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

Robert E. Mace[1] and Chelsea Jones[2]

Abstract: Up until the end of the oil and gas boom in 2014, much of the sand used in the Permian Basin for hydraulic fracturing was sourced from upper Midwest of the United States. Because of substantial cost savings, producers in the Permian Basin began using local sand resources in 2015, creating an associated boom in local frac sand mining in the Monahans-Mescalero Shinnery Sands. By December 2018, 17 frac sand operations had registered with the Texas Commission on Environmental Quality with a cumulative annual capacity of 56.8 million tons and a self-reported 2,927 acres of disturbed land. We identified 230 production wells for the 16 facilities with depths ranging from 80 to 1,199 feet. Most were completed in the Pecos Valley Alluvium and/or Dockum aquifers. Estimated frac sand facility water use (10,000–40,000 acre-feet per year, based on 60–250 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 counties) with active frac sand facilities (23,500 acre-feet per year). Modeling suggests that long-term pumping of the unconfined Pecos Valley Aquifer may be a challenge requiring additional wells over time or the use of alternative water supplies. For the confined Dockum Aquifer, simulations suggest that pumping might completely deplete artesian pressure at the well field after 10 years.

Keywords: frac sand, groundwater, Permian Basin, fracking

[1] The Meadows Center for Water and the Environment, Texas State University, San Marcos, Texas
[2] Texas Comptroller of Public Accounts, Austin, Texas
* Corresponding author: robertmace@txstate.edu

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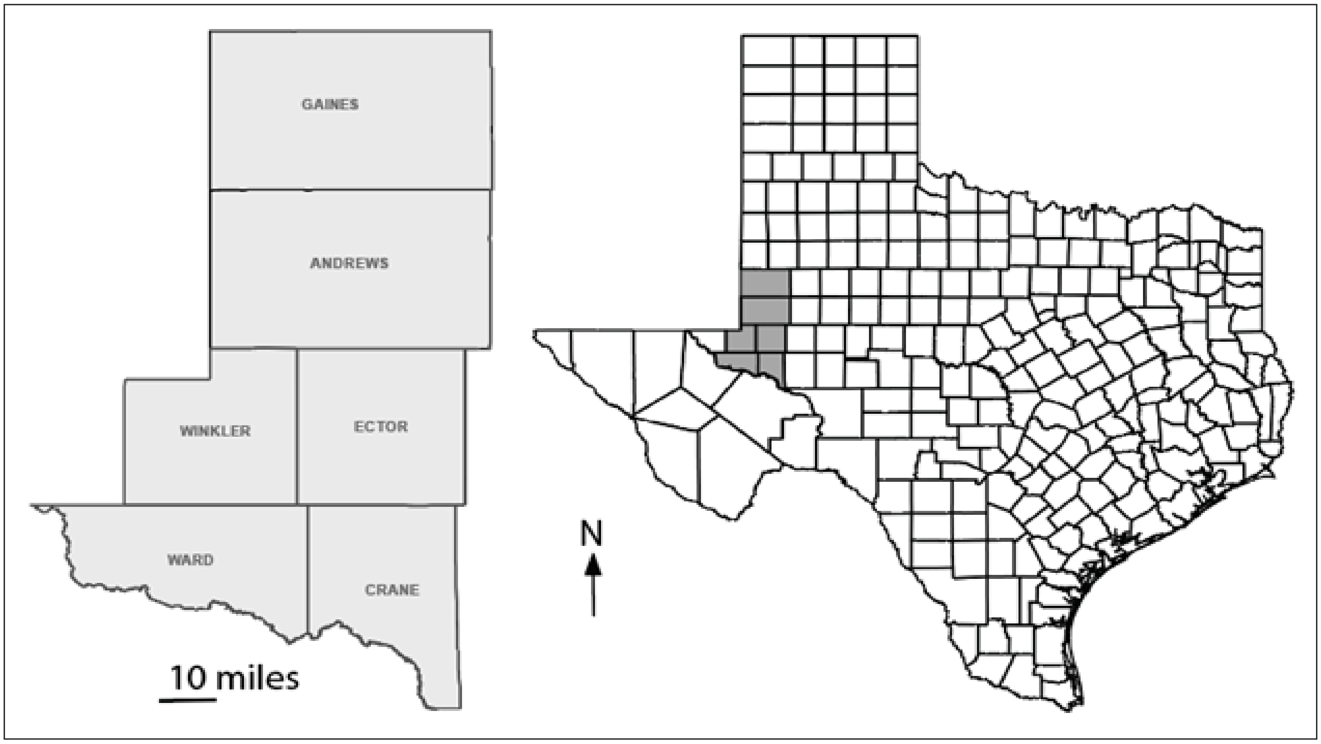

Figure 1. Study area is located in Andrews, Crane, Ector, Loving, Ward, and Winkler counties.

INTRODUCTION

There are many aspects to successfully hydraulic fracturing 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. Water and sand work together to create passageways for oil and gas to flow to a producing well.

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 was sourced from the Northern White or Ottawa White in the upper Midwest (Benson and Wilson 2015). However, the cost of transportation, which is generally by rail and truck, can double to triple the price of sand sourced from the upper Midwest and delivered to the Permian Basin (based on numbers provided by Bleiwas 2015; McEwen 2017).

After a downturn in oil prices in 2015, engineers in the Permian Basin began experimenting with local sand from the Monahans-Mescalero Shinnery Sands and found them passable (McEwen 2017; Mentz 2018; Zdunczyk 2018). By reducing transportation costs through using local sources, cost savings can be $45 per ton of sand (Zdunczyk 2018). Triepke (2018a) estimated that 20 local frac sand facilities could save the oil and gas industry in the Permian Basin $3.5 billion per year.

As with any mining and processing activity, frac sand facilities have their potential environmental impacts, including air quality degradation, land damage, surface-water and groundwater contamination, and groundwater depletion (Orr and Krumenacher 2015), as well as increased noise and traffic (Maslowski 2012 as cited in Benson and Wilson 2015) and deleterious impacts to wildlife habitat (e.g., Kline and Osterberg 2014).

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

STUDY AREA

The study area includes Andrews, Crane, Ector, Gaines, Ward, and Winkler counties in West Texas (Figure 1). These counties are part of the Southern High Plains physiographic province, which is characterized by its flatness, playa lakes, and local dune fields (Wermund 1996). Average annual precipitation is about 15 inches and is unimodal, with most precipitation falling between May and October (TWDB 2012). Aver-

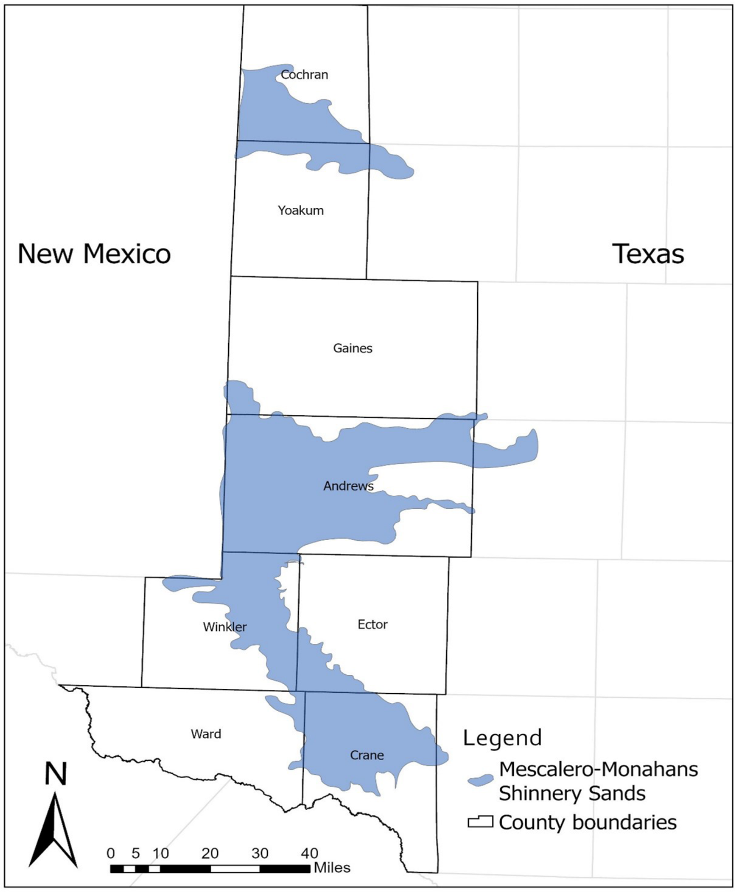

Figure 2. Approximate extent of the Monahans-Mescalero Shinnery Sands in Texas.

age annual gross lake evaporation is about 70–75 inches per year, and average annual temperature is about 58–60 degrees Fahrenheit (TWDB 2012 p. 149). All six counties of the study area include parts of the Monahans-Mescalero Shinnery Sands (Figure 2). Havard Shin Oak, Havard Shin Oak-Mesquite, and Mesquite-Lotebush brush communities exist in the dune area (TPWD 1984).

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; George et al. 2011). The two aquifers locally used for frac sand production in the study area are the Pecos Valley and Dockum aquifers; therefore, we will only present hydrologic information on these two.

The Pecos Valley Aquifer consists of alluvial and windblown sediments in the Pecos River Valley (George et al. 2011) and underlies all of Ward County, most of Crane and Winkler counties, and parts of Andrews and Ector counties (Figure 3a). 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 et al. 2011). The lower, productive part of the Dockum Aquifer is often referred to locally and on well logs as the Santa Rosa Aquifer. The Dockum Aquifer 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 3b). Before oil and gas activities in the area, most aquifer production from the Pecos Valley and Dockum aquifers in the study area was for municipal purposes, with some agricultural use in Ward County (Table 1). Jones (2004) noted that minor amounts of saline groundwater flow from the deeper Permian sediments into the Pecos Valley Aquifer.

There are historical and contemporary reports of long-term standing water among the Monahans-Mescalero Shinnery Sands. Many Indian artifacts have been found among the dunes, indicating that humans were drawn to the area (Justice and Leffler 2016). In 1848, Captain R.B. Marcy of the Corps of Topographical Engineers traveled through the dunes and noted "…several large, deep pools of pure water the very last place on earth where one would ever think of looking for it";

Table 1. Groundwater pumping in acre-feet in the study area in 2016 for the Ogallala and Dockum aquifers (data from TWDB 2018c).

County	Aquifer	Municipal	Manufacturing	Mining	Electric	Irrigation	Livestock	Total
Andrews	Dockum	-	-	8	-	-	2	10
	Pecos Valley	110	-	-	-	-	28	138
Crane	Dockum	154	-	-	-	-	21	175
	Pecos Valley	1,014	-	-	-	-	41	1,055
Ector	Dockum	61	4	-	-	-	2	67
	Pecos Valley	-	-	-	-	-	-	-
Gaines	Dockum	17	-	-	-	-	-	17
Ward	Dockum	6	-	-	-	21	8	35
	Pecos Valley	5,273	-	-	16	1,650	50	6,989
Winkler	Dockum	1,438	29	-	-	-	6	1,473

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.

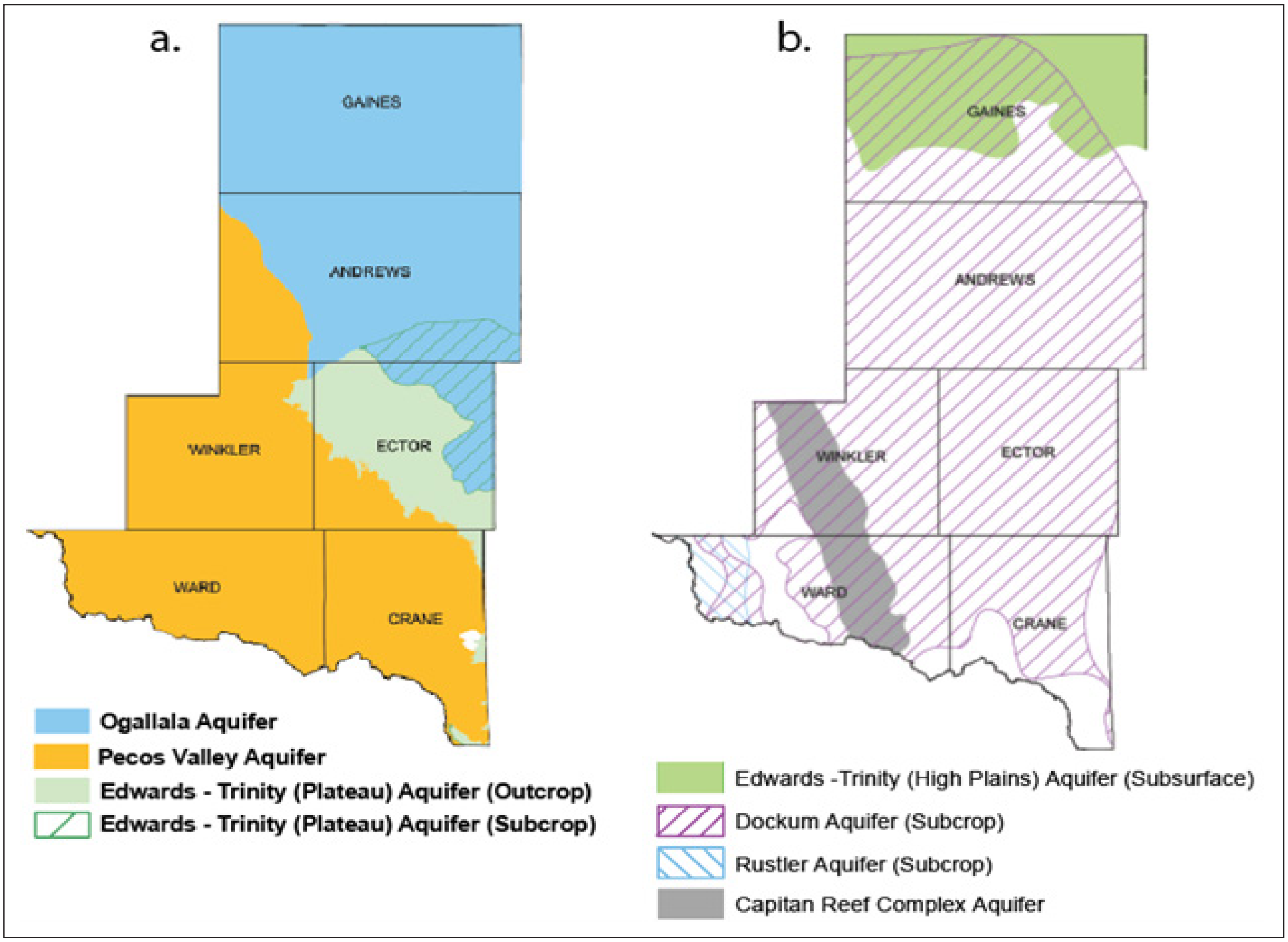

Figure 3. Major and minor aquifers in the study area (modified from TWDB 2018a).

Table 2. Modeled available groundwater and 2016 groundwater production for the relevant aquifers in the counties of the study area.

County	Aquifer(s)	Modeled available groundwater in 2020 (acre-feet/year)	Pumping in 2016[a] (acre-feet)
Andrews	Pecos Valley Alluvium	-	138
	Dockum	1,319	10
Crane	Edwards-Trinity (Plateau) and Pecos Valley[a]	4,991	-
	Dockum	94	1,055
Ector	Edwards-Trinity (Plateau), Pecos Valley, and Trinity[b]	5,542	2,463
	Dockum	-	67
Gaines	Dockum	0	17
Ward	Edwards-Trinity (Plateau) and Pecos Valley[c]	49,976	6,989
	Dockum	2,150	35
Winkler	Edwards-Trinity (Plateau) and Pecos Valley[d]	49,949	9,366
	Dockum	6,000	1,473

[a] 1,055 acre-feet for the Pecos Valley Aquifer and 0 acre-feet for the Edwards-Trinity (Plateau) Aquifer for pumping

[b] 2,453 acre-feet for the Edwards-Trinity (Plateau) Aquifer, 10 acre-feet for the Trinity Aquifer, and 0 acre-feet for the Pecos Valley Aquifer for pumping

[c] 6,989 acre-feet for the Pecos Valley Aquifer and 0 acre-feet for the Edwards-Trinity (Plateau) Aquifer for pumping

[d] 9,364 acre-feet for the Pecos Valley Aquifer and 2 acre-feet for the Edwards-Trinity (Plateau) Aquifer for pumping

Data for modeled available groundwater are from TWDB (2018d, e, f), and numbers for pumping are from TWDB (2018c).

his guide told him that the water was always there, even during dry seasons (Marcy 1850, Mace 2006). Machenberg (1982, 1984) mentioned "interdunal ponds" at Monahans Sandhills State Park and includes photographs of them. Machenberg (1982) noted 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 noted that perched water tables form where underlying caliche is sufficiently thick. If these dune pools source from perched aquifers—as they appear to be—then pumping from the Pecos Valley Aquifer beneath would have no impact on the pools or vegetation communities associated with dunes sagebrush lizard habitat. However, removing contributing dunes or pumping or potential pumping from the pools, as described by Triepke (2018c, 2018d), would likely impact these perched aquifers.

The study area has one groundwater conservation district: the Llano Estacado Underground Water Conservation District in Gaines County. 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 on well construction and submitting a driller's report with the Texas Department of Licensing and Regulation.

Groundwater conservation districts are required to establish desired future conditions for relevant groundwater resources in their groundwater management area every 5 years (with 2016 being the most recent year). 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, or the amount of water that can be pumped to achieve the desired future conditions. 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. Alternative (such as private) funding could still be used to implement the groundwater project.

Modeled available groundwater for the Pecos Valley and Dockum aquifers is about 50,000 acre-feet per year in Ward and Winkler counties, with most in the Pecos Valley Aquifer (96% in Ward County and 89% in Winkler County; Table 2). Except for the Dockum Aquifer in Gaines County, estimated pumping is below modeled available groundwater for 2016 (Table 2).

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 subsequent 5-year revisions of desired future conditions.

Table 3. 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	Unimin Corporation[c]/Covia Crane Facility	5/9/2018	228	AP0002685	3
	U.S. Silica/Crane County Plant	12/1/2017	188	AP0002546	4
Ector	Preferred Sands of Monahans	10/23/2017	100	AP0002853	3.3
Gaines	U.S. Silica/Seagraves Sand Plant	5/23/2017	33	Idled	0.5
Ward	Wisconsin Proppants/E Ranch Facility	5/24/2018	213	AP0002697	3
	Black Mountain Sand/Sealy Smith Facility	9/21/2018	150	AP0002792	1
Winkler	Hi-Crush Permian Sand/Hi-Crush	4/4/2017	70	AP0002202	3
	Black Mountain Sand/Vest Facility	12/11/2017	348	AP0002552	6
	High Roller Sand Operating[d]/Kermit Plant	12/21/2017	134	AP0002560	4
	Lonestar Prospects[e]/West Texas Sand Plant	1/19/2018	250	AP0002587	3
	FML Sand[c]/FML Kermit	3/26/2018	250	AP0002645	3
		10/16/2018	300	AP0002849	
	Black Mountain Sand/El Dorado Facility	4/27/2018	247	AP0002673	6
	Alpine Silica/Alpine Silica	5/4/2018	60	AP0002679	3
	Badger Mining Corporation/Kermit Plant	5/4/2018	125	AP0002680	3
	Atlas Sand Company/Atlas North	6/8/2018	83	AP0002721	4
	Atlas Sand Company/Atlas South	8/29/2018	88	AP0002804	4
	Hi-Crush Permian Sand/Kermit Plant North	12/14/2018	60	AP0002879	3
	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; we 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; we include this as a potential future frac sand facility.

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. 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. We 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 been registered, with all the actively registered facilities clustered along the dunes between southeast of Monahans and northeast of Kermit in a 20-mile by 40-mile area (Table 3, Figure 4). 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 facilities (Table 3).

Based on operator-reported or press reports of annual production amounts, the 17 facilities had a combined 56.8 million tons of annual capacity (Table 3). Not including an idled plant, the 16 frac sand facilities average about 3.6 million tons of annual capacity per facility. More frac sand facilities—in addition to Smart Sand listed in Table 3—may be in development. Triepke (2018e) identified more than 30 potential facilities for the area. Current frac sand capacity is meeting about 40% of total demand and is expected to grow to 50% by 2023 (Rock Products News 2018).

Figure 4. 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.

WATER USE FOR FRAC SAND FACILITIES

The production of frac sand may require water for mining, 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, which removes the fine particles, can be done in multiple ways. Water can either be sprayed on sand on a vibrating screen or be sprayed through an up-flow clarifier, where the sand is fully immersed in wash-water and the sand falls to the bottom (WDNR 2012) while the fine particles 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 (e.g., Triepke 2017a; Triepke 2018b). 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 evaporates out of the pile or drains down out of the pile (WDNR 2012). One operator, Hi-Crush (2018), claimed to deliver sand to the surge pile with less than 12% moisture. Water that drains downward out of the pile may be collected and reused (e.g., Triepke 2017). A drainage system beneath these piles can reduce moisture content to 2–4% (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 2018; 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 creating greater paved areas, road cleaning, using dust control chemicals, limiting exposure, minimizing wind exposure, and using stabilized berms.

It is 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. Consumption refers to the amount of water lost during the process, perhaps from evaporation, leaks, or incorporation into a product. Use and consumption can be equal, but with water recycling, consumption will be less than use. Unfortunately, use and consume are employed interchangeably in reference to water in frac sand operations, making it difficult to determine what is used and what is consumed. Furthermore, it can be challenging to identify what processes are included in use and efficiency estimates.

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 because 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% 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 6.6 million–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 is not normalized to sand production (and the use of the word "can" by the authors