water. This use may be less than half or almost twice the 23,500 acre-feet of water currently produced in Crane, Ector, Ward, and Winkler counties for other uses (these are the counties that include active frac sand facilities).

Municipal suppliers also source their water from area aquifers. Besides the local communities, the City of Midland, the Midland County Freshwater Supply District #1, and the Colorado River Municipal Water District have well fields in the area. Many of the larger communities, including Monahans, seek water from the Monument Draw Trough of the Pecos Valley Aquifer to the west of the frac sand facilities. The City of Crane has a well field about 7 miles southeast of Monahans in the Pecos Valley Aquifer. The City of Kermit has water supply wells in the Pecos Valley and Dockum aquifers in and near the city. There are also numerous household and stock wells across the area as well as supply wells for the oil and gas industry.

Because the Monahans-Mescalero Sand Ecosystem rests in the middle of the Central Basin Platform between the Midland and Delaware basins (sub-basins of the Permian Basin), most of the local drilling is for conventional oil and gas accessed through vertical, unfracked wells, which require "low water volumes" (Scanlon and others 2017). In the Central Basin Platform, 96 to 152 non-conventional (fracking) horizontal wells were drilled per year between 2012 and 2015 (as compared to 1,256 wells drilled in the Midland Basin, Scanlon and others 2017 Table S3b). With an average of 100,000 m^3 of water used to frac an oil well in the Permian Basin (Kondash and others 2018), 100 fracked wells in the Central Basin Platform would use about 8,000 acre-feet of water per year.

A total of 1,557 conventional wells were drilled in the Permian Basin outside of the Midland and Delaware basins in 2015 down from 2,967 in 2014 (Scanlon and others 2017 Table S3a). If half of those were drilled in the Central Basin Platform, and assuming water use of 300,000 to 600,000 gallons per well for drilling (Mielke and others

2010), water use for conventional drilling could range between 1,400 to 5,500 acre-feet per year. Note that these water estimates for oil and gas activities in the Central Basin Platform are over a much larger area than where frac sand facilities in the study area currently focused. Furthermore, drilling intensity in the Central Basin Platform has generally been away from the Monahans-Mescalero Sand Ecosystem (see Figure 1 of Scanlon and others 2017).

Summing the above pumping estimates results in a range of 42,900 to 77,000 acre-feet of water possibly being pumped in Crane, Ector, Ward, and Winkler counties. Groundwater availability for the Pecos Valley and Dockum aquifers for the four counties (the modeled available groundwater in Table 4.2) sums to 118,702 acre-feet per year; therefore, at least for the combined four counties, all uses, including those for frac sand facilities, are below the estimated groundwater availability with the ability to accommodate additional pumping.

7.2 Water-level trends

There is some published and anecdotal information on water-level impacts for the study area. Stephens (2016a and 2016b as quoted by Scanlon and others 2017) noted that groundwater pumping for hydraulic fracturing has resulted in local drawdowns of up to 100 feet; however, this is not in the study area. Wight (2018), a landowner near the dunes and frac sand facilities, noted that "There is an inevitable conflict between the people who need water and the folks who have it. Even though the nascent sand industry is not the largest water user in the sandhills, we are starting to see some dramatic effects on the supply of water since they arrived." Wight (2018) noted that he's seen some small decreases in the water table and has one well with a water-level decline of over 70 feet in the previous year.

To attempt to assess ongoing water-level trends from existing pumping, I queried long-term monitor well data with data over the past five years for the Pecos Valley and Dockum aquifers in the study area from the Texas Water Development Board (Figure 7.2). Most of this data is to the west of the Monahans-Mescalero Sand Ecosystem where the Pecos Valley Aquifer is thicker in the Monument Draw Trough, but wells 10, 12, and 16—all completed in the Pecos Valley Aquifer—are in the southern reaches of the dunes and are relatively close (2 miles or less) to frac sand facilities (Figure 7.2). Appendix C includes all the hydrographs; I will only show a few key ones here.

One hydrograph of interest is Well 10, which is a stock tank well just east of the Monahans Sandhills State Park north of Interstate 20 and about 2 miles away from the E Ranch Facility (Figure 7.2). Depth to water at this well has ranged from 35 feet to 44 feet since the late 1960s (Figure 7.3). Water levels appear to have slightly declined since the late 1980s (Figure 7.3). Well 12 is located about 1 mile to the north of the Covia Crane Facility (Figure 7.2). Depth to water at this well has ranged from 33 feet to 70 feet since the late 1950s (Figure 7.4). Water levels have been relatively steady since the 1970s and have increased over the past few years (Figure 7.4). Well 16 is located about 1.5 miles to the southeast of the Crane County Plant (Figure 7.2). Depth to water in this well has ranged from 94 to 100 feet since 2015 with levels rising over the past three years (Figure 7.5).

Pumping at nearby frac sand facilities does not appear to have affected these wells. As will be seen later in this section, this lack of impact is not surprising given the distances these wells are from the facilities, the short amount of time for pumping, and the unconfined nature of the Pecos Valley Aquifer.

None of the monitor wells completed in the Dockum Aquifer are close to frac sand facilities, but wells 4 and 5 are 6 to 9 miles away from three different facilities (Figure 7.2). Well 4 has shown a steady decline in water levels since the mid-1950s dropping from about 70 feet below land surface to 120 feet (Figure 7.6). Well 5 has been relatively stable at about 120 feet below land surface (Figure 7.7).

The Texas Water Development Board's water-level monitoring network does not have wells in place to adequately monitor water-level effects from pumping at frac sand facilities. An expanded and strategic monitoring well network would have to be designed and measured to capture the effects of pumping at frac sand facilities.

7.3 Groundwater modeling

Water-level declines due to pumping can be estimated given information on the aquifer (saturated thickness, hydraulic heads, hydraulic conductivity, storativity) and the pumping well (pumping rate, duration of pumping, well radius). Because I lack specifics on the facilities discussed in this report, I investigated two type cases that are representative of the hydrogeology beneath frac sand facilities in the study area, one for the Pecos Valley Aquifer and one for the Dockum Aquifer. These type cases are intended to provide a sense of how area aquifers might respond to pumping. An assessment of specific impacts at specific sites requires site-specific information that is not publicly available.

Based on the data collected in the previous section as well as the description of the hydrogeology in Section 3, I identified a type case for the Pecos Valley Aquifer as having a saturated thickness of 70 feet, a hydraulic conductivity of 10 feet per day, and a storativity of 0.2. This type case facility for the Pecos Valley Aquifer produces 3.6 million tons per year and has 12 wells with 8-inch diameters spaced 1,000 feet apart pumping 70 gallons of water per ton of sand, which amounts to about 40 gallons per minute per well. I chose 70 gallons of water per ton of sand on the low end of the range I reported because, as we will see in Section 7.3.1, my type case would not support much higher amounts of pumping over 10 years.

The type case for the Dockum Aquifer includes a saturated thickness of 200 feet, a hydraulic conductivity of 1.0 feet per day, a confined storativity of 2.5×10^{-4}, an unconfined storativity of 0.15, and 300 feet of artesian pressure above the top of the aquifer. This type case facility for the Dockum Aquifer has 7 wells with 8-inch diameters spaced 2,000 feet apart pumping 70 gallons per minute per well (again assuming a facility that produces 3.6 million tons per year pumping 70 gallons of water per ton of sand).

To model these type cases, I first used the Theis (1935) non-equilibrium equation for unsteady radial flow (with Jacob's [1963] correction for unconfined aquifers for the Pecos Valley Aquifer) to investigate water-level declines around a single well and then developed simple numerical groundwater flow models using MODFLOW-2000 (Harbaugh and others 2000) through Groundwater Vistas (Rumbaugh and Rumbaugh 2017). To verify the numerical groundwater model, I compared its results for a single well to the results from the Theis (1935) analysis. For the numerical groundwater flow model, I allowed transmissivity to vary with saturated thickness for the Pecos Valley Aquifer and allowed the Dockum Aquifer to convert from a confined to an unconfined aquifer when water levels fell below the top of the aquifer.

For the modeling results presented below, I first discuss water-level declines around a single well pumping 40 gallons per minute in the Pecos Valley Aquifer and 70 gallons per minute in the Dockum Aquifer after pumping 1 year and 10 years. I then present a sensitivity analysis on a single well pumping 10 years where I plot water-level decline at the well for different pumping rates and hydraulic conductivities. I present these single well analyses to demonstrate how the unconfined Pecos Valley Aquifer responds differently to pumping than the confined Dockum Aquifer and how a single well responds to different levels of pumping and hydraulic conductivity.

After that, I present results from the numerical model where all the wells are included, 12 for the Pecos Valley Aquifer and 7 for the Dockum Aquifer, first for 1 year of pumping and then for 10 years of pumping. These are the simulations that show the water-level declines around the frac sand facility type cases, what might be expected in the Permian Basin. As a sensitivity analysis on the numerical model, I increased the pumping rate until the aquifer could no longer support the pumping (in modeling parlance, cells in the model go dry when the simulated water-level falls below the base of the aquifer). I did this for the 1 year and 10 years simulation periods.

7.3.1 Modeling results for the Pecos Valley Aquifer

For a single well pumping the Pecos Valley Aquifer, there would be about 18 feet of water-level decline at the well after one year of pumping and 20 feet of water-level decline after 10 years of pumping. After one year of pumping, the radius of influence to 5 feet of water-level decline (in other words, the distance from the pumping well to the 5-foot water-level decline point) would be about 100 feet. After ten years of pumping, the radius of influence for 5 feet of water-level decline would be about 300 feet. After 1 year of pumping, the radius of influence for a 1 foot of water-level decline would be about 1,000 feet, and after 10 years of pumping the radius of influence for 1 foot of water-level decline would be about 3,000 feet wide.

A single well in the Pecos Valley Aquifer with a hydraulic conductivity of 10 feet per day can support up to 80 gallons per minute of pumping for 10 years before going dry (Figure 7.8; follow the blue line for K =10 feet/day). If the hydraulic conductivity is 15 feet per day, a single well can support upwards of 115 gallons per minute of pumping before going dry (Figure 7.8; follow the green line for K = 15 feet/day). At the highest reported hydraulic conductivity of 26.9 feet per day (as reported in Figure 3.7), a single well could support more than 140 gallons per minute of pumping (Figure 7.8; follow the purple line for K = 26.9 feet/day).

Returning to the type case with a well field of 12 wells arranged in a 3 by 4 well pattern, it’s about 550 feet to the 5-foot water-level decline contour from an outer well in the well field after one year of pumping (Figure 7.9). It’s about 2,100 feet to the 1-foot water-level decline contour from an outer well in the well field after one year of pumping (Figure 7.10). Using superposition and the Theis (1935) equation corrected for an unconfined aquifer, a well in the center of the well field would have about 25 feet of drawdown after pumping the well field for 1 year.

Using the MODFLOW model, I increased the pumping rate for each well from 40 gallons per minute to identify when the type case would no longer support pumping after one year. According to the model, the well field could support increased pumping until it reached about 101 gallons per minute per well, which equates to 177 gallons of water consumed per ton of sand produced.

Returning to the type case and pumping the well field for 10 years, it’s about 4,000 feet to the 5-foot water-level decline contour from an outer well in the well field (Figure 7.11). It’s about 9,000 feet to the 1-foot water-level decline contour from an outer well in the well field after 10 years of pumping (Figure 7.12). Using superposition and the Theis (1935) equation corrected for an unconfined aquifer, a well in the center of the well field would have about 47 feet of drawdown after the well field has been pumped for 10 years.

Using the MODFLOW model, I increased the pumping rate to identify when my type case of the aquifer would no longer support pumping after 10 years. The well field could support increased pumping until it reached about 45 gallons per minute per well, which equates to 79 gallons of water consumed per ton of sand produced. This simulation and the reported use by U.S. Silica in Section 6.2 is why I used 70 gallons of water consumed per ton of sand produced for the type cases.

7.3.2 Modeling results for the Dockum Aquifer

For a single well pumping the lower part of the Dockum Aquifer, there would be about 124 feet of water-level decline at the well after one year of pumping and 136 feet of water-level decline after 10 years of pumping. After 1 year of pumping, the radius of influence for 5 feet of water-level decline would be about 16,000 feet (3 miles). After ten years of pumping, the radius of influence for 5 feet of water-level decline would be about 51,000 feet (9.7 miles). After 1 year of pumping, the radius of influence for a 1 foot of water-level decline would be about 23,000 feet (4.4 miles), and after 10 years of pumping the radius of influence for 1 foot of water-level decline would be about 74,000 feet (14 miles).

A single well in the Dockum Aquifer with a hydraulic conductivity of 1 feet per day can support up to 150 gallons per minute of pumping for 10 years before drawing water levels below the top of the aquifer (Figure 7.13; follow the light blue line where K = 1 feet/day). If the hydraulic conductivity is 2 feet per day, a single well can support more than 250 gallons per minute of pumping (Figure 7.13; follow the dark blue line for K = 2 feet/day). At the highest reported hydraulic conductivity, a single well could support considerably more than 250 gallons per minute of pumping (Figure 7.13; follow the green line for K = 5 feet/day).

With a well field of 7 wells arranged in a 2 by 3 pattern with a single well on top, it's about 40,000 feet (7.5 miles) to the 5-foot water-level decline contour from an outer well in the well field after one year of pumping (Figure 7.14). It's about 65,000 feet (12.3 miles) to the 1-foot water-level decline contour from an outer well in the well field after one year of pumping. Using superposition and the Theis (1935) equation corrected for an unconfined aquifer, a well in the center of the drawdown would have about 272 feet of drawdown after the well field has been pumped for 1 year.

After pumping for 10 years, it's about 130,000 feet (24.6 miles) to the 5-foot water-level decline contour from an outer well in the well field (Figure 7.15). A pumping well in the center of the well field would have about 360 feet of drawdown after pumping the well field for 10 years. For the Dockum Aquifer, this simulation suggests that pumping might completely deplete the artesian pressure in the well field by 10 years of operation.

Using the MODFLOW model, I increased the pumping rate to identify when my type case of the aquifer would no longer support pumping after 10 years. The well field could support increased pumping until it reached about 115 gallons per minute per well, which equates to 115 gallons of water consumed per ton of sand produced.

7.3.4 Discussion

As mentioned in Section 6.3, facility operators likely have to drill and string together wells until they meet their water needs. How many wells are required is a function of water needs (tied back to sand production and water efficiency), local aquifer properties, and how long they pump. The modeling presented in this section shows that, if operators optimize well fields to today's needs, additional wells will likely be needed in the future as water levels decline over time.

The modeling also shows how broad the water-level decline effects might be: 4,000 feet to a 5-foot decline after 10 years of pumping in the Pecos Valley Aquifer compared to 130,000 feet after 10 years of pumping in the Dockum Aquifer. Pumping effects over the long term will likely remain relatively local in the Pecos Valley Aquifer—a common attribute of unconfined aquifers—and will probably be countywide in the Dockum Aquifer—a common trait of confined aquifers. The unconfined and confined conditions of the aquifers have implications for any monitoring networks that might be conceived to assess facility effects: monitor wells will need to be within a mile of a well field in the Pecos Valley Aquifer while monitor wells in the Dockum are ideally close to the well field, there's more room to maneuver.

As discussed, wells in well fields can interfere with each other, but well fields can also interfere with each other. For the Pecos Valley Aquifer, facilities with well fields within two miles of each other are likely to interfere with each other in as soon as a year and more as time goes on. This interference may result in lowering well yields, leading to more wells being drilled. For the Dockum Aquifer, well fields within 50 miles of each other will likely interfere with each other. Again, this interference may result in lowering well yields, leading to more wells to compensate.

In my type cases, I used well fields that spaced wells in a grid—a clumping scenario. Some facilities certainly clump their wells (for example, see the wells drilled at Atlas South, Appendix A, p. 108); however, others arrange their wells linearly (for example, see the wells drilled at the Vest Facility, Appendix A, p. 99). A linear well arrangement decreases overall well interference.

Frac sand facilities join a long history of groundwater production in the study area. With hydraulic fracturing, growing populations, declining surface-water reservoirs, a lack of water-supply alternatives, and new demands for water, the Pecos Valley and Dockum aquifers are experiencing a great deal of new drilling and pumping by existing and new users. At this point, given all the new interest in the area's groundwater resources, it's unclear what the effects might be, but water levels will inevitably decline over time. How much they drop and how much they affect groundwater resources—and the people and species that rely on them—remains to be seen.

I recommend following ongoing activity in the area by all pumpers and, if possible, expanding water-level monitoring to gain a better understanding of how additional pumping is affecting the aquifers. This study suffered from a lack of site-specific information on water use and produced sand tonnage. If the state wishes to have a better understanding of potential effects from pumping at these facilities, then requiring this information would be useful.

Finally, well completions across different aquifers should be discouraged. Even when pumping at these wells stop, formations with higher water-level elevations will continue to drain into depleted formations, thus affecting the water resources for remaining users.

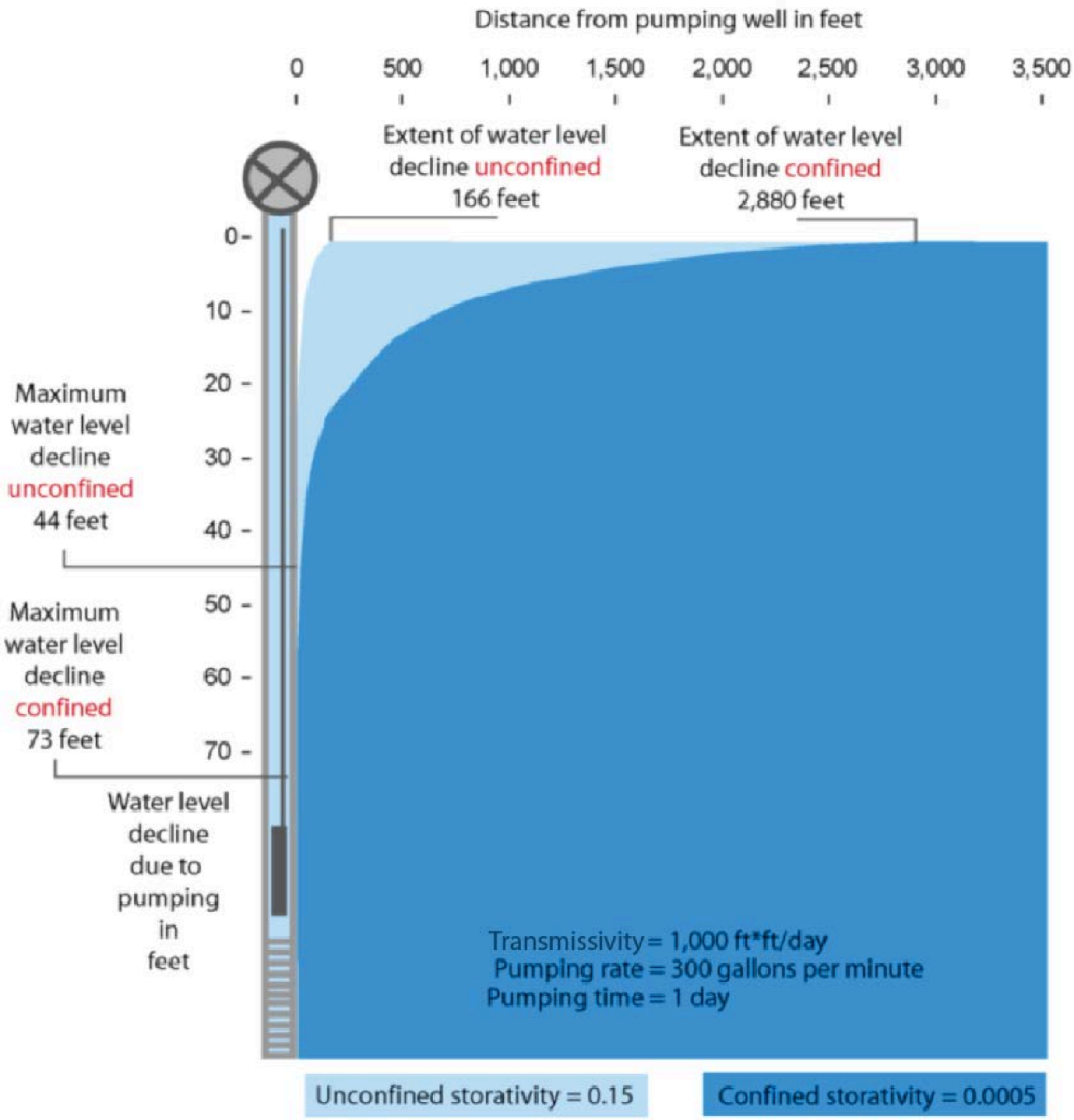

Figure 7.1: Comparison of water-level declines around a well in the exact same aquifer except that one is unconfined and one is confined. Aquifer properties shown are not meant to reflect those of the aquifers discussed in this study.

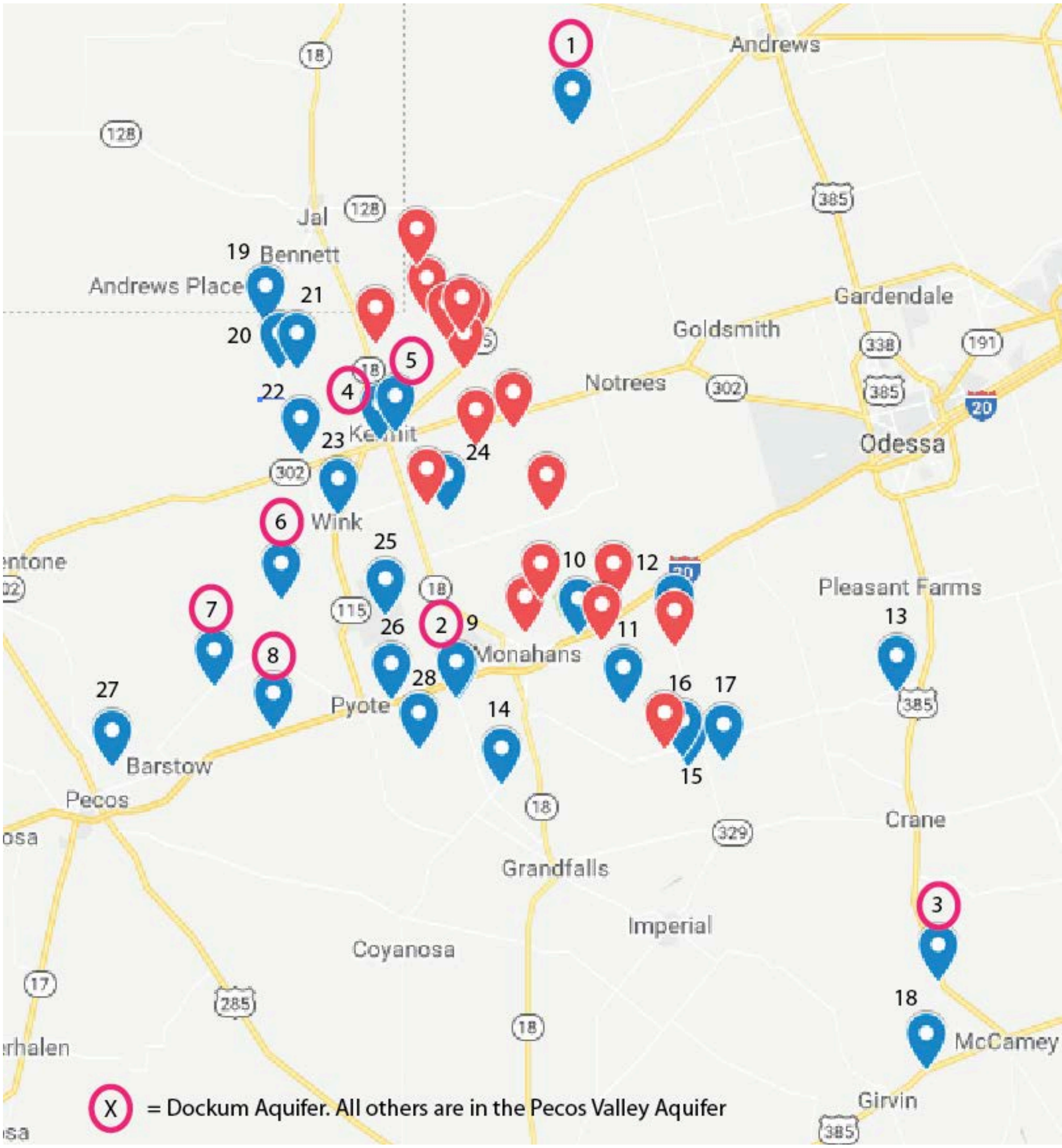

Figure 7.2: Location of wells with water-level measurements during at least the past five years. The red markers indicate where the locations of frac sand facilities.

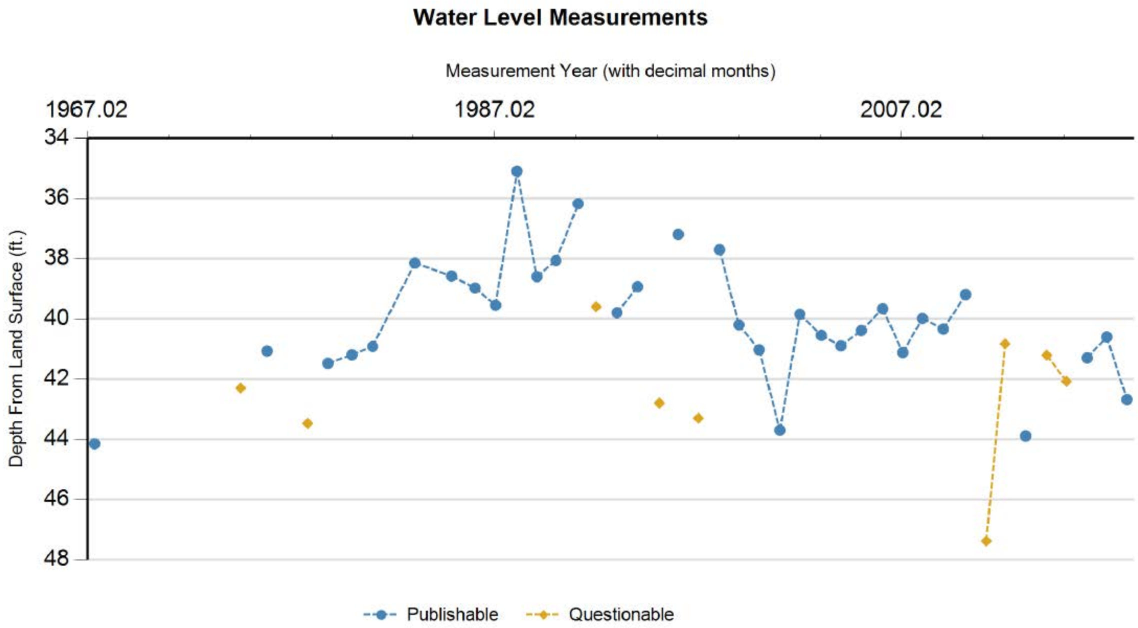

Figure 7.3: Water-level measurements in Well 10 completed in the Pecos Valley Aquifer (as numbered in this report; State Well Number 4526202).

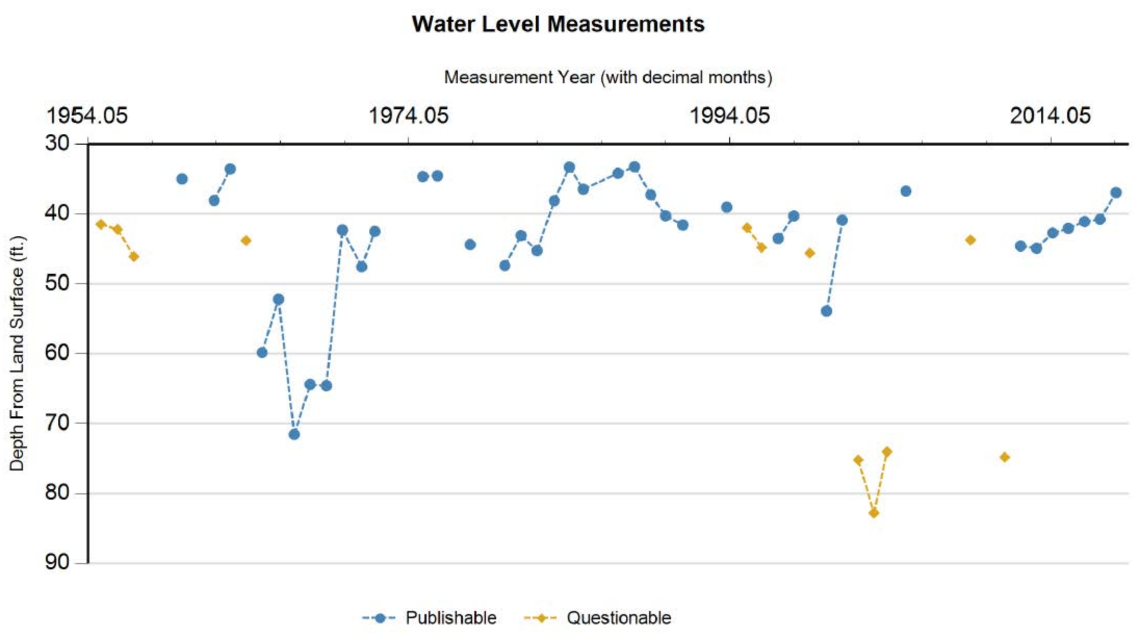

Figure 7.4: Water-level measurements in Well 12 completed in the Pecos Valley Aquifer (as numbered in this report; State Well Number 4527203).

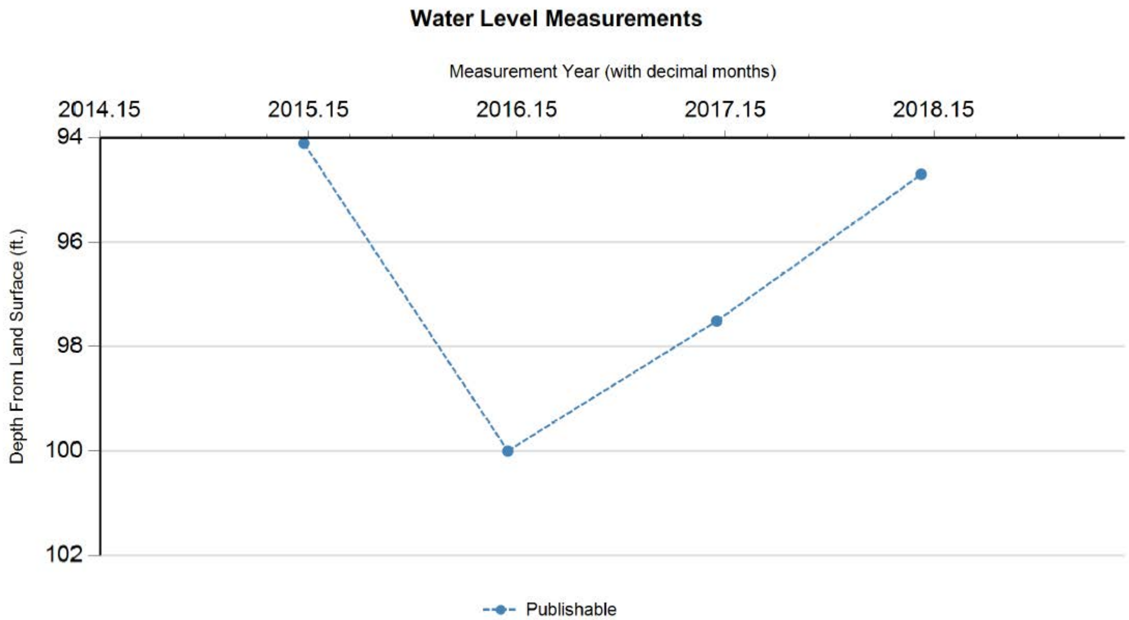

Figure 7.5: Water-level measurements in Well 16 completed in the Pecos Valley Aquifer (as numbered in this report; State Well Number 4535210).

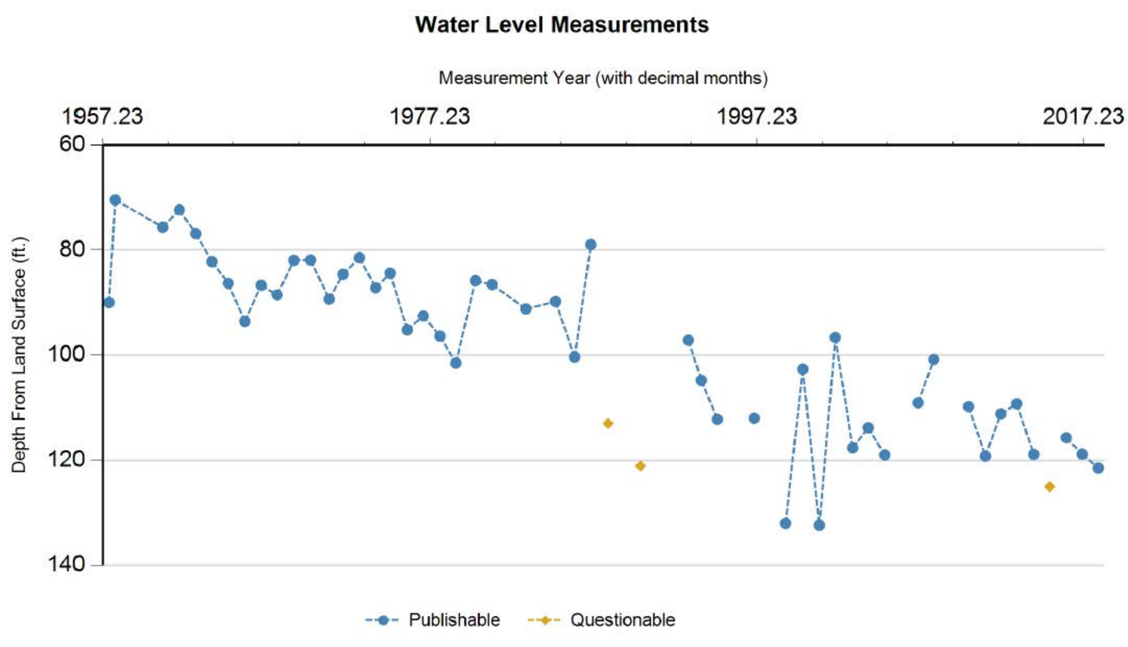

Figure 7.6: Water-level measurements in Well 4 completed in the Dockum Aquifer (as numbered in this report; State Well Number 4616101).

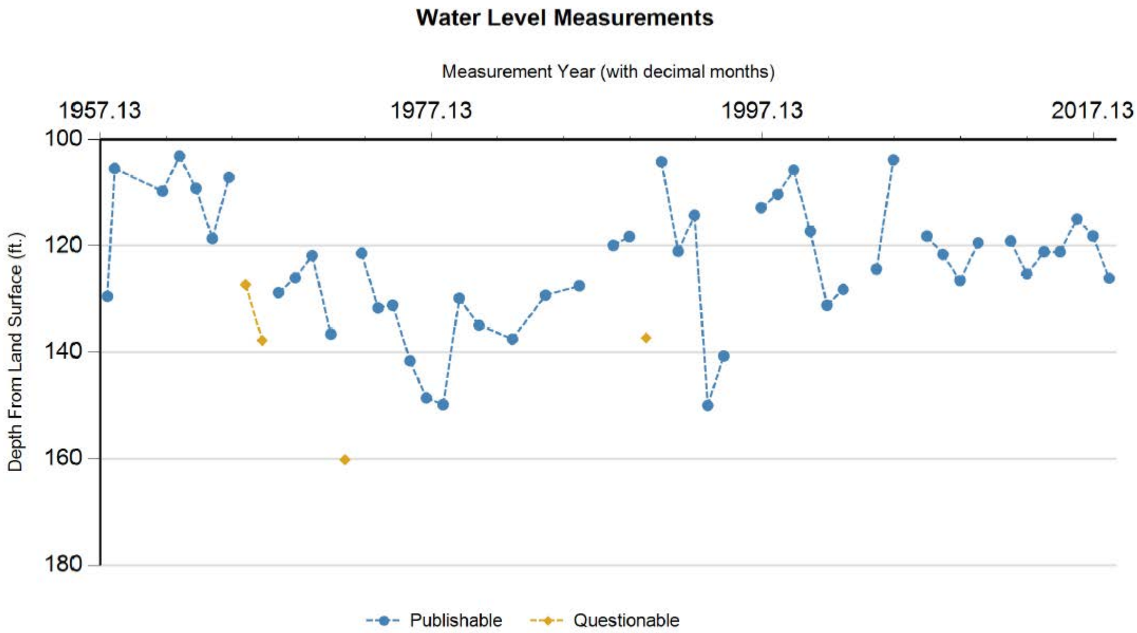

Figure 7.7: Water-level measurements in Well 5 completed in the Dockum Aquifer (as numbered in this report; State Well Number 4616201).

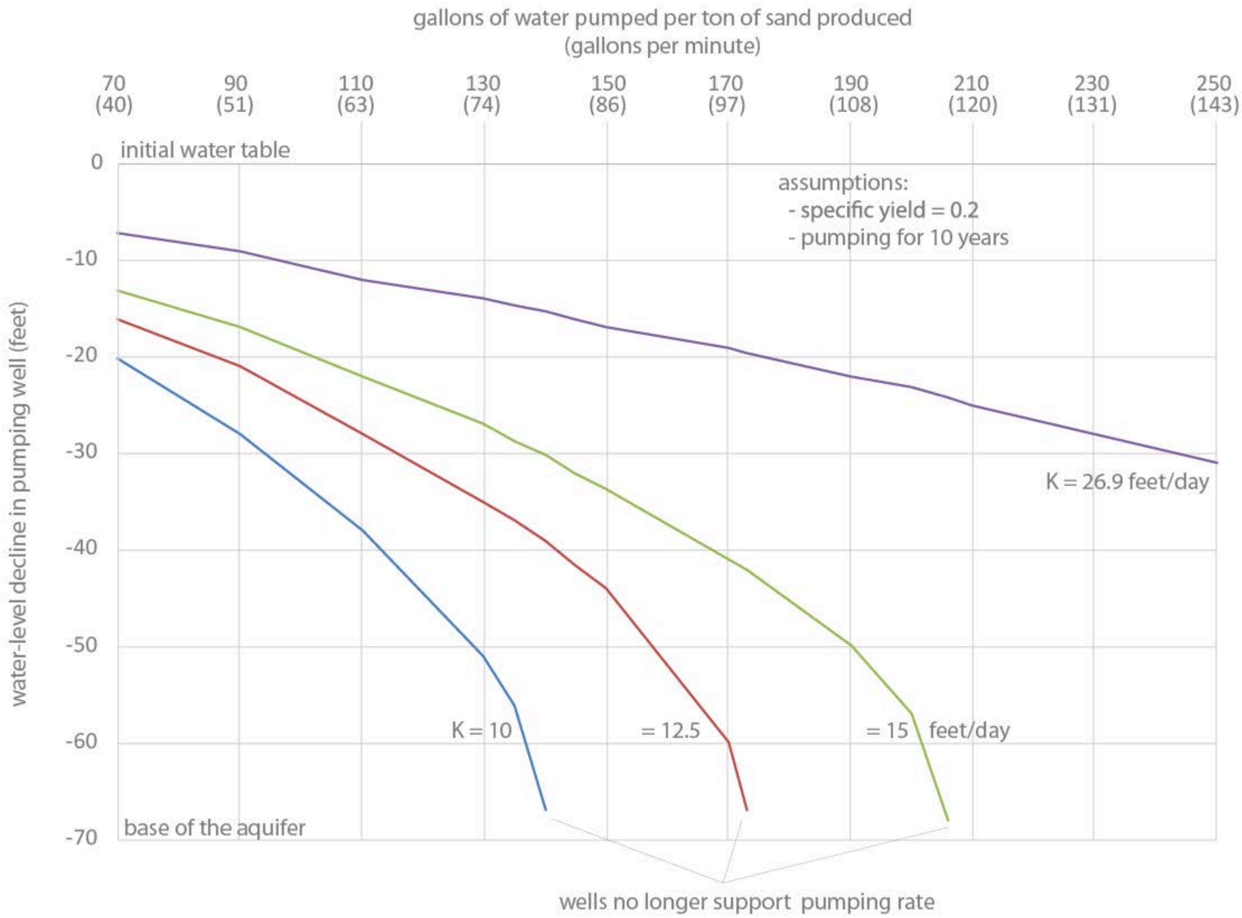

Figure 7.8: Sensitivity analysis of pumping rate and hydraulic conductivity on water-level declines in a single well in the Pecos Valley Aquifer after pumping 10 years.

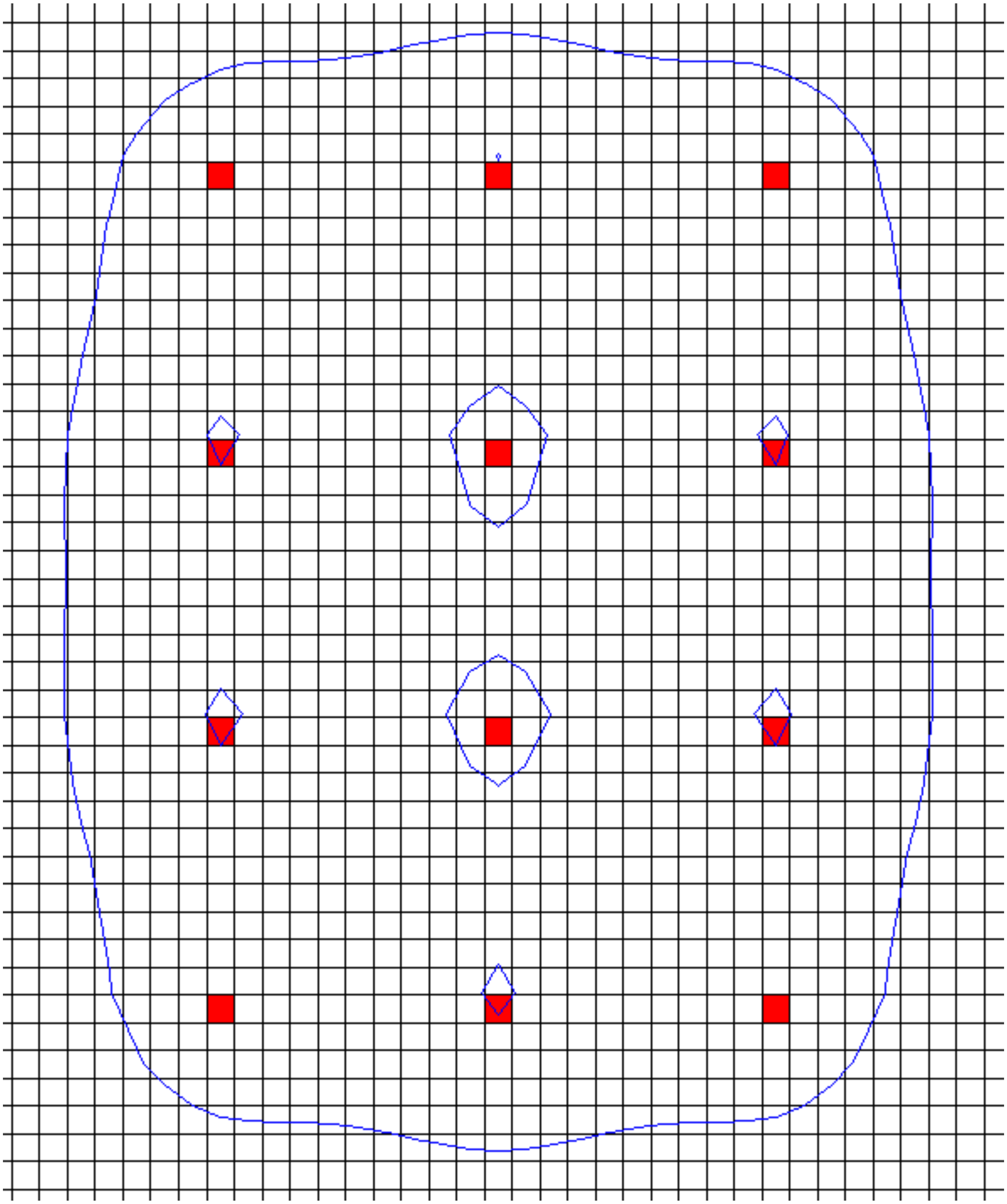

Figure 7.9: Water-level declines at a 5-foot interval around a hypothetical well field in the Pecos Valley Aquifer after pumping for 1 year. The cells (squares) are 100 by 100 feet.

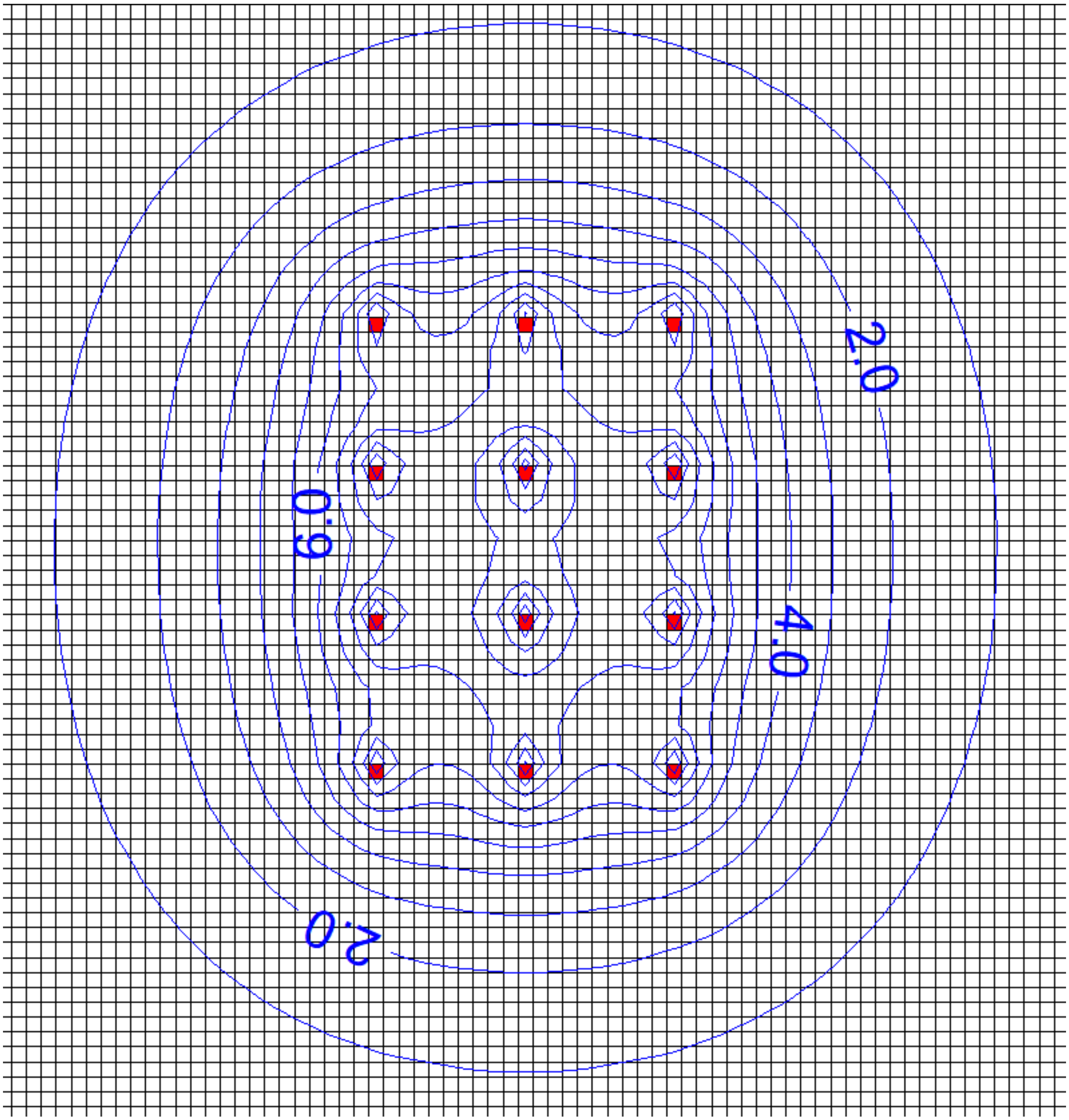

Figure 7.10: Water-level declines at a 1-foot interval around a hypothetical well field in the Pecos Valley Aquifer after pumping for 1 year. The cells (squares) are 100 by 100 feet.

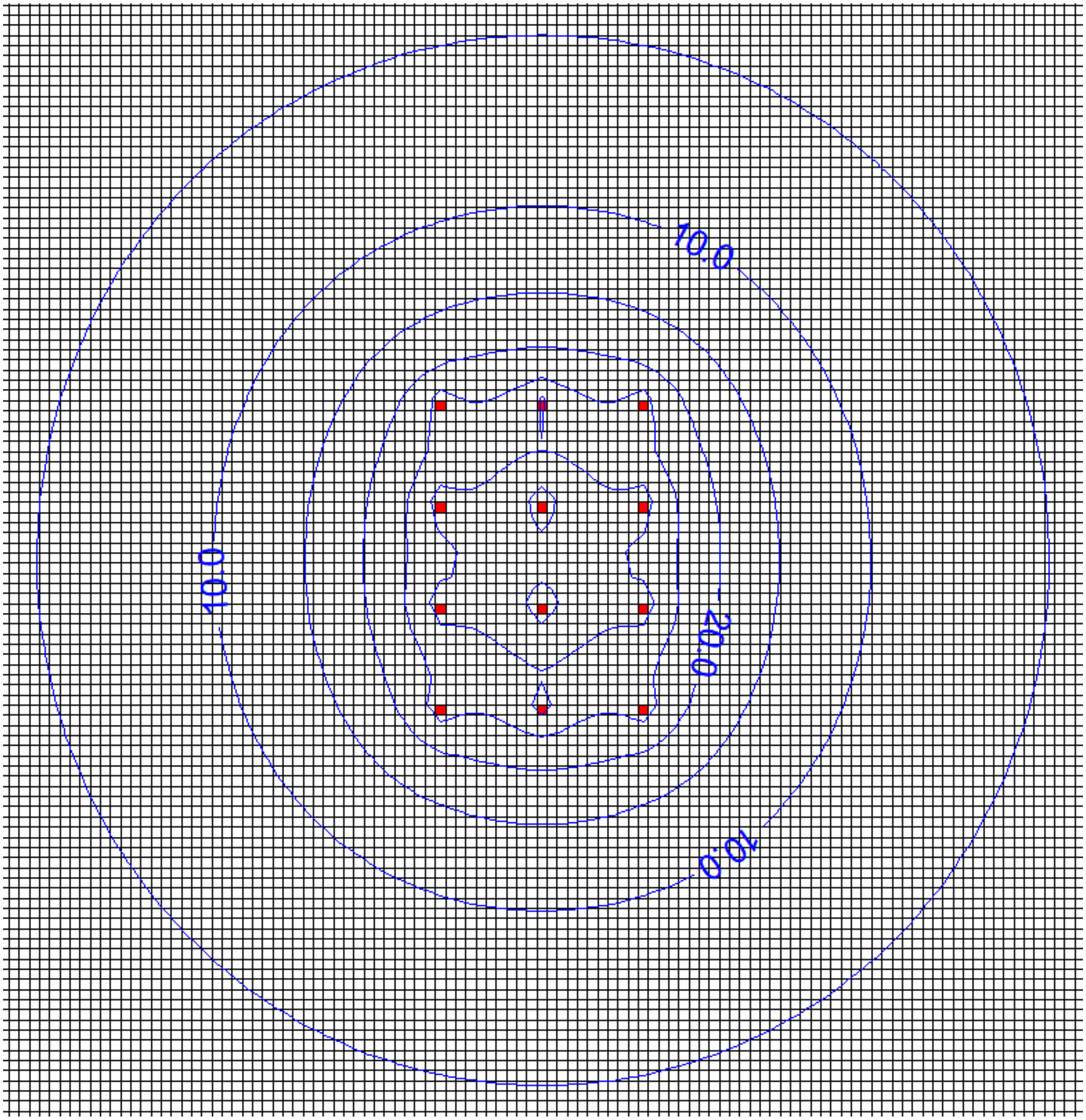

Figure 7.11: Water-level declines at a 5-foot interval around a hypothetical well field in the Pecos Valley Aquifer after pumping for 10 years. The cells (squares) are 100 by 100 feet.

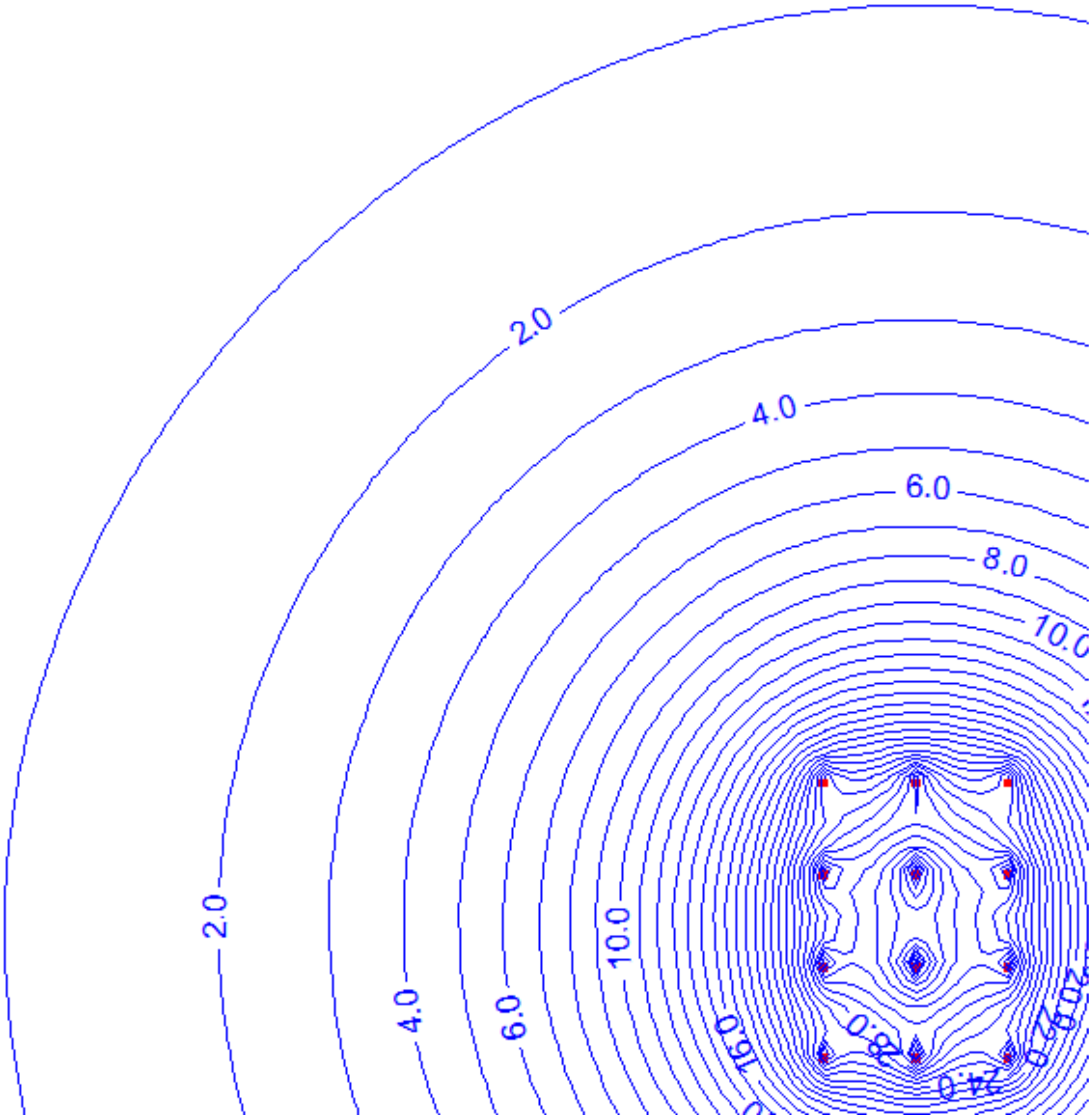

Figure 7.12: Water-level declines at a 1-foot interval around a hypothetical well field in the Pecos Valley Aquifer after pumping for 10 years. The wells (red squares) are spaced 1,000 feet apart.

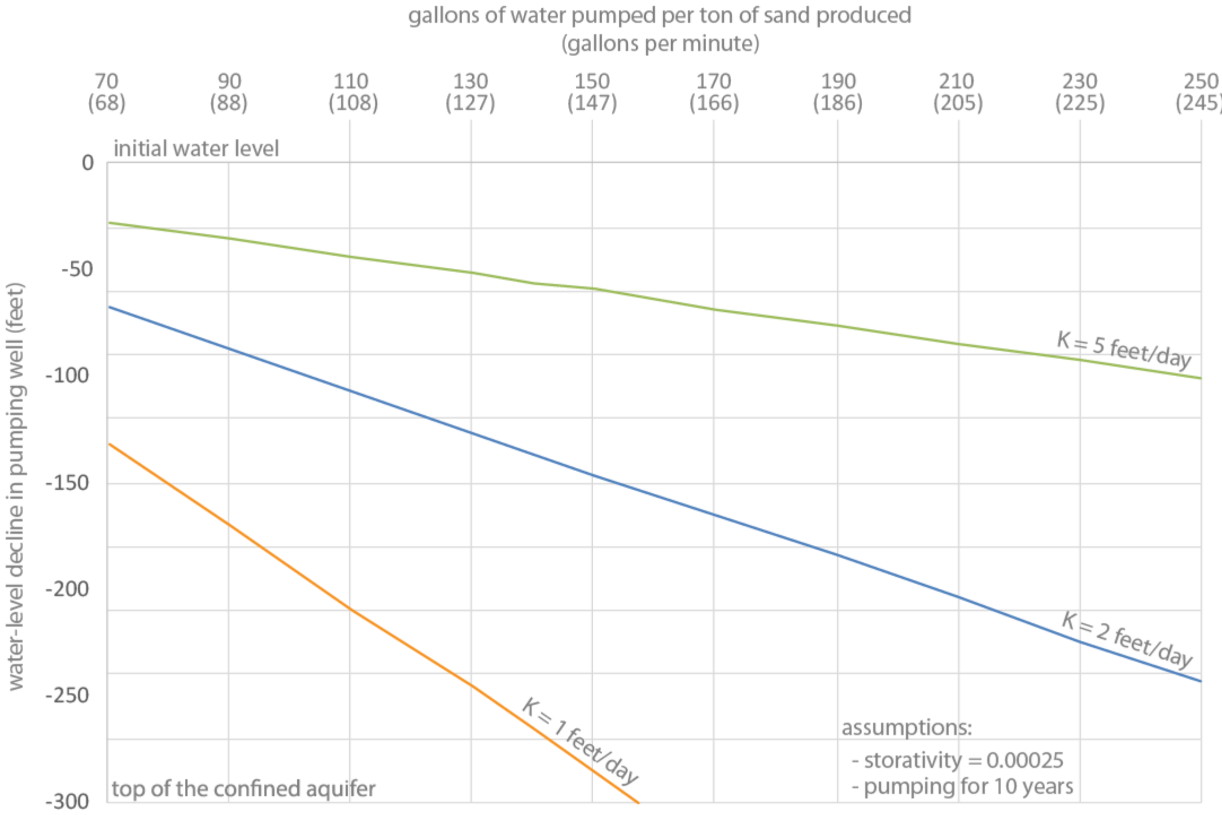

Figure 7.13: Sensitivity analysis of pumping rate and hydraulic conductivity on water-level declines in a single well in the Dockum Aquifer after pumping 10 years.

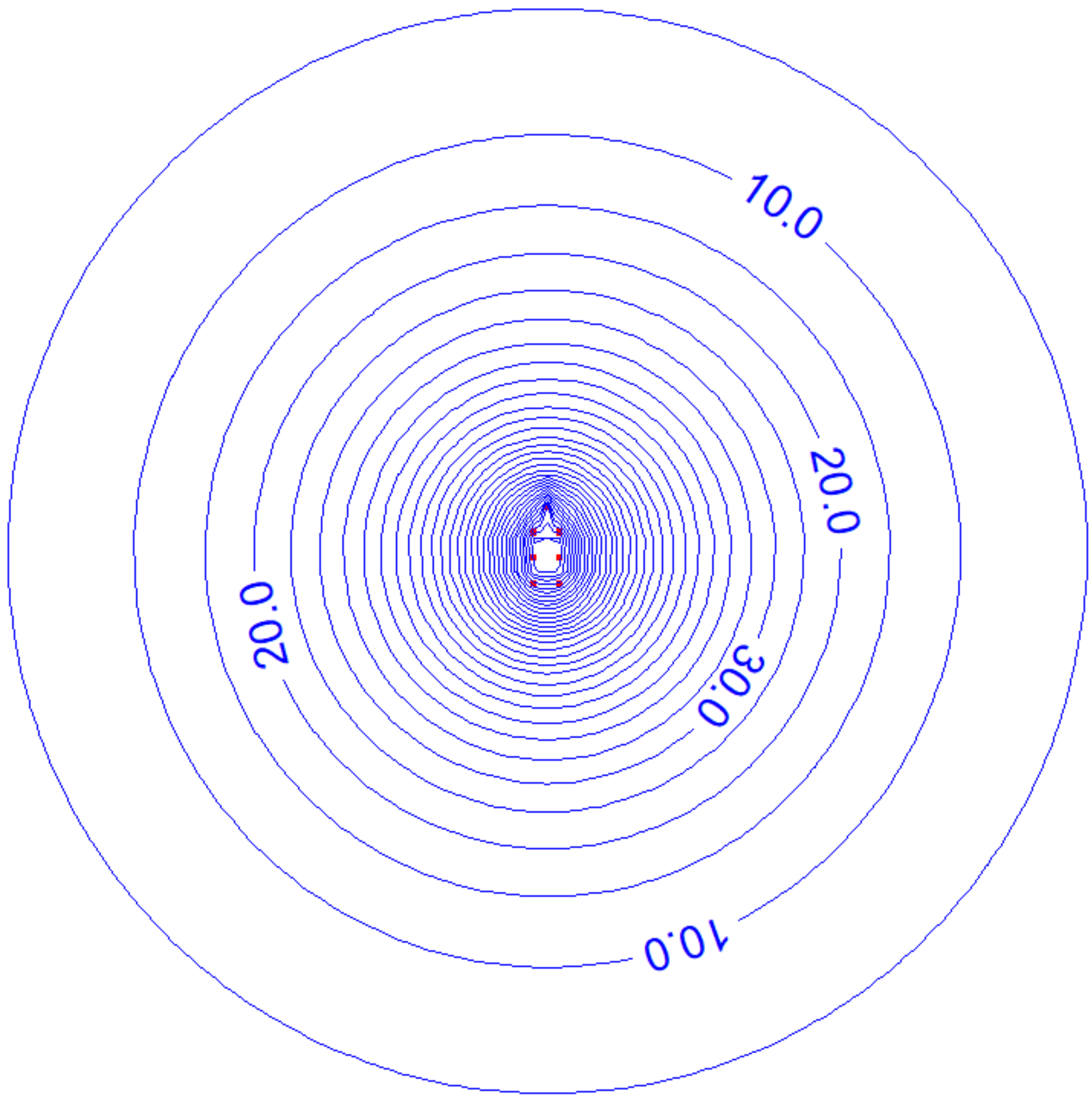

Figure 7.14: Water-level declines at a 5-foot interval around a hypothetical well field in the Dockum Aquifer after pumping for 1 year. The wells (red squares) are spaced 2,000 feet apart.

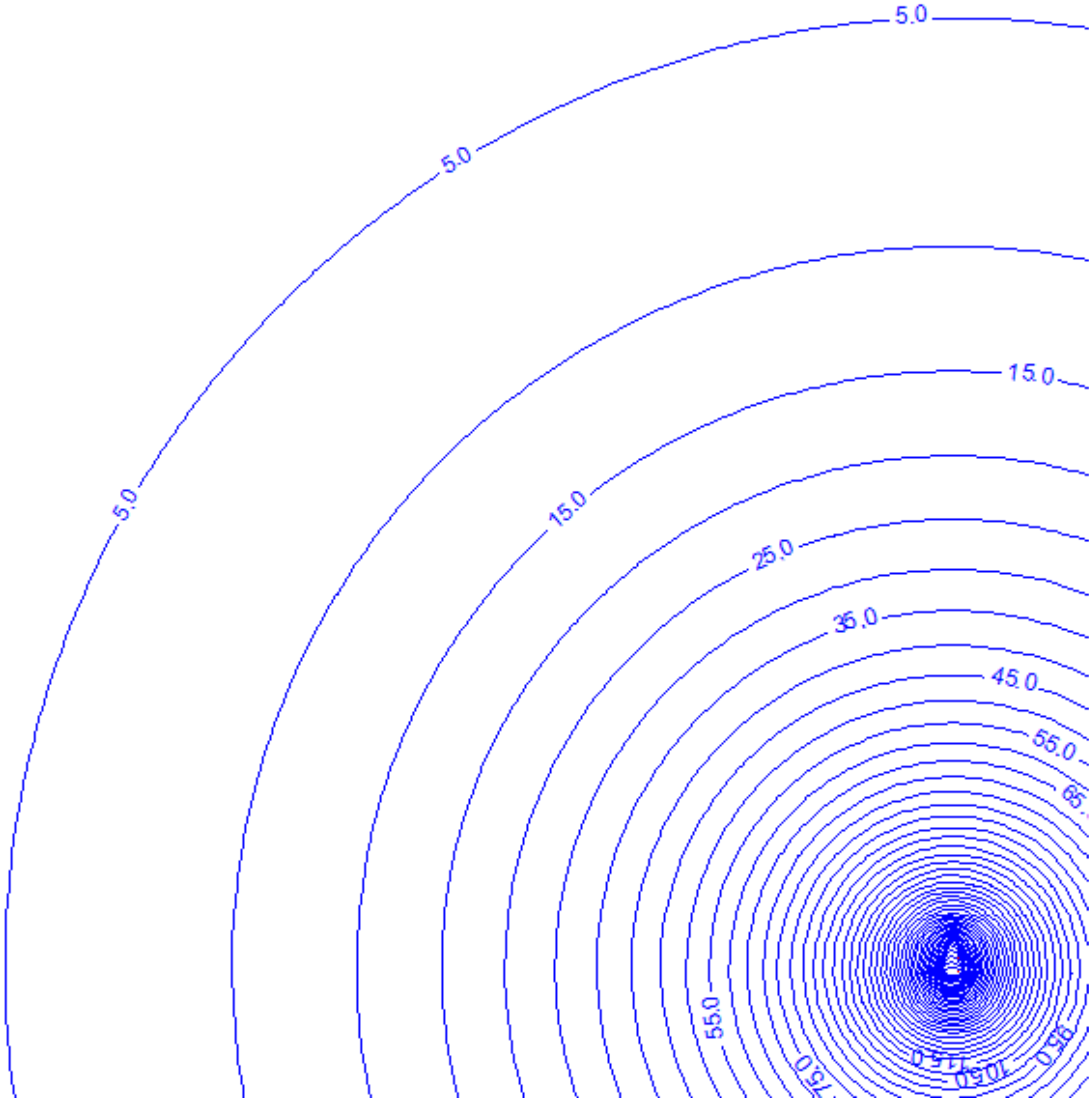

Figure 7.15: Water-level declines at a 5-foot interval around a hypothetical well field in the Dockum Aquifer after pumping for 10 years. The distance from the 5-foot contour to the well field in the lower right is about 130,000 feet (about 25 miles).

8. Conclusions

Since the first facility registered with the state in the study area in April 2017, a total of 17 frac sand facilities (one of which is idled) had registered with the Texas Commission on Environmental Quality by the end of 2018. All of the 16 active frac sand facilities are clustered along the Monahans-Mescalero Sand Ecosystem in a 20-mile by 40-mile area. These frac sand facilities have an annual capacity of 56.8 million tons.

There is no public data on how much water frac sand facilities in the Permian Basin consume. Limited local information suggests that frac sand facilities in the study area consume between 60 and 250 gallons of water per ton.

Water for frac sand production in the Permian Basin is primarily sourced on-site from the Pecos Valley and the Dockum aquifers. Perched aquifers form in the dune area where caliche slows the downward movement of water through the ground. These perched aquifers will be unaffected by pumping from deeper aquifers but may be locally impacted by pumping from pools or shallow quarries and by removing contributing dunes.

I identified 230 production wells for the 16 facilities with production wells drilled at their locations. The relatively large number of wells drilled at many of these facilities suggests that the aquifers in this area are not highly productive, a conclusion supported by the thin saturated thickness of the Pecos Valley Aquifer and the low hydraulic conductivity of the Dockum Aquifer. Facility operators have to drill and string together wells until they meet their water needs.

It’s too soon to see possible impacts from pumping beneath frac sand facilities with available state-collected data since the frac sand facilities are new, and the state measures water levels annually during the winter months. Furthermore, the wells the state measures are not in the best locations to assess effects of frac sand facility pumping. Also, pumping by the oil and gas industry and various municipalities may make it difficult to see the effects of frac sand facilities without purpose-built monitoring. Current estimated frac sand facility water use (10,000 to 40,000 acre-feet per year, based on 60 to 250 gallons of water consumed per ton of produced sand) rivals or exceeds that of water used in the four counties (Crane, Ector, Ward, and Winkler) with active frac sand facilities (23,500 acre-feet per year).

With a lack of site-specific water use and hydraulic properties, I modeled two hypothetical situations for a typical frac sand facility for a typical Pecos Valley Aquifer source and a typical Dockum Aquifer source consuming 70 gallons of water per ton of produced sand.

For a well field of 12 wells in the Pecos Valley Aquifer, the distance to the 5-foot water-level decline is 550 feet after 1 year of pumping and 4,000 feet after 10 years of pumping. Given that the saturated thickness of the typical Pecos Valley Aquifer in the study area is

70 feet, this suggests that long-term pumping of the aquifer in the area may be a challenge requiring additional wells over time or the use of alternative water supplies.

For a well field of 7 wells in the Dockum Aquifer, the distance to the 5-foot water-level decline contour is about 40,000 feet (7.5 miles) after 1 year of pumping and 130,000 feet (24.6 miles) after 10 years of pumping. A well in the interior of the well field would have 272 feet of water-level decline after 1 year of pumping and 360 feet of decline after 10 years of pumping. Pumping the Dockum Aquifer results in larger and broader declines because, in large part, it's a confined aquifer whereas the Pecos Valley Aquifer is unconfined. For the Dockum Aquifer, these simulations suggest that pumping might completely deplete artesian pressure at the well field after 10 years.

The Pecos Valley and Dockum aquifers are witnessing a great deal of new well drilling and pumping by existing users such as local municipalities and the oil and gas industry and new users such as non-local water suppliers east of the study area and frac sand facilities. At this point, given all the new interest in the area's groundwater resources and the uncertainty in pumping rates, it's unclear what the effects of increased pumping might be, but water levels will surely decline over time. How much they decline and how much they affect groundwater resources—and the people and species that rely on them—remains to be seen.

I recommend following ongoing activity in the area by all pumpers and, if possible, expanding water-level monitoring to gain a better understanding of how additional pumping is affecting the aquifers. This study suffered from a lack of site-specific information on water use and produced sand tonnage. If the state wishes to have a better understanding of potential effects from pumping at these facilities, then requiring the reporting of this information would be useful. Finally, well completions across different aquifers should be discouraged. Even when pumping at these wells stop, aquifers with higher water-level elevations—such as the Pecos Valley Aquifer—will continue to drain into deeper, depleted formations, thus affecting the water resources for remaining users as long as the well connection exists.

9. Acknowledgments

I thank Dr. Robert Gulley and Ms. Chelsea Jones at the Texas Comptroller of Public Accounts for the many fruitful discussions and guidance; Mark Krumenacher with GZA GeoEnvironmental, Inc., Doug Shields with West Texas Water Well Service, and Wes Penn with U.S. Silica for helping me better understand water use and demands; and Sharla Gutierrez, Synthia Tuma, and Susan Hankins with the Meadows Center for Water and the Environment for administrative support.

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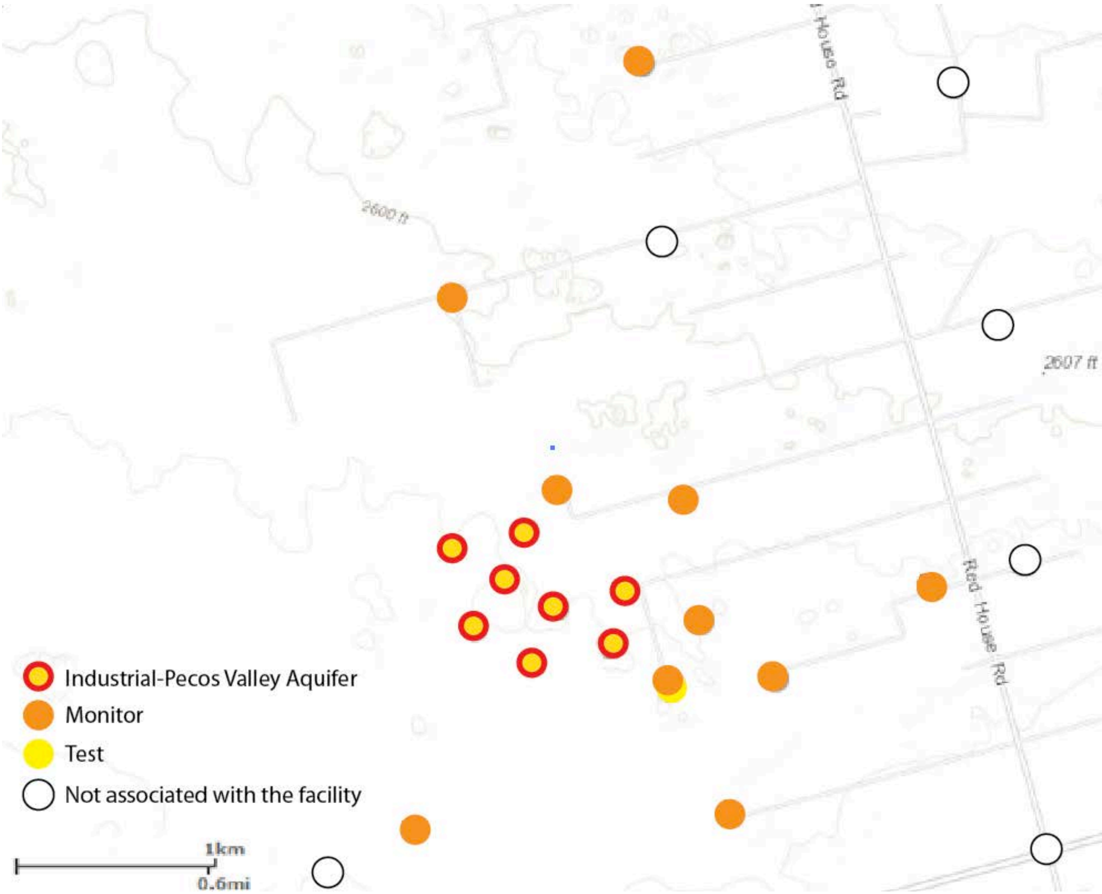
Appendix A

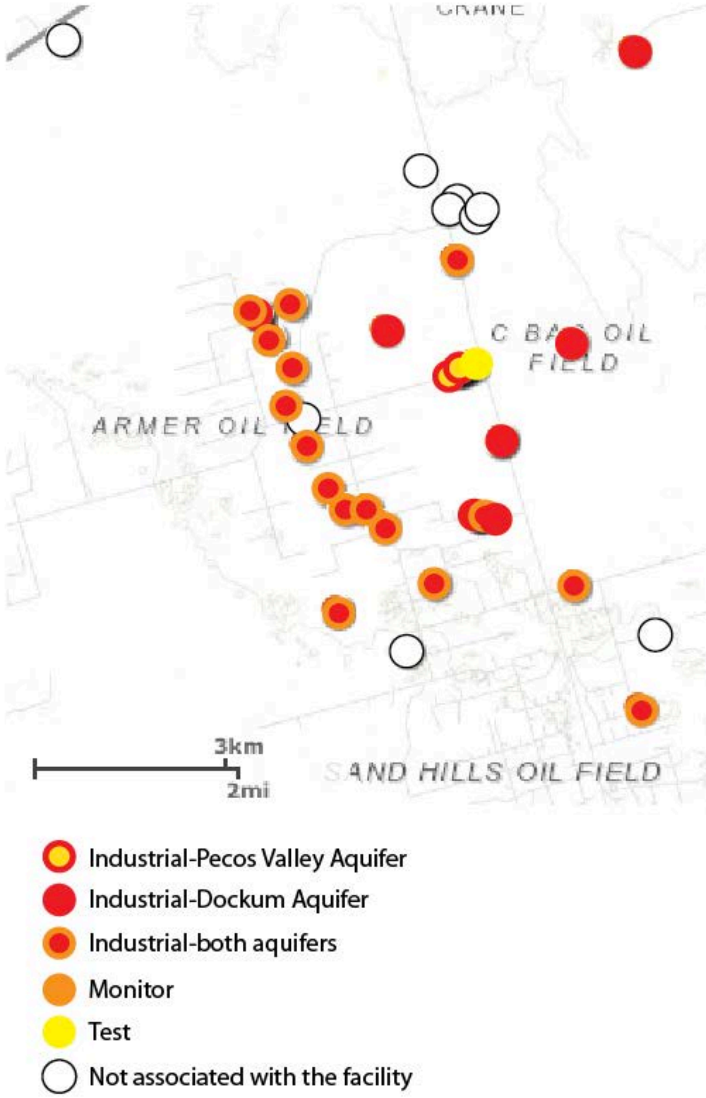
Aerial images and well maps for the facilities

Aerial images from Google maps

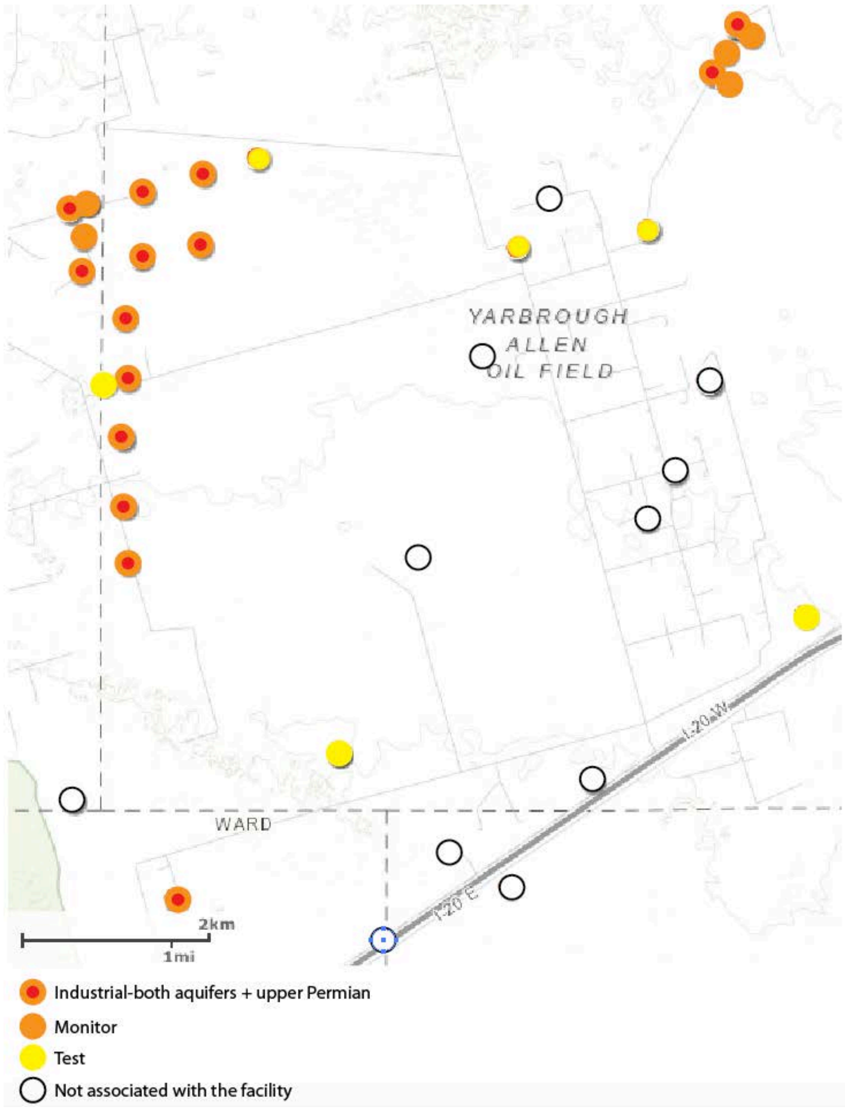
Unimin Corporation, Covia Crane Facility



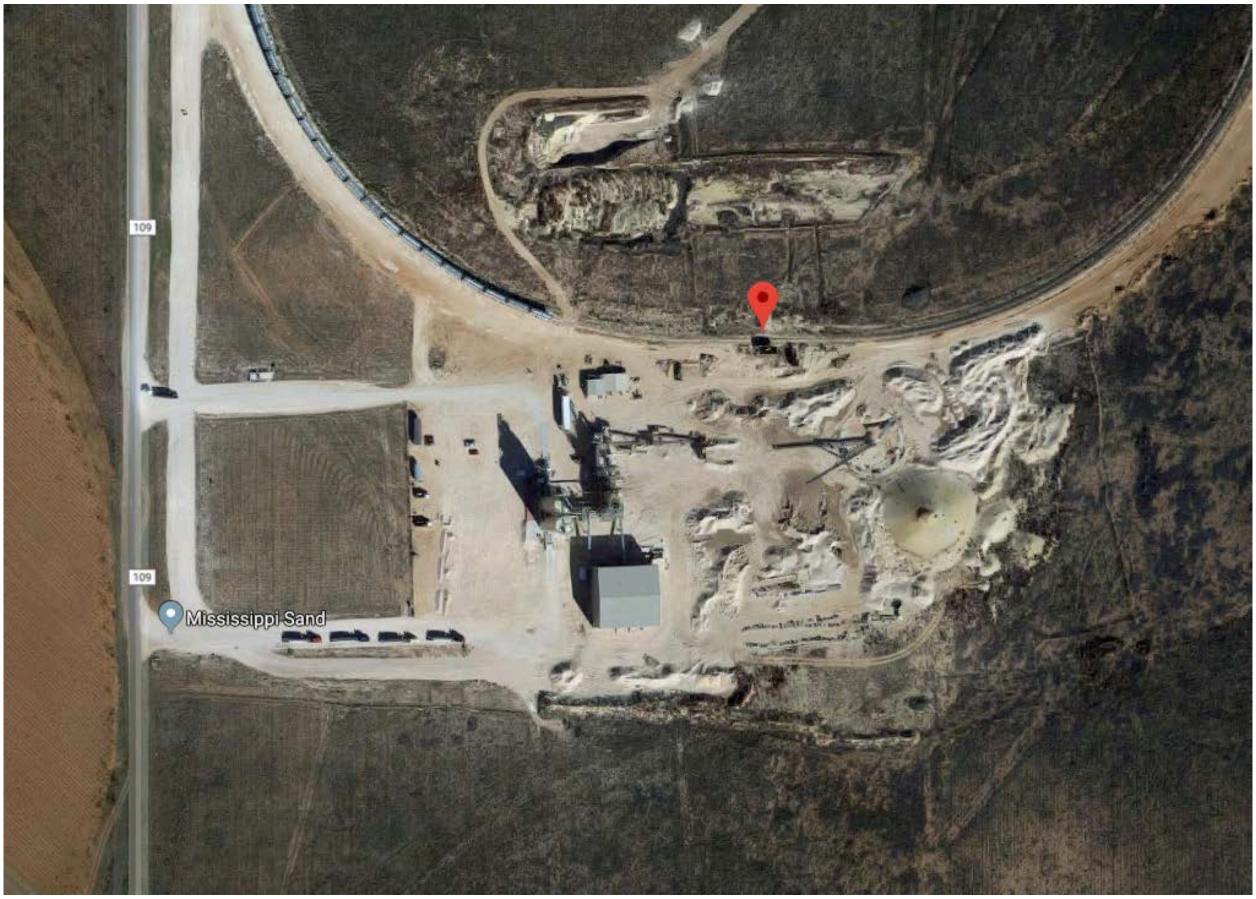
U.S. Silica Company, Crane County Plant


CRANE
C BAR OIL FIELD
ARMER OIL FIELD
SAND HILLS OIL FIELD
3km
2mi
Industrial-Pecos Valley Aquifer
Industrial-Dockum Aquifer
Industrial-both aquifers
Monitor
Test
Not associated with the facility

Preferred Sands of Monahans

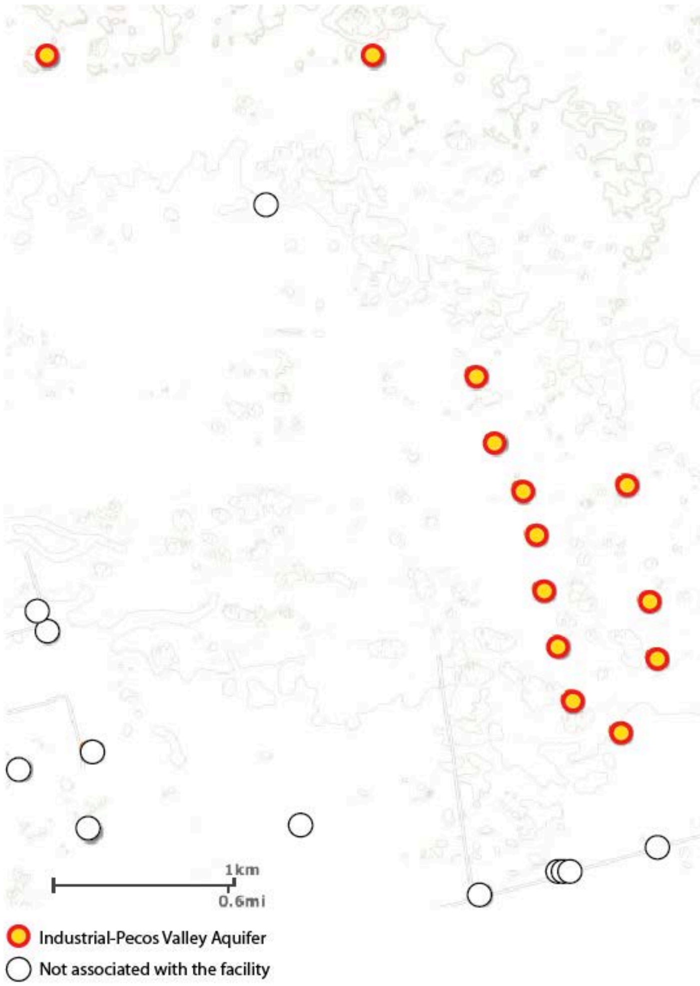

YARBROUGH
ALLEN
OIL FIELD
WARD
I-20 W
I-20 E
2km
1mi
Industrial-both aquifers + upper Permian
Monitor
Test
Not associated with the facility

Mississippi Sand LLC, Seagraves Sand Plant

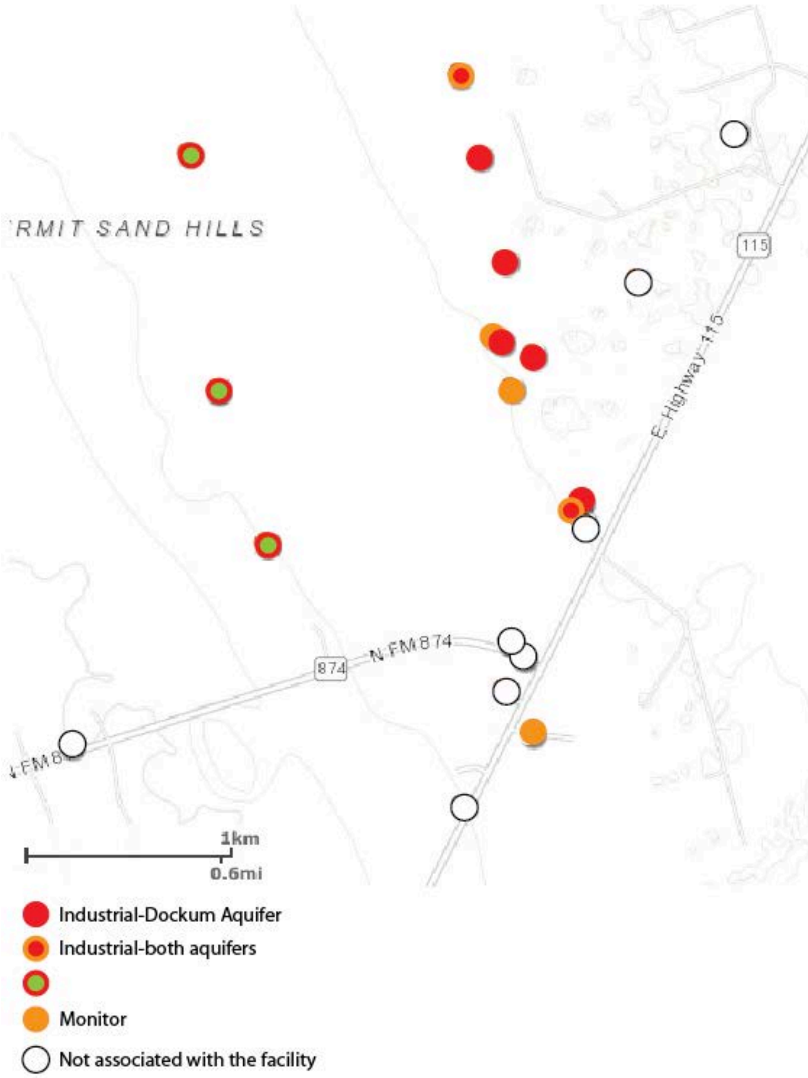


No wells identified at this facility.

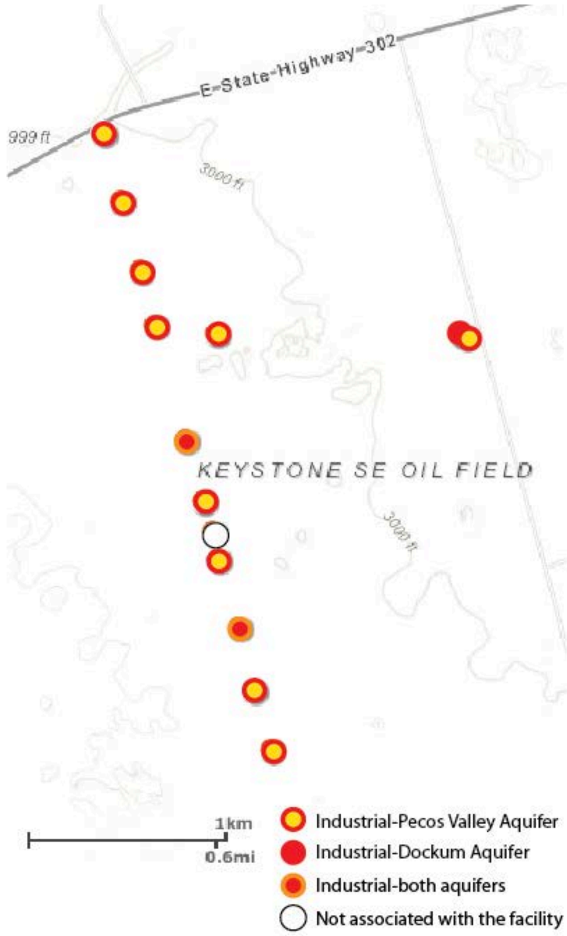
Wisconsin Proppants, E Ranch Facility


1km
0.6mi
Industrial-Pecos Valley Aquifer
Not associated with the facility

Hi-Crush Permian Sand LLC, Hi-Crush


RMIT SAND HILLS
115
E Highway 115
874
N FM 874
FM 8
1km
0.6mi
Industrial-Dockum Aquifer
Industrial-both aquifers
Monitor
Not associated with the facility

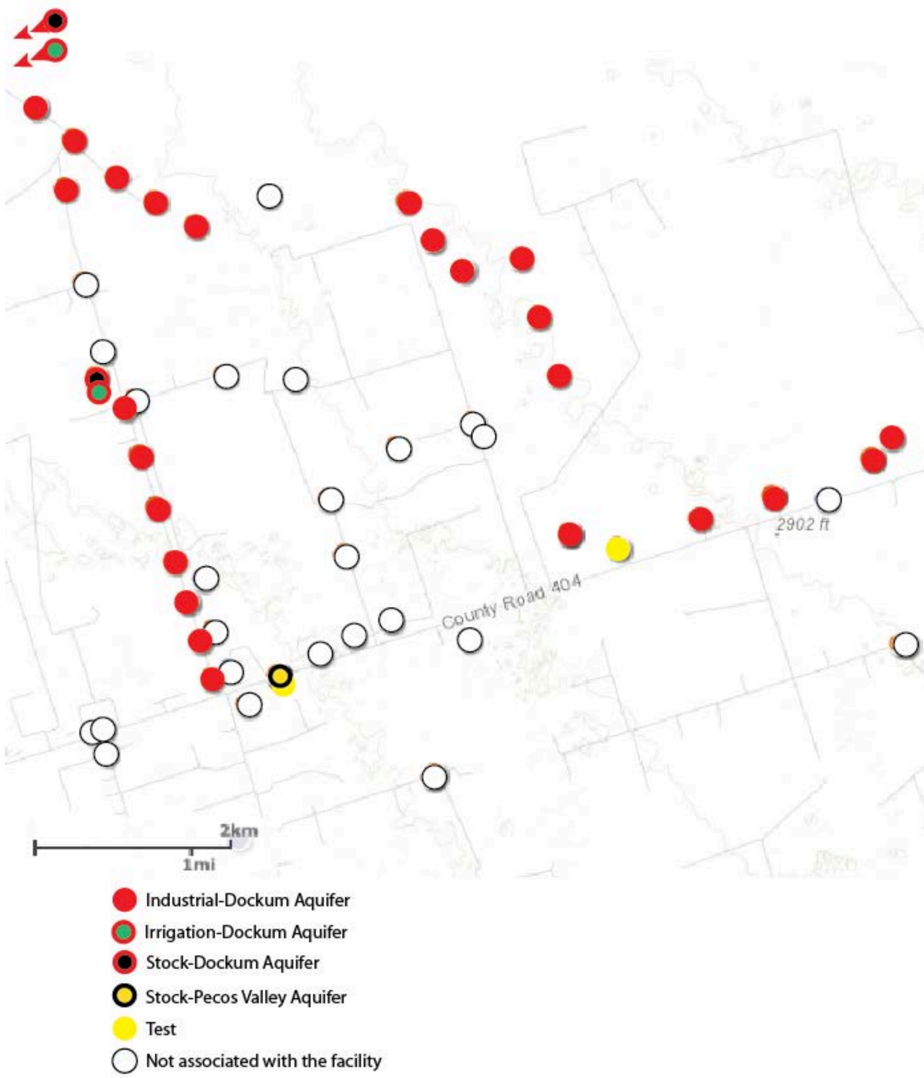
Black Mountain Sand LLC, Vest Facility


E-State-Highway-302
999 ft
3000 ft
KEYSTONE SE OIL FIELD
3000 ft
1km
0.6mi
Industrial-Pecos Valley Aquifer
Industrial-Dockum Aquifer
Industrial-both aquifers
Not associated with the facility

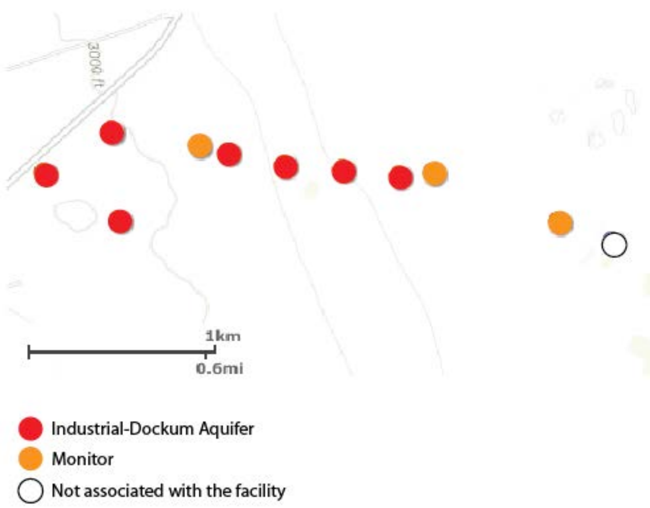
High Roller Sand Operating, LLC, Kermit Plant


2986 ft
N FM 1218
1218
1km
0.6mi
Industrial-Pecos Valley Aquifer
Industrial-Dockum Aquifer
Test
Not associated with the facility

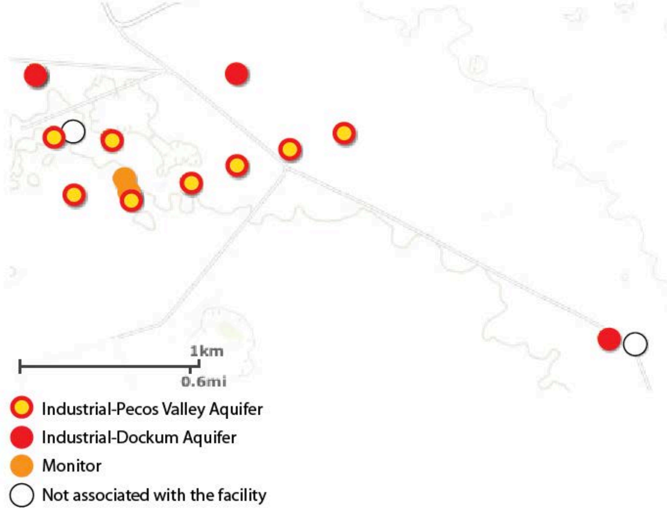
Lonestar Prospects, LTD., West Texas Sand Plant


County Road 404
2902 ft
2km
1mi
Industrial-Dockum Aquifer
Irrigation-Dockum Aquifer
Stock-Dockum Aquifer
Stock-Pecos Valley Aquifer
Test
Not associated with the facility

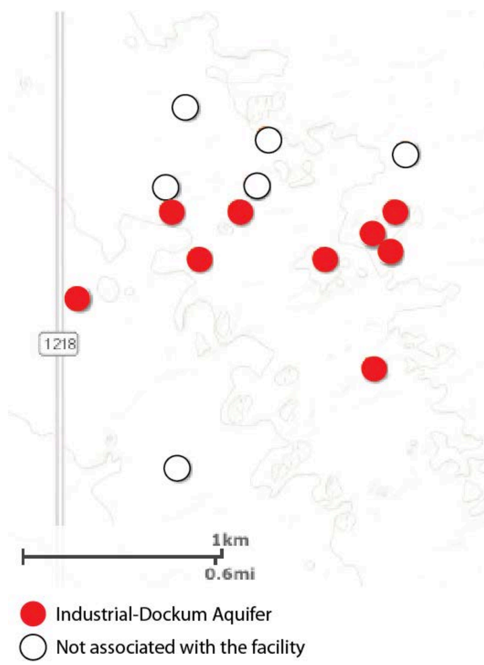
FML Sand, LLC, FML Kermit



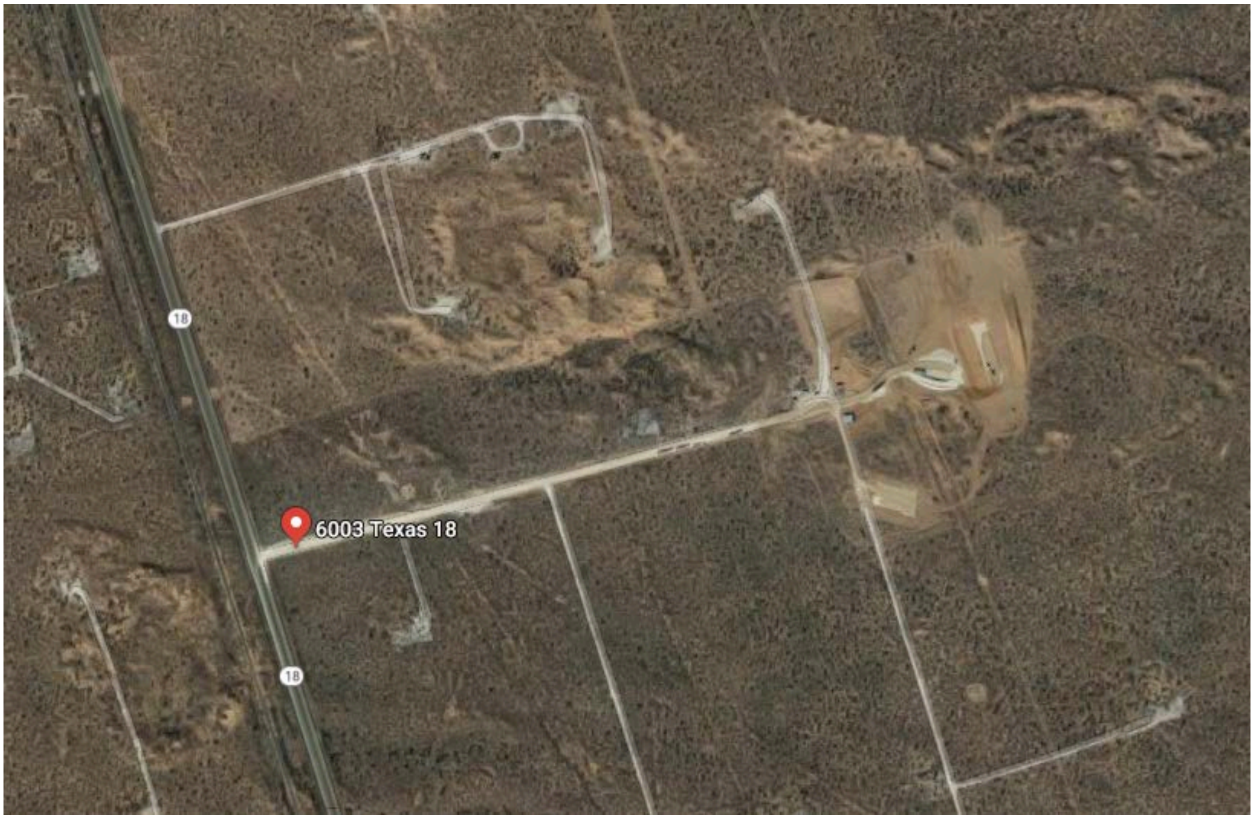
Black Mountain Sand LLC, El Dorado Facility

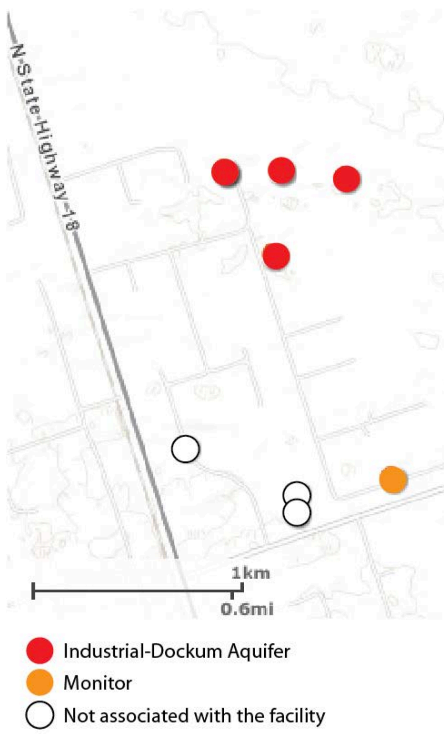


Alpine Silica, LLC, Alpine Silica

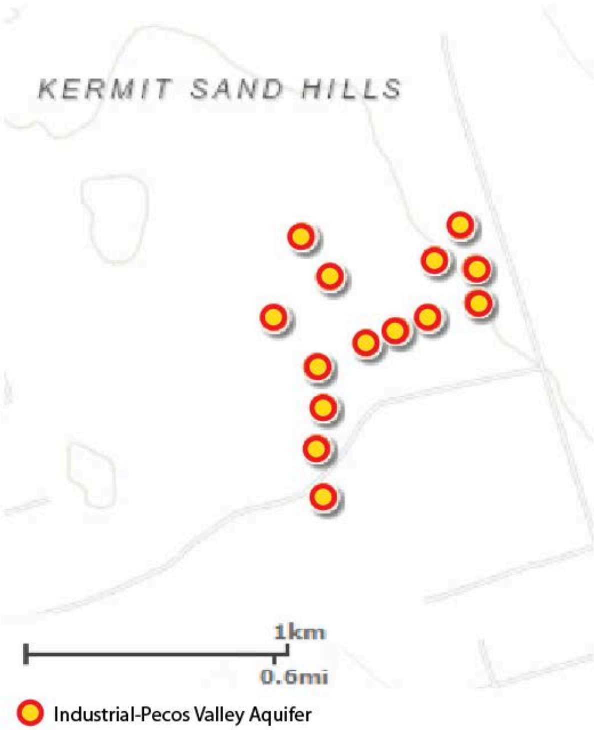


Badger Mining Corporation, Kermit Plant

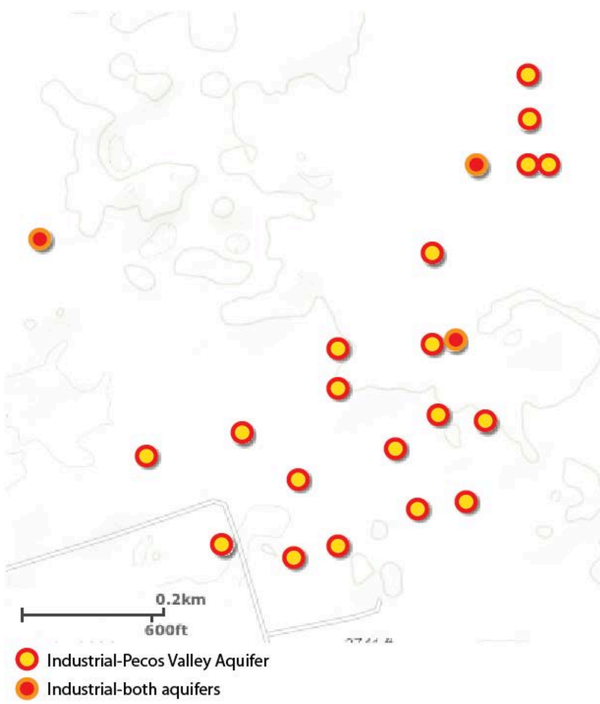




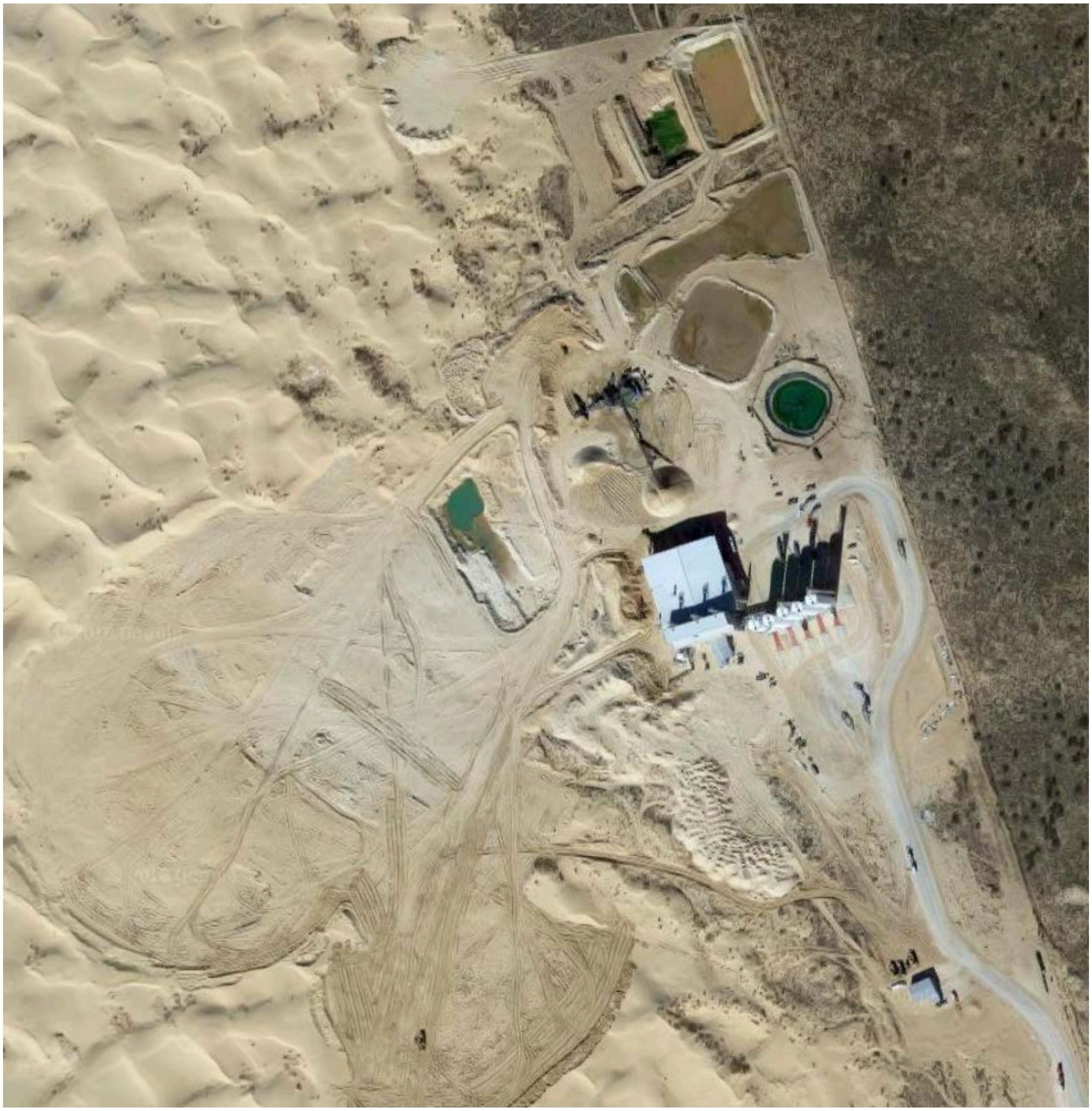
Atlas Sand Company, LLC, Atlas North

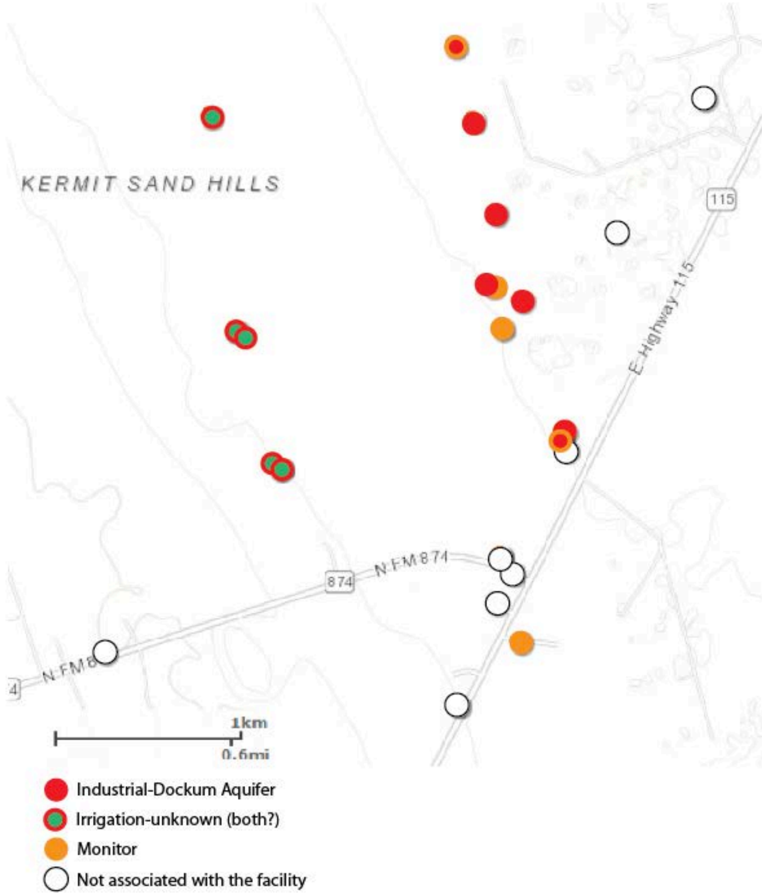


Atlas Sand Company, LLC, Atlas South

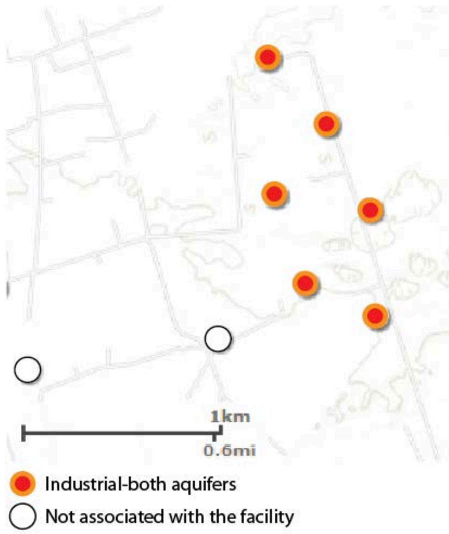


Hi-Crush Permian Sand LLC/Kermit Plant North




KERMIT SAND HILLS
115
E Highway 115
874
N FM 874
N FM 8
1km
0.6mi
Industrial-Dockum Aquifer
Irrigation-unknown (both?)
Monitor
Not associated with the facility

Smart Sand Inc.



Appendix B

List of production wells for the facilities

- **[County]**
    - [Operator, Facility Name]
        - [Well Number (purpose)]
- **Andrews County** (none)
- **Crane County**
    - Unimin Corporation, Covia Crane Facility
        - 477820 (extraction)
        - 477821 (extraction)
        - 477822 (extraction)
        - 477823 (extraction)
        - 477824 (extraction)
        - 477825 (extraction)
        - 477826 (extraction)
        - 477827 (extraction)
    - U.S. Silica Company, Crane County Plant
        - 461287 (industrial)
        - 461289 (industrial)
        - 461301 (industrial)
        - 461304 (industrial)
        - 461560 (industrial)
        - 461562 (industrial)
        - 461565 (industrial)
        - 472656 (industrial)
        - 472664 (industrial)
        - 472666 (industrial)
        - 472670 (industrial)
        - 472690 (industrial)
        - 472696 (industrial)
        - 472697 (industrial)
        - 472699 (industrial)
        - 472700 (industrial)
        - 472701 (industrial)
        - 472703 (industrial)
        - 472704 (industrial)
        - 472706 (industrial)
        - 472709 (industrial)
        - 472711 (industrial)
        - 472717 (industrial)
        - 472719 (industrial)
        - 472720 (industrial)
        - 472721 (industrial)
        - 472733 (industrial)

- Unimin Corporation, Covia Crane Facility
  - 477820 (extraction)
  - 477821 (extraction)
  - 477822 (extraction)
  - 477823 (extraction)
  - 477824 (extraction)
  - 477825 (extraction)
  - 477826 (extraction)
  - 477827 (extraction)
- **Ector County**
  - Preferred Sands of Monahans, LLC
    - 447137 (industrial)
    - 463944 (industrial)
    - 463964 (industrial)
    - 463980 (industrial)
    - 470402 (industrial)
    - 470404 (industrial)
    - 470408 (industrial)
    - 470426 (industrial)
    - 470433 (industrial)
    - 470442 (industrial)
    - 470443 (industrial)
    - 470444 (industrial)
    - 470445 (industrial)
    - 470455 (industrial)
- **Gaines County** (0 active sites)
- **Ward County**
  - Wisconsin Proppants, E Ranch Facility
    - 472493 (industrial)
    - 472517 (industrial)
    - 472546 (industrial)
    - 472548 (industrial)
    - 472648 (industrial)
    - 472650 (industrial)
    - 472660 (industrial)
    - 472678 (industrial)
    - 472686 (industrial)
    - 472708 (industrial)
    - 472780 (industrial)
    - 472787 (industrial)
    - 472789 (industrial)

- **Winkler County**
  - Hi-Crush Permian Sand LLC, Hi-Crush
    - 448930 (industrial)
    - 448943 (industrial)
    - 449664 (industrial)
    - 456551 (industrial)
    - 484136 (industrial)
    - 484138 (industrial)
    - 484140 (industrial)
    - 496191 (irrigation)
    - 496688 (irrigation)
    - 496689 (irrigation)
    - 496690 (irrigation)
  - Black Mountain Sand LLC, Vest Facility
    - 455319 (industrial)
    - 455323 (industrial)
    - 455876 (industrial)
    - 461715 (industrial)
    - 464768 (industrial)
    - 464770 (industrial)
    - 464771 (industrial)
    - 464779 (industrial)
    - 464799 (industrial)
    - 464806 (industrial)
    - 464808 (industrial)
    - 480321 (industrial)
    - 480562 (industrial)

- High Roller Sand Operating, LLC, Kermit Plant
  - 457523 (industrial)
  - 463480 (industrial)
  - 464943 (industrial)
  - 464946 (industrial)
  - 464948 (industrial)
  - 464950 (industrial)
  - 465266 (industrial)
  - 466553 (industrial)
  - 466555 (industrial)
  - 466560 (industrial)
  - 466567 (industrial)
  - 466569 (industrial)
  - 466572 (industrial)
  - 469137 (industrial)
  - 469138 (industrial)
  - 469139 (industrial)
  - 469141 (industrial)
  - 500565 (industrial)
  - 500568 (industrial)
  - 500571 (industrial)
  - 500574 (industrial)
  - 500575 (industrial)
  - 500577 (industrial)
  - 500584 (industrial)
  - 500586 (industrial)
  - 500587 (industrial)
  - 500588 (industrial)
  - 500590 (industrial)
  - 500592 (industrial)

- Lonestar Prospects, LTD., West Texas Sand Plant
  - 477805 (irrigation)
  - 477818 (irrigation)
  - 480813 (industrial)
  - 480818 (industrial)
  - 480824 (industrial)
  - 480827 (industrial)
  - 480897 (industrial)
  - 480900 (industrial)
  - 480914 (industrial)
  - 480926 (industrial)
  - 480931 (industrial)
  - 480981 (industrial)
  - 480984 (industrial)
  - 480985 (industrial)
  - 482066 (industrial)
  - 482068 (industrial)
  - 482069 (industrial)
  - 493482 (industrial)
  - 493737 (industrial)
  - 496244 (industrial)
  - 497254 (irrigation)
  - 497256 (industrial)
  - 499220 (industrial)
  - 499340 (industrial)
  - 499341 (industrial)
  - 499343 (industrial)
  - 499345 (industrial)
- FML Sand, LLC, FML Kermit
  - 465847 (industrial)
  - 466035 (industrial)
  - 467134 (industrial)
  - 476151 (industrial)
  - 476154 (industrial)
  - 476157 (industrial)
  - 476880 (industrial)

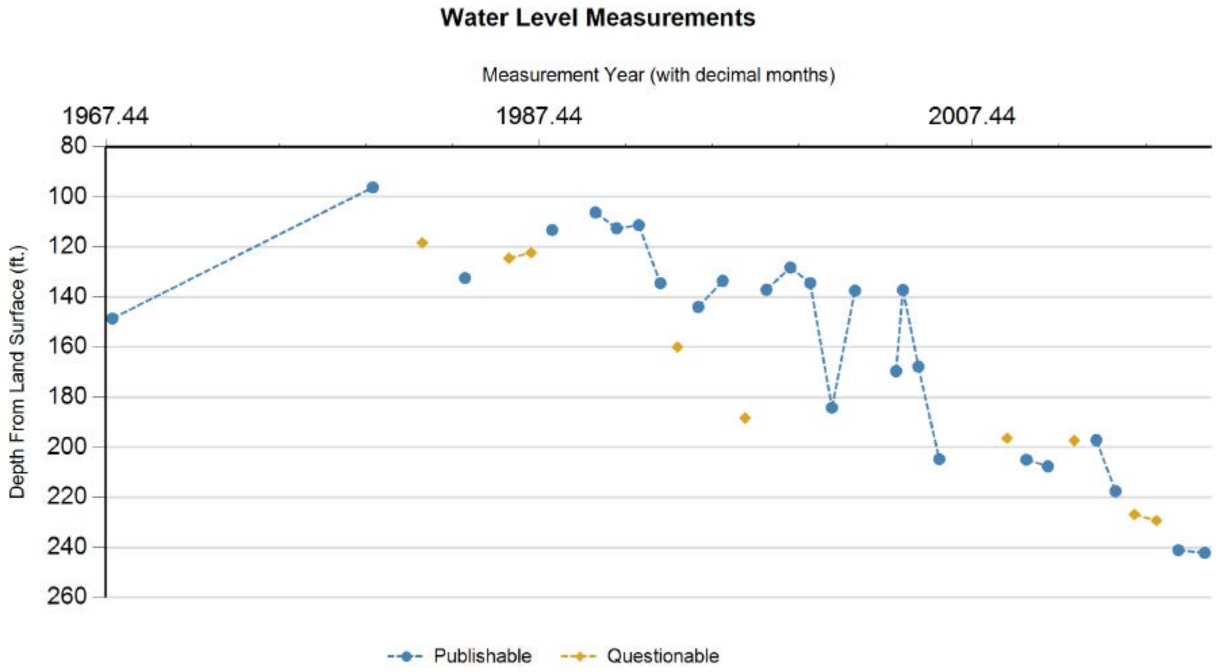
- Black Mountain Sand LLC, El Dorado Facility
    - 464896 (industrial)
    - 464900 (industrial)
    - 464902 (industrial)
    - 464903 (industrial)
    - 464906 (industrial)
    - 464908 (industrial)
    - 464910 (industrial)
    - 464914 (industrial)
    - 464944 (industrial)
    - 468086 (industrial)
    - 468090 (industrial)
    - 468097 (industrial)
- Alpine Silica, LLC, Alpine Silica
    - 488173 (industrial)
    - 489186 (industrial)
    - 491158 (industrial)
    - 491159 (industrial)
    - 492462 (industrial)
    - 492748 (industrial)
    - 492752 (industrial)
    - 492762 (industrial)
    - 495134 (industrial)
- Badger Mining Corporation, Kermit Plant
    - 492422 (industrial)
    - 492453 (industrial)
    - 492470 (industrial)
    - 492478 (industrial)
- Atlas Sand Company, LLC, Atlas North
    - 465210 (industrial)
    - 466984 (industrial)
    - 467654 (industrial)
    - 467657 (industrial)
    - 482150 (industrial)
    - 482892 (industrial)
    - 482895 (industrial)
    - 482899 (industrial)
    - 482901 (industrial)
    - 482902 (industrial)
    - 482903 (industrial)
    - 482905 (industrial)
    - 482906 (industrial)
    - 482908 (industrial)

- Atlas Sand Company, LLC, Atlas South
    - 484969 (industrial)
    - 484971 (industrial)
    - 484973 (industrial)
    - 484975 (industrial)
    - 484978 (industrial)
    - 484979 (industrial)
    - 492160 (industrial)
    - 492161 (industrial)
    - 492162 (industrial)
    - 492163 (industrial)
    - 492164 (industrial)
    - 492165 (industrial)
    - 493178 (industrial)
    - 493182 (industrial)
    - 493184 (industrial)
    - 493186 (industrial)
    - 493188 (industrial)
    - 493189 (industrial)
    - 493191 (industrial)
    - 493192 (industrial)
    - 493193 (industrial)
    - 493194 (industrial)
- Hi-Crush Permian Sand LLC/Kermit Plant North
    - 448930 (industrial)
    - 448943 (industrial)
    - 449664 (industrial)
    - 456551 (industrial)
    - 484136 (industrial)
    - 484138 (industrial)
    - 484140 (industrial)
    - 496191 (industrial)
    - 496688 (irrigation)
    - 496689 (irrigation)
    - 496690 (irrigation)
    - 496691 (irrigation)
- Smart Sand Inc.
    - 472115 (industrial)
    - 472117 (industrial)
    - 474199 (industrial)
    - 474202 (industrial)
    - 474205 (industrial)
    - 474208 (industrial)

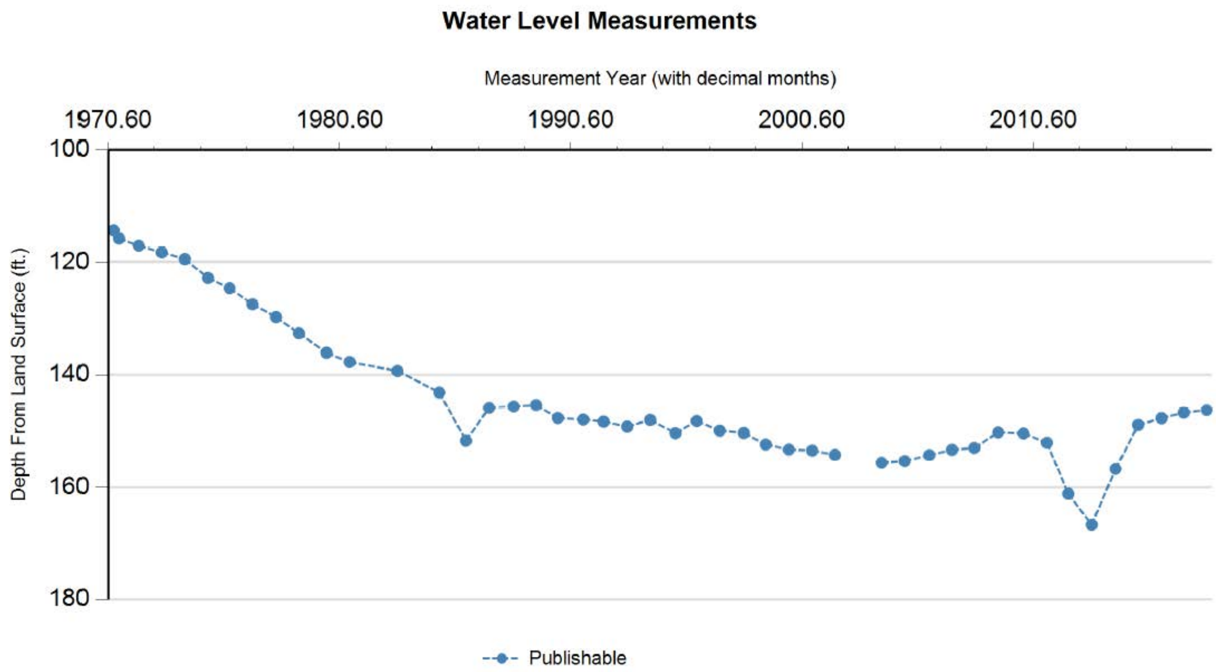
Appendix C

Hydrographs for monitor wells in the study area in the Pecos Valley and Dockum aquifers

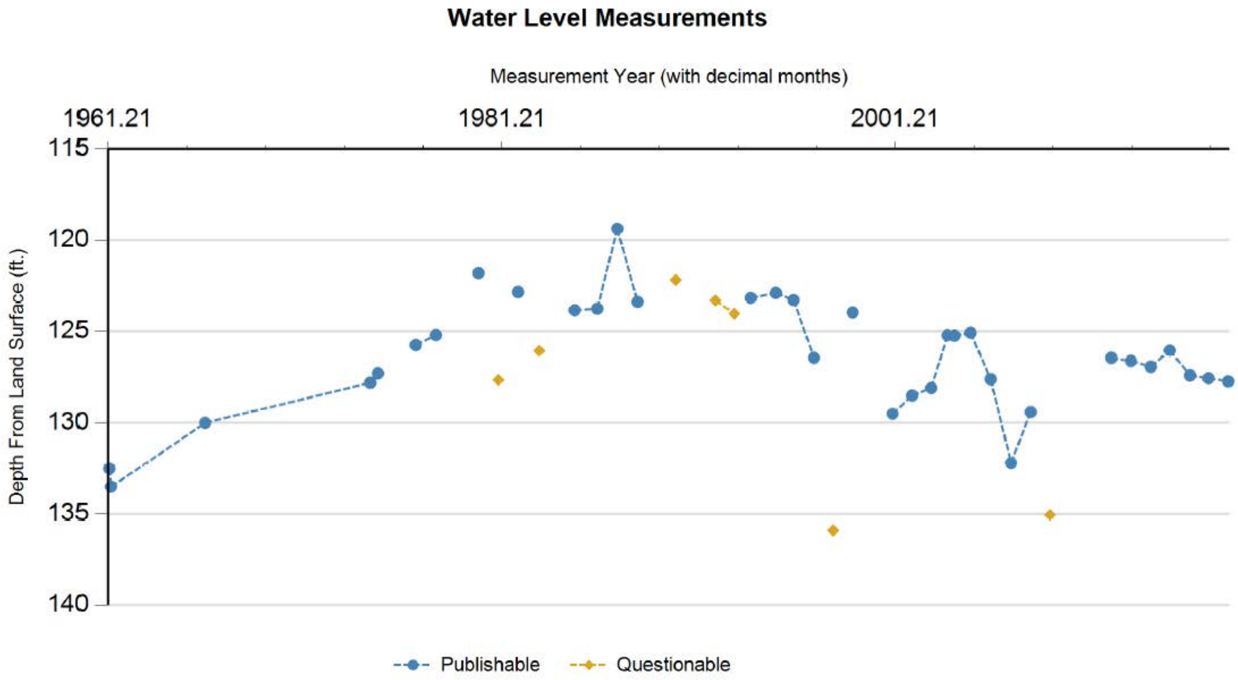
Well 1; State Well Number 2750201; Dockum Aquifer



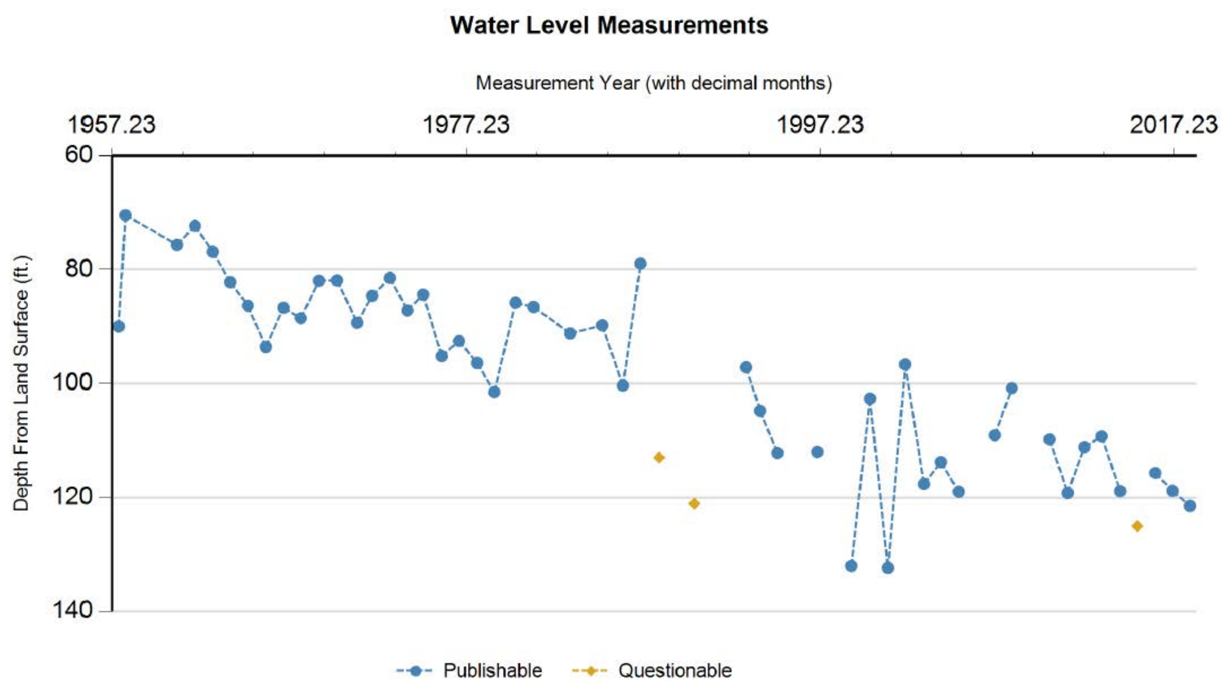
Well 2; State Well Number 4525713; Dockum Aquifer



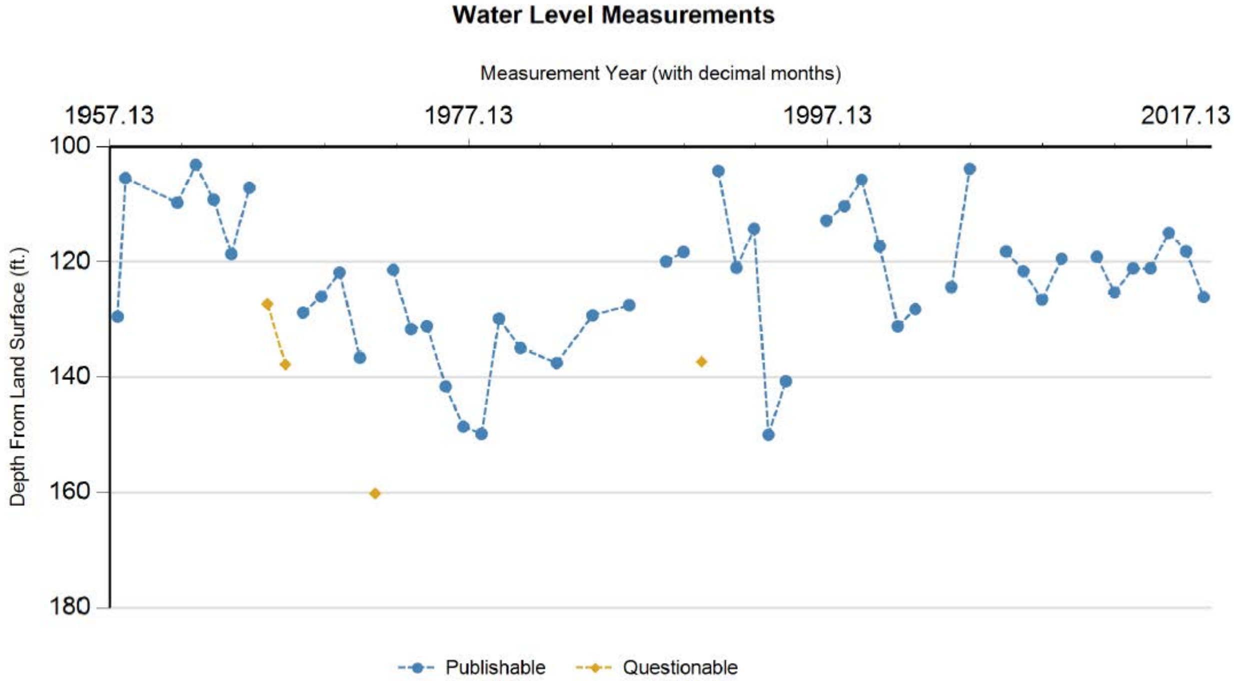
Well 3; State Well Number 4554501; Dockum Aquifer



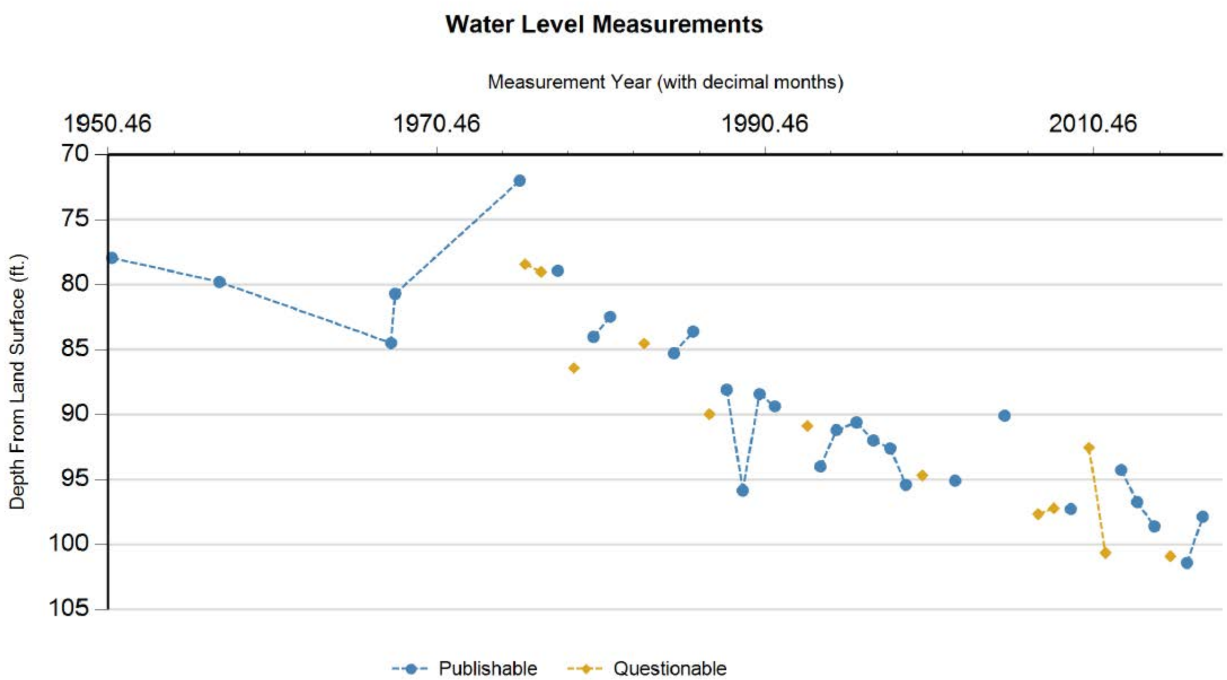
Well 4; State Well Number 4616101; Dockum Aquifer



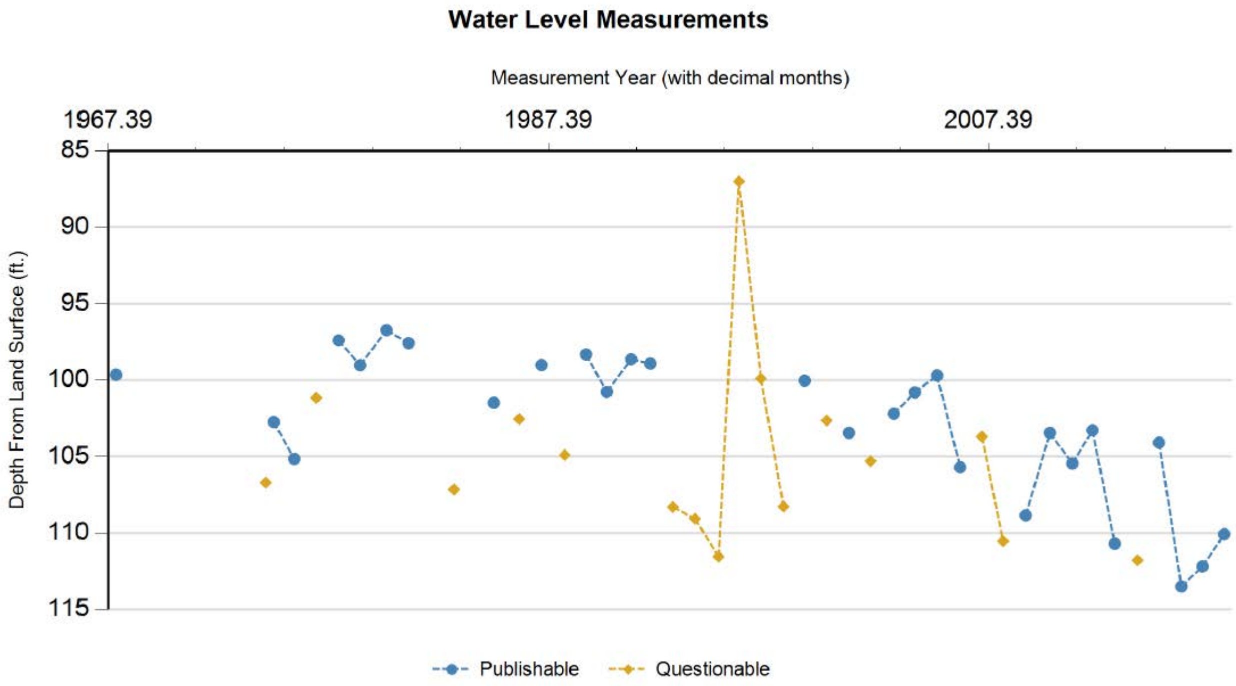
Well 5; State Well Number 4616201; Dockum Aquifer



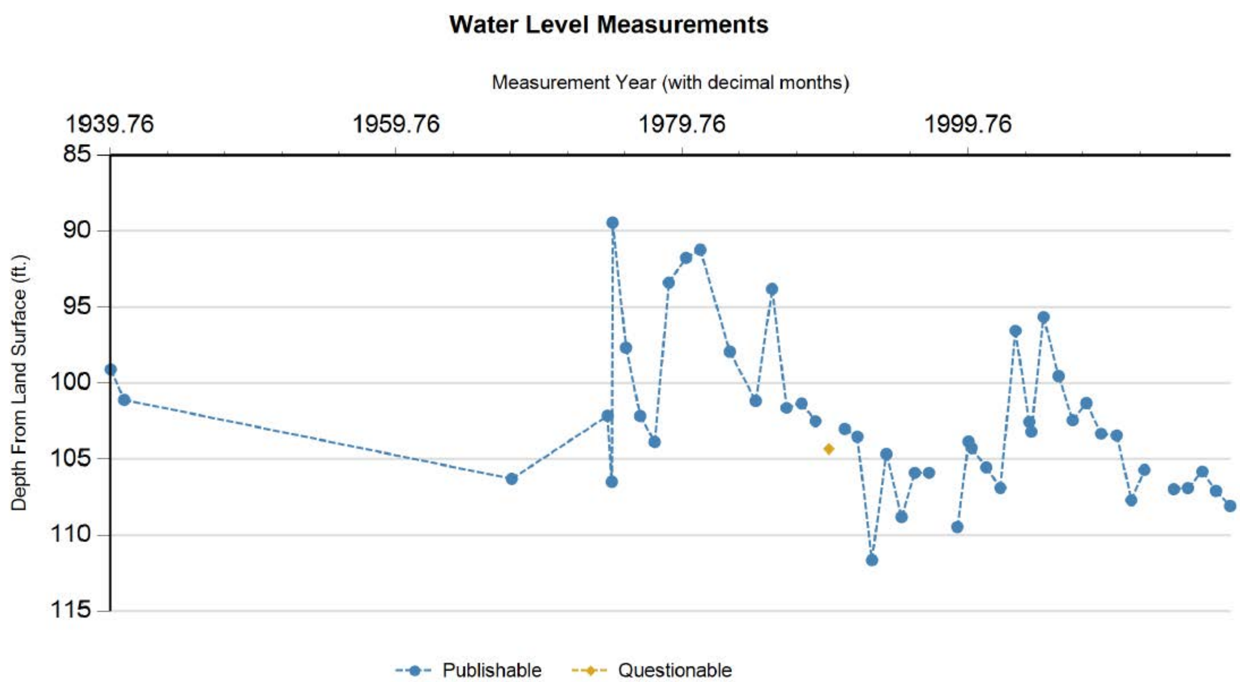
Well 6; State Well Number 4623701; Dockum Aquifer



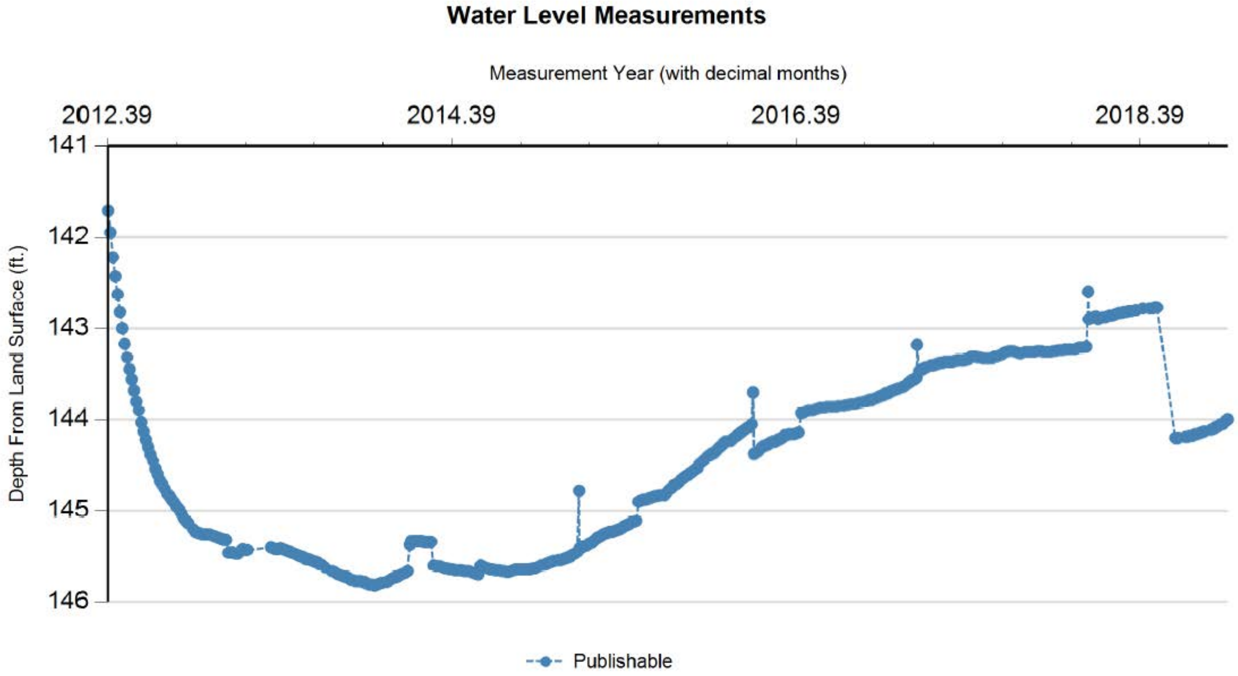
Well 7; State Well Number 4630501; Dockum Aquifer



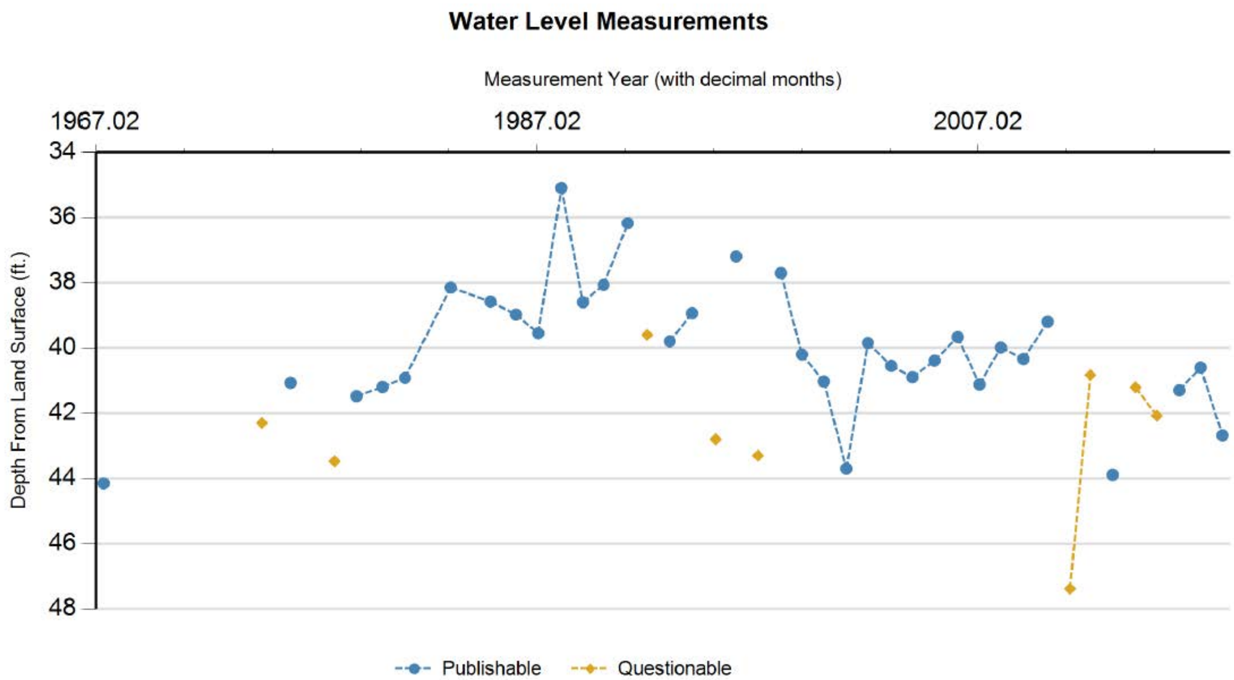
Well 8; State Well Number 4631702; Dockum Aquifer



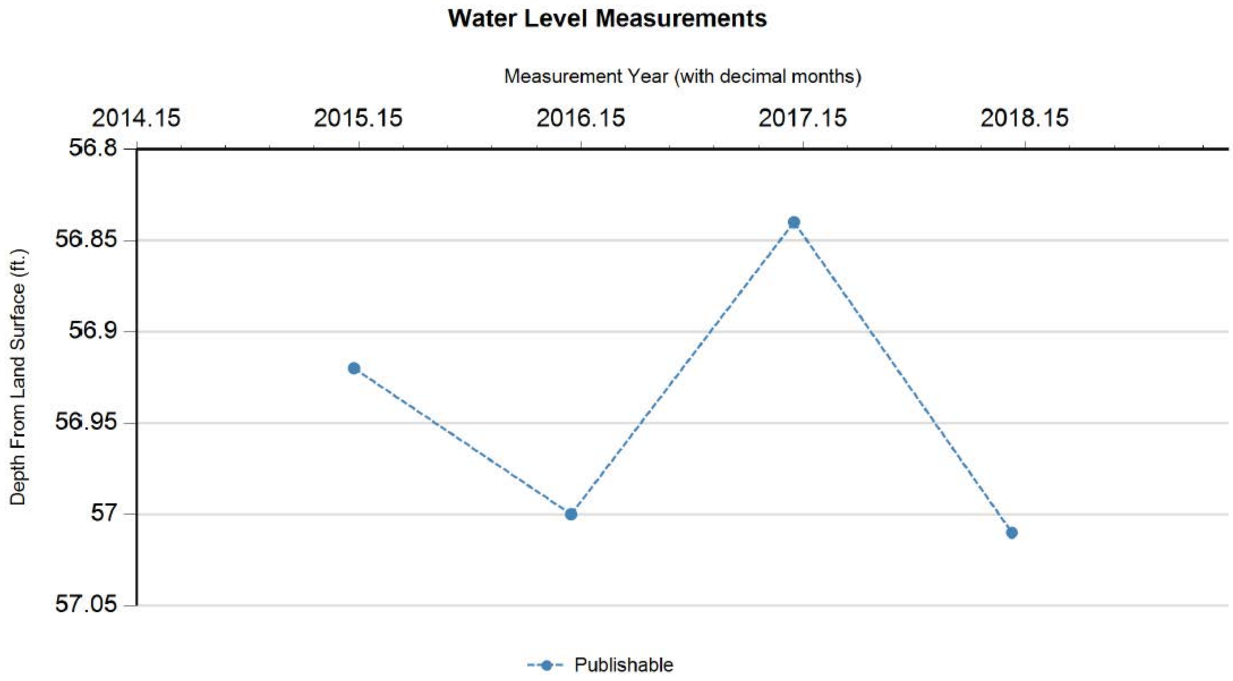
Well 9; State Well Number 4525715; Pecos Valley Aquifer



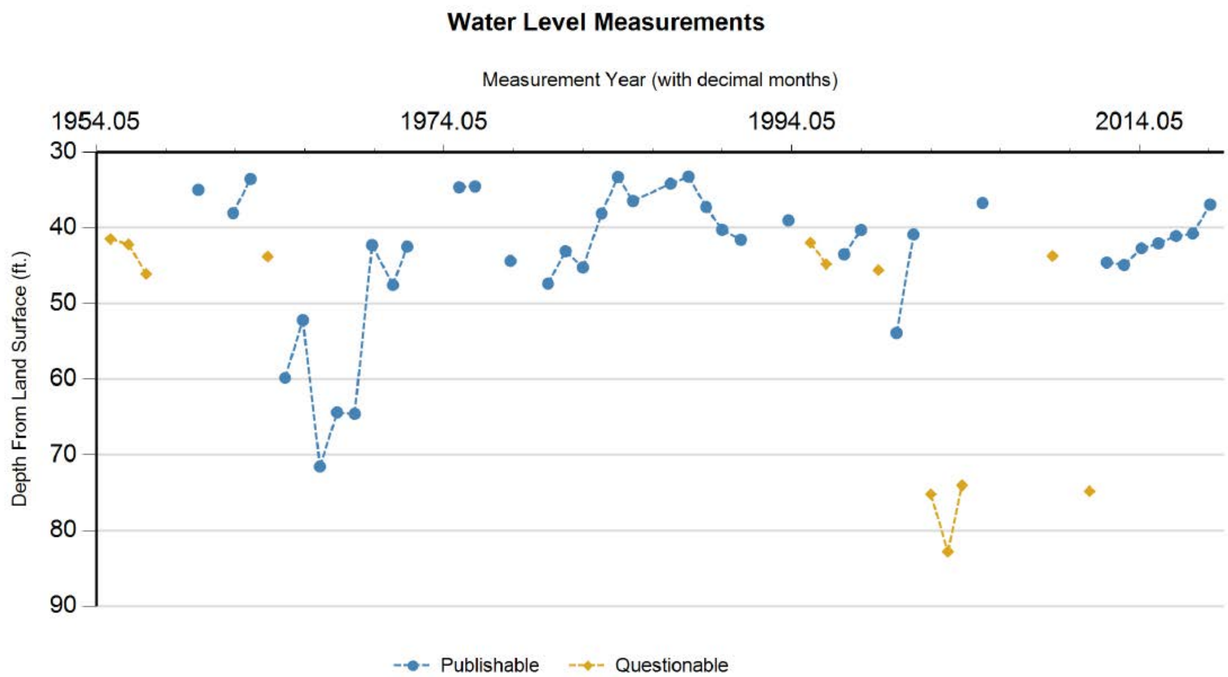
Well 10; State Well Number 4526202; Pecos Valley Aquifer



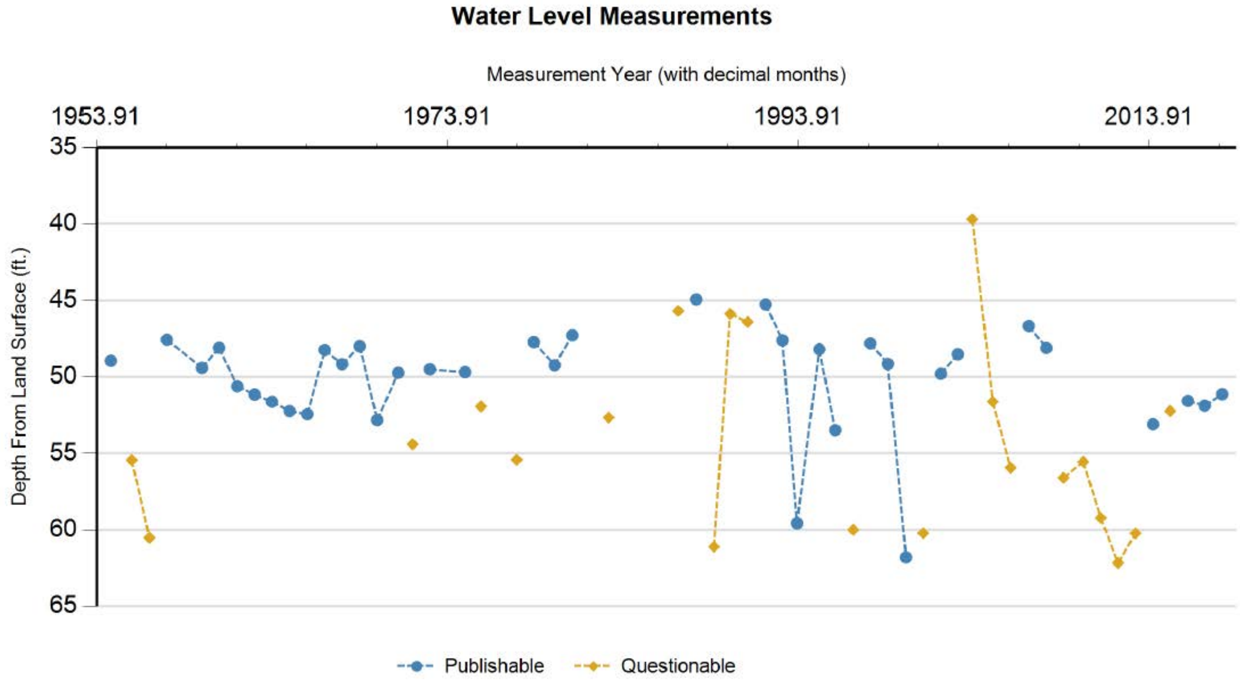
Well 11; State Well Number 4526908; Pecos Valley Aquifer



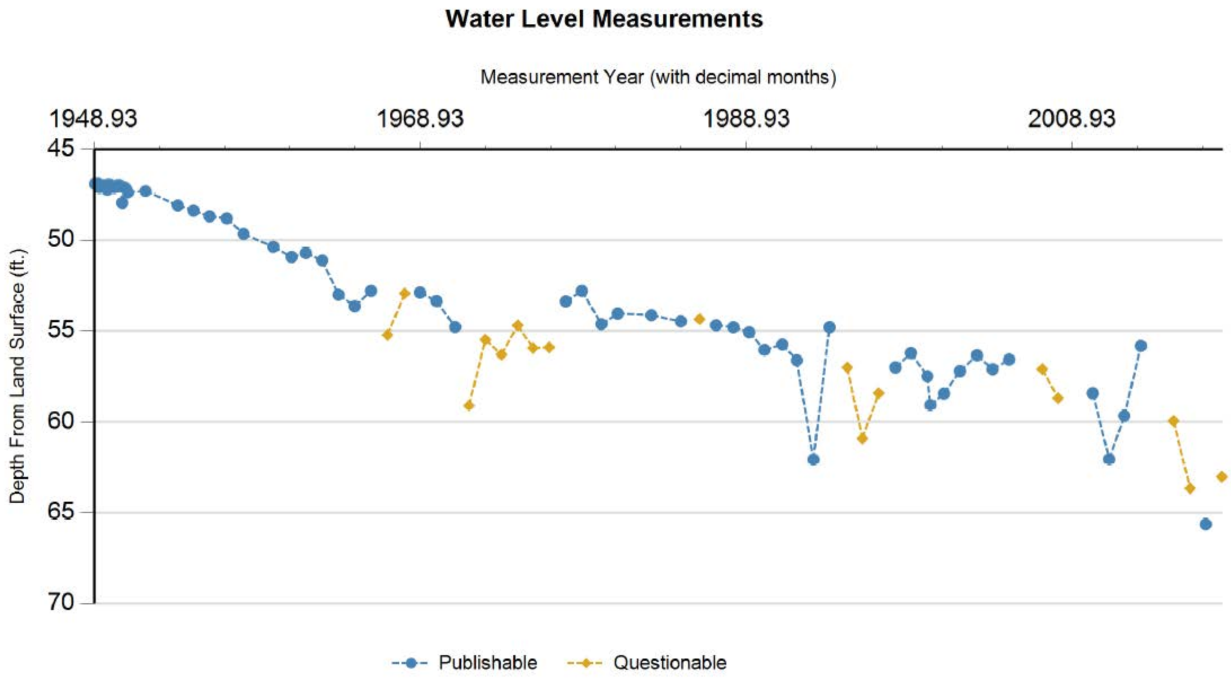
Well 12; State Well Number 4527203; Pecos Valley Aquifer



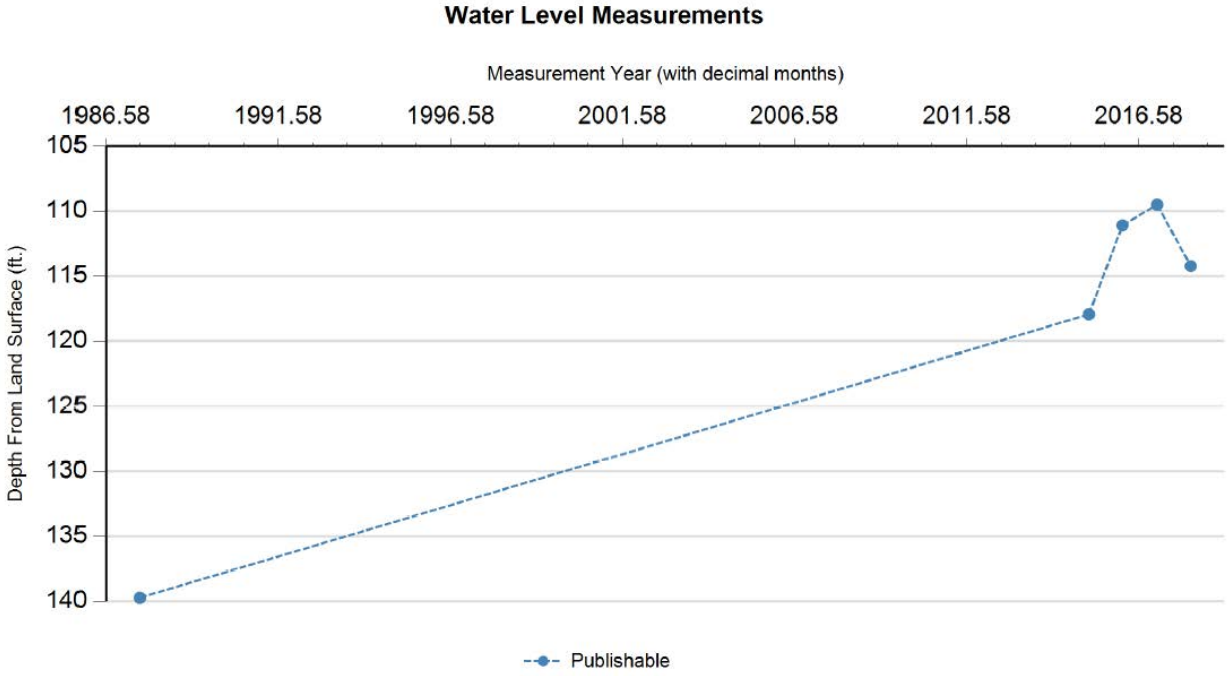
Well 13; State Well Number 4529601; Pecos Valley Aquifer



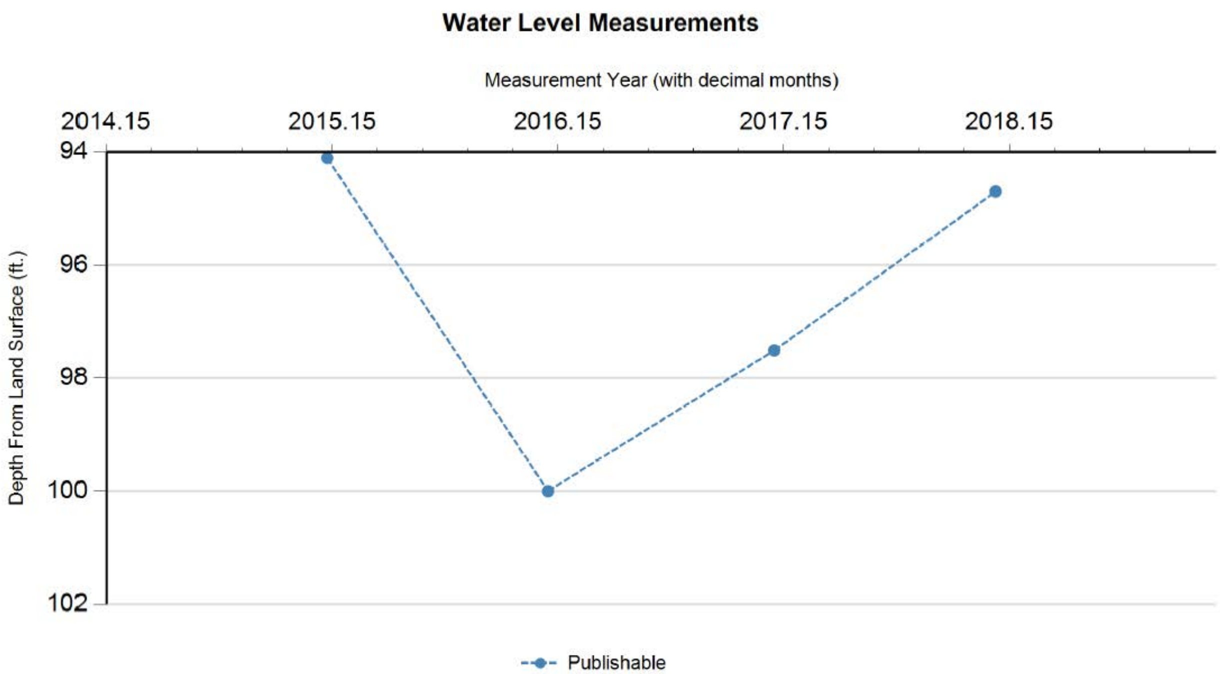
Well 14; State Well Number 4533501; Pecos Valley Aquifer



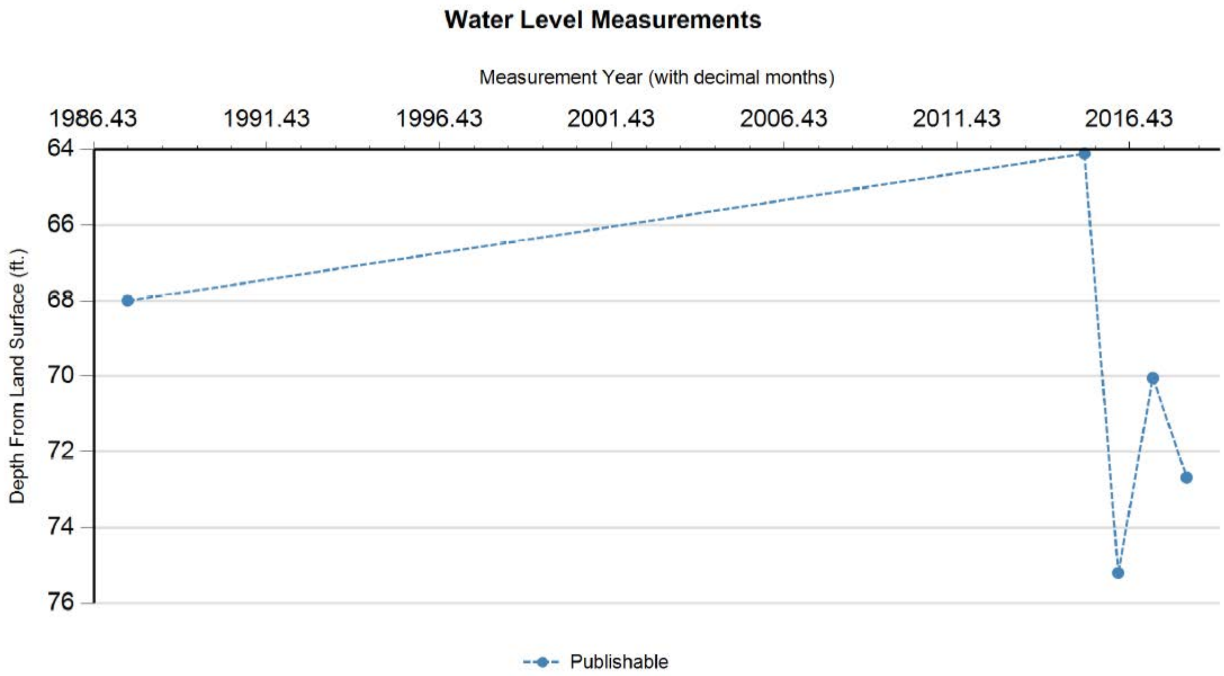
Well 15; State Well Number 4535205; Pecos Valley Aquifer



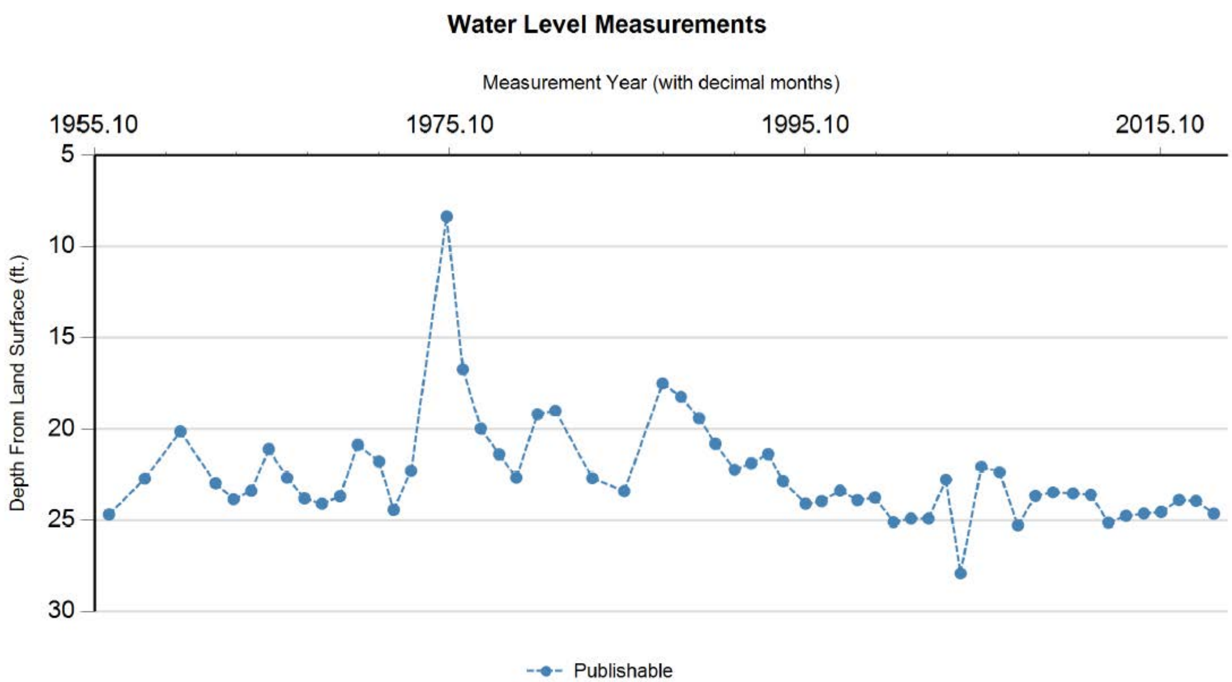
Well 16; State Well Number 4535210; Pecos Valley Aquifer



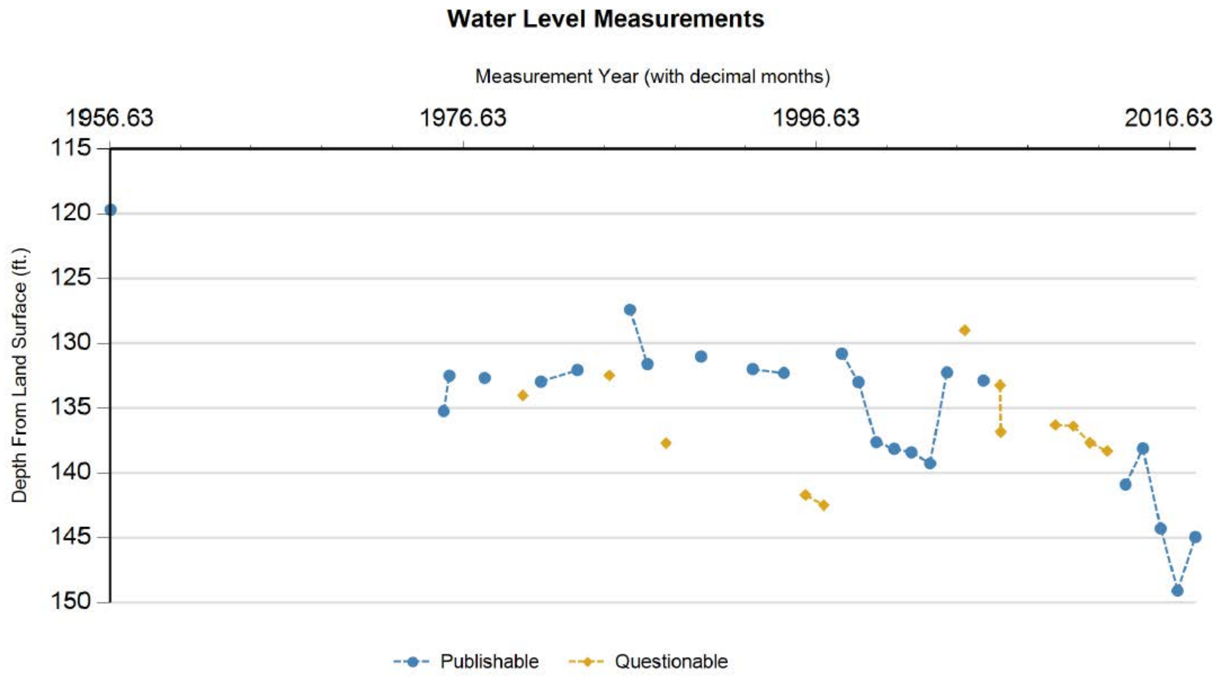
Well 17; State Well Number 4536109; Pecos Valley Aquifer



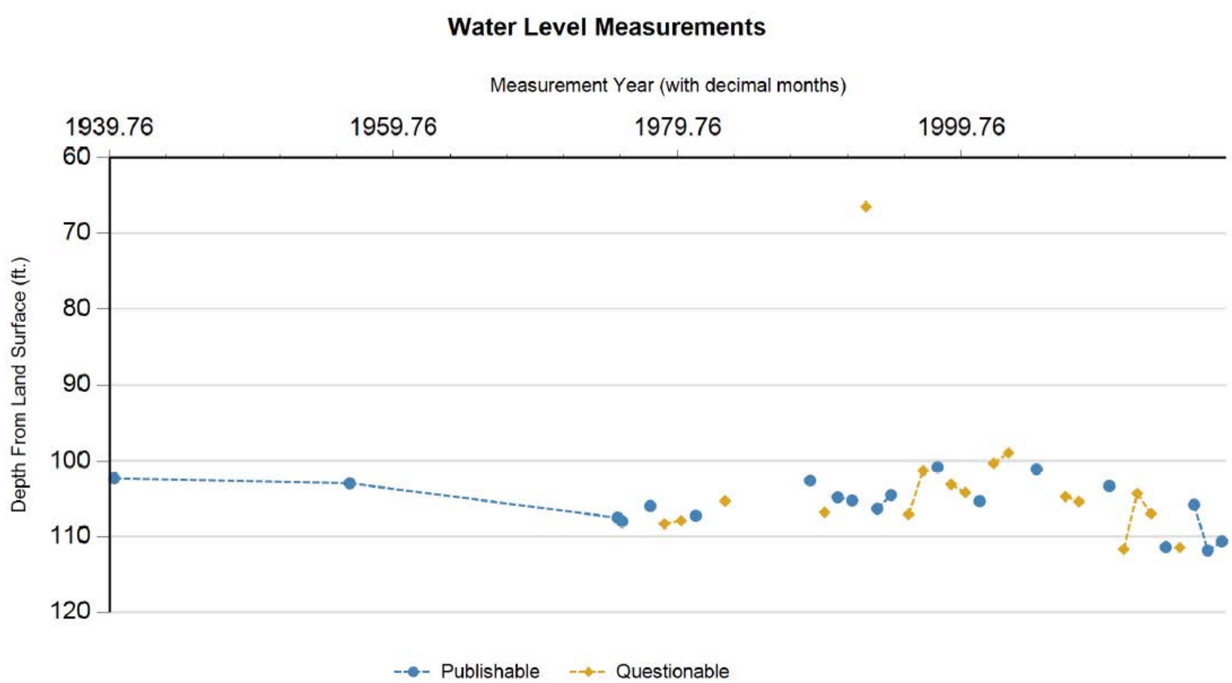
Well 18; State Well Number 4562101; Pecos Valley Aquifer



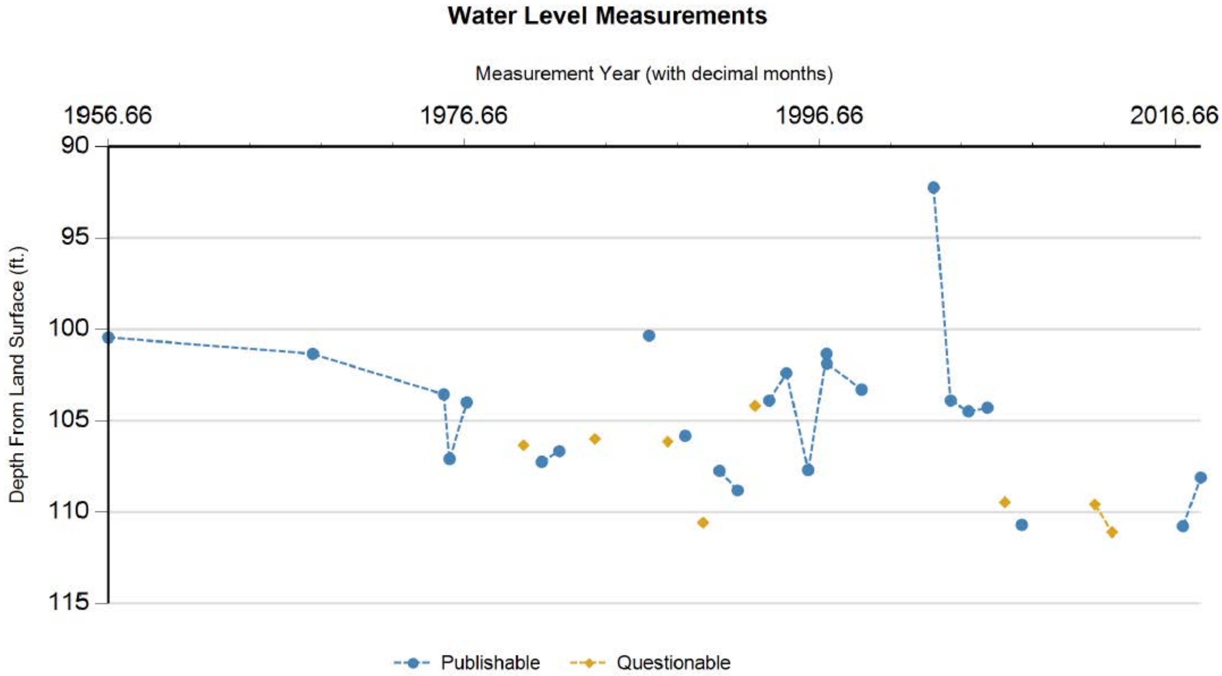
Well 19; State Well Number 4606301; Pecos Valley Aquifer



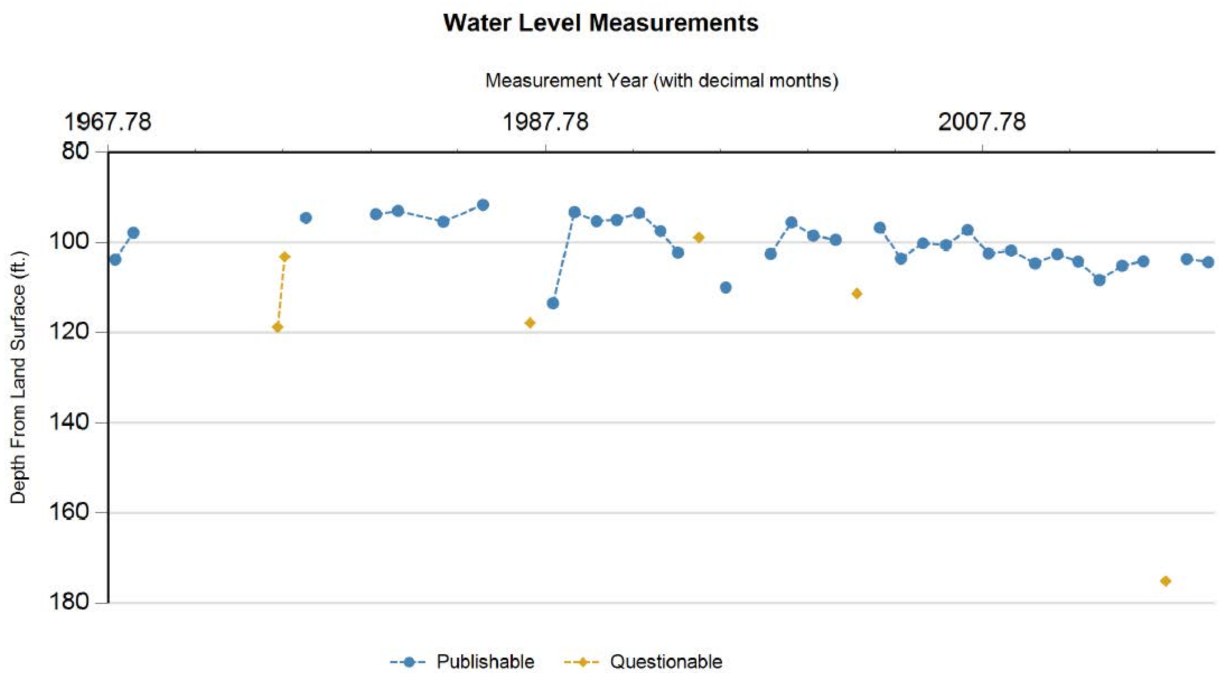
Well 20; State Well Number 4607401; Pecos Valley Aquifer



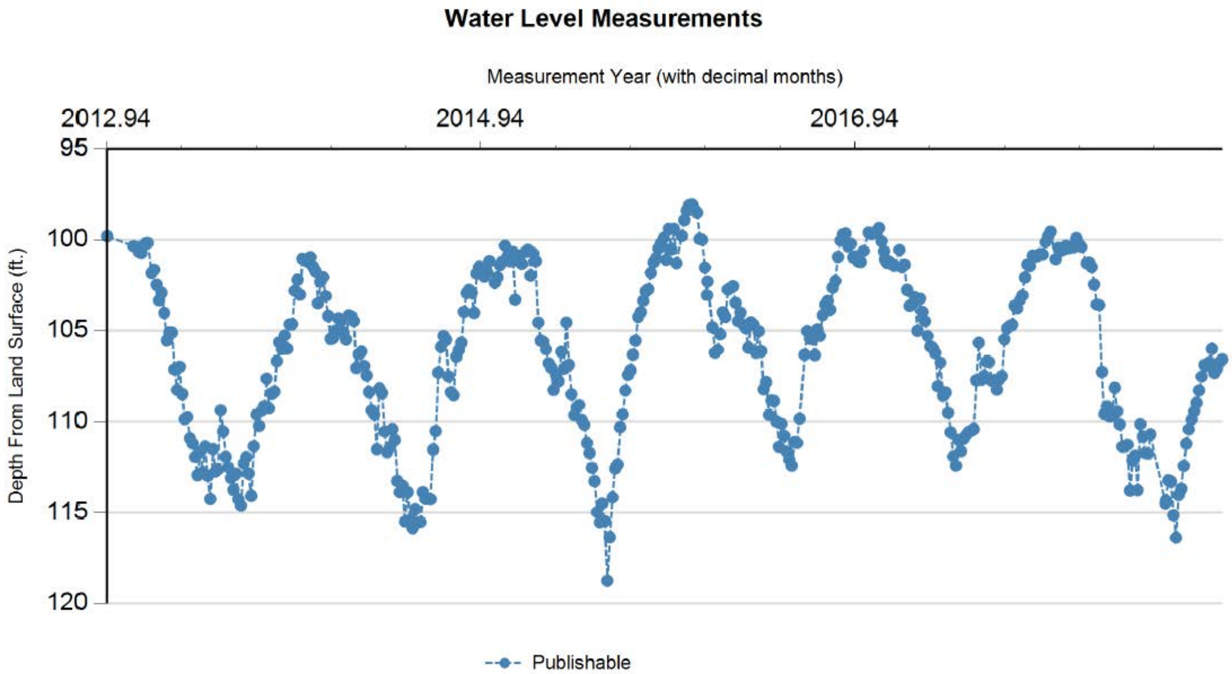
Well 21; State Well Number 4607402; Pecos Valley Aquifer



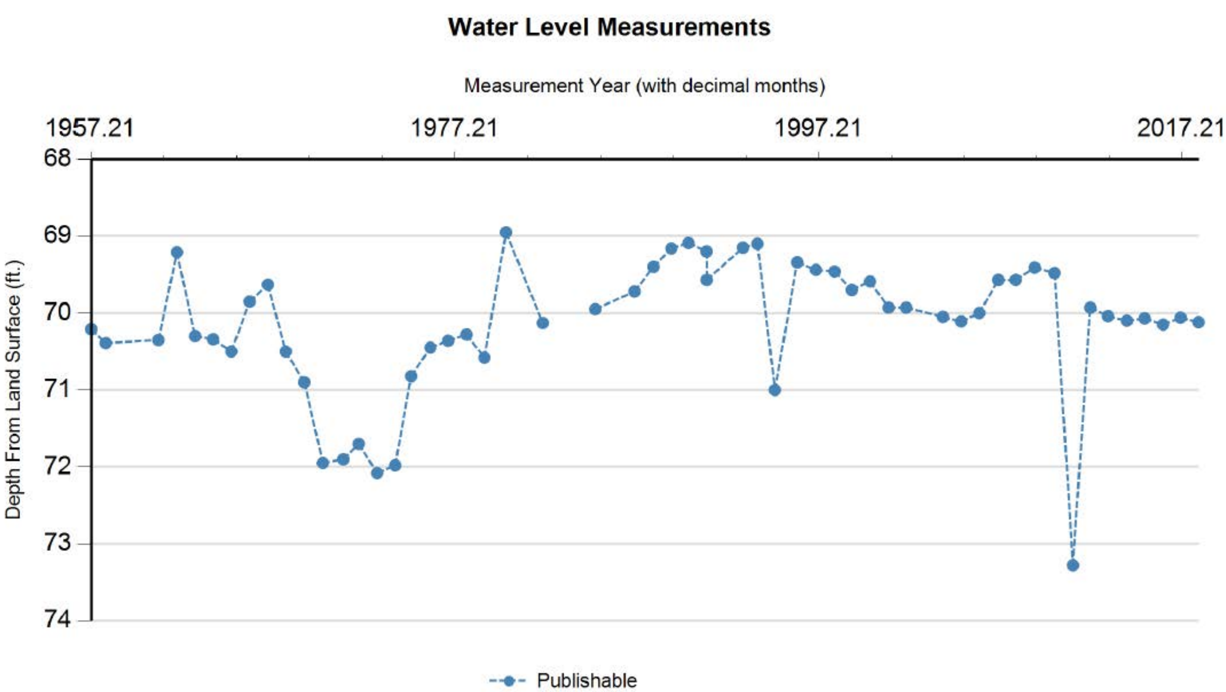
Well 22; State Well Number 4615402; Pecos Valley Aquifer



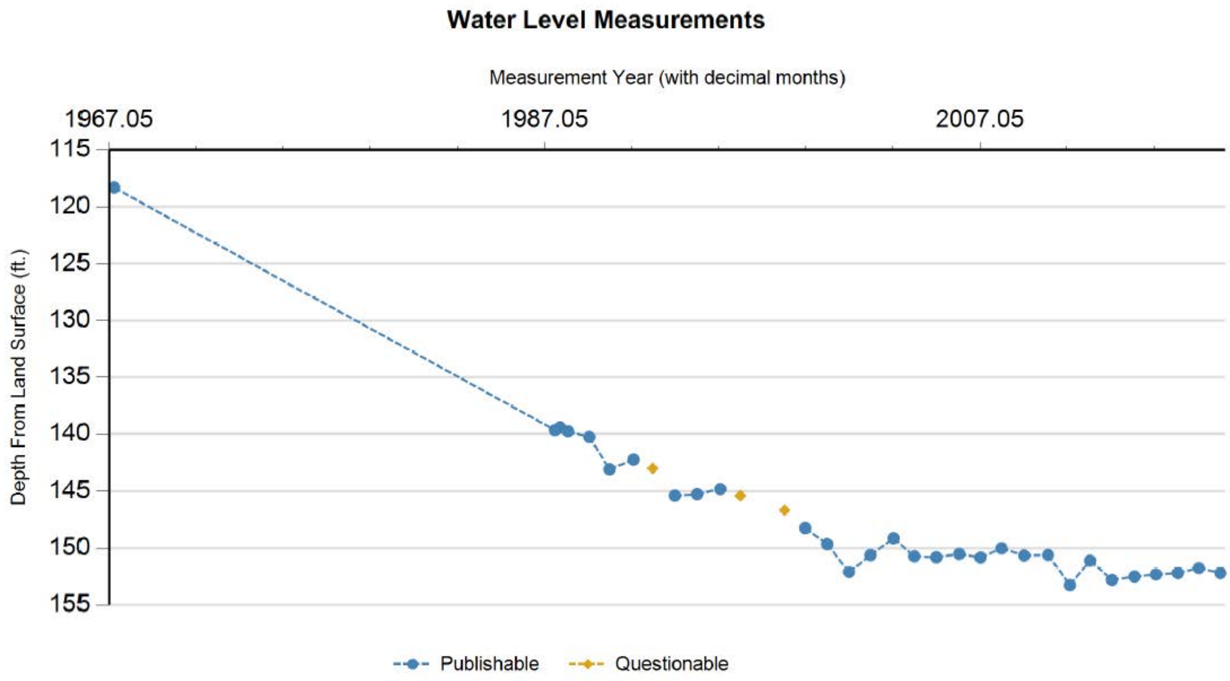
Well 23; State Well Number 4615924; Pecos Valley Aquifer



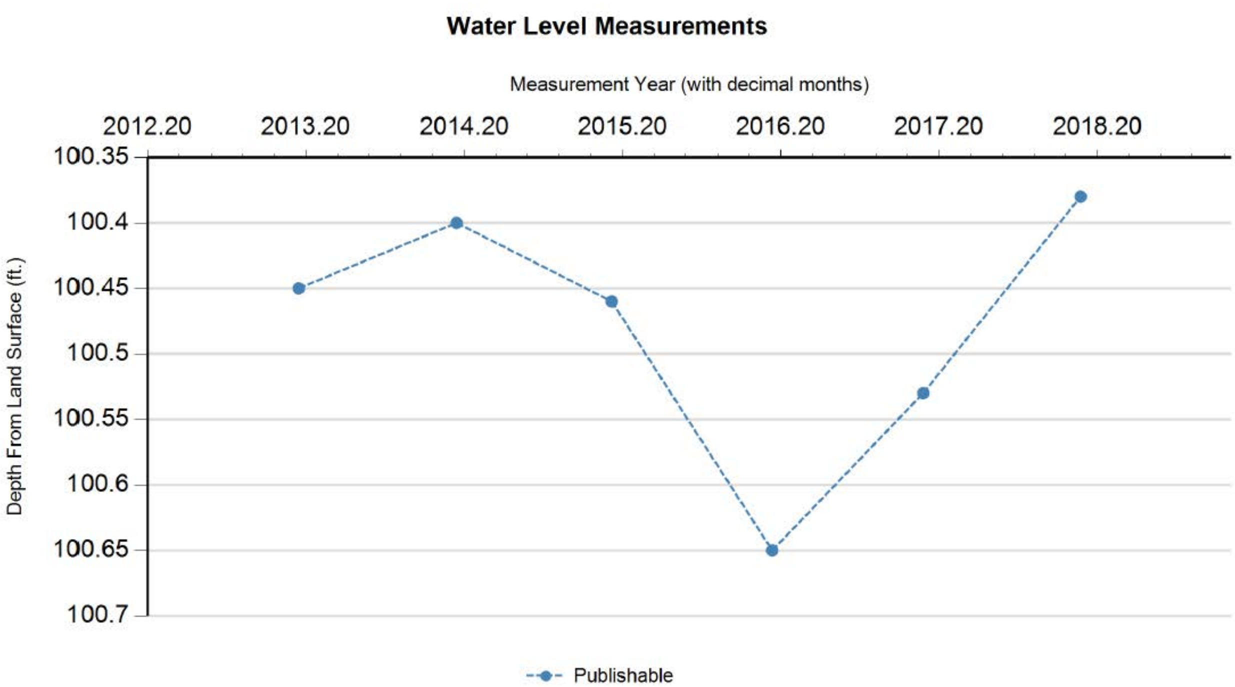
Well 24; State Well Number 4616901; Pecos Valley Aquifer



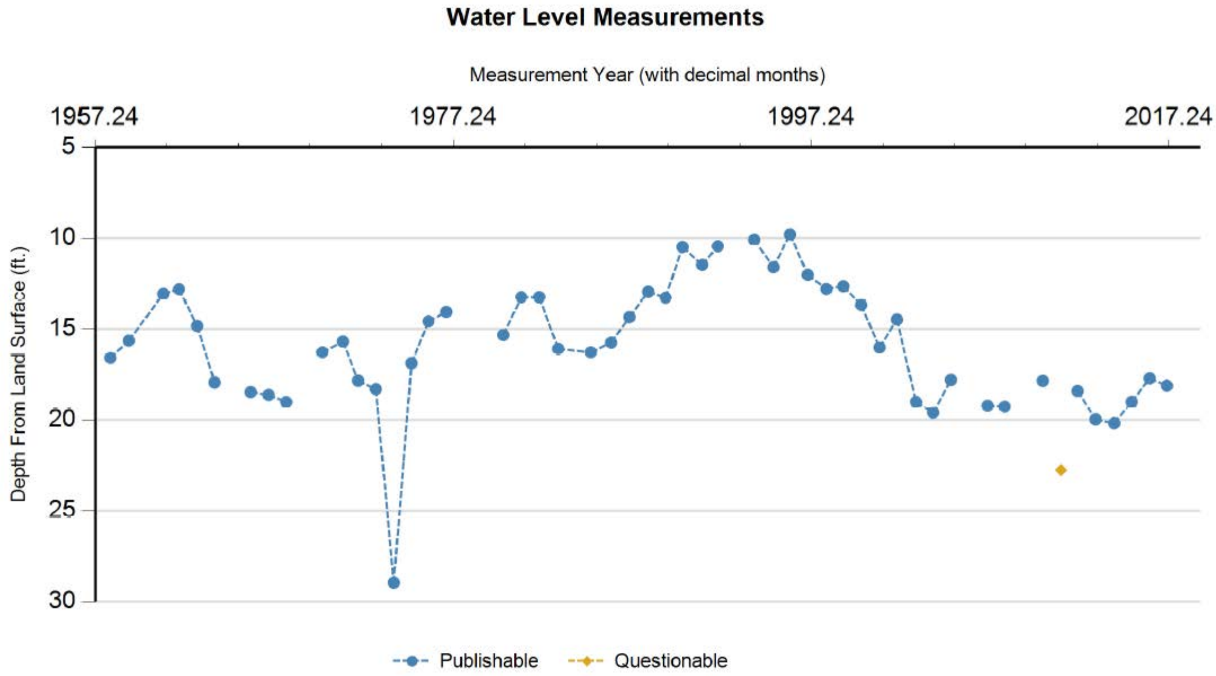
Well 25; State Well Number 4624705; Pecos Valley Aquifer



Well 26; State Well Number 4632706; Pecos Valley Aquifer



Well 27; State Well Number 4637101; Pecos Valley Aquifer



Well 28; State Well Number 4640206; Pecos Valley Aquifer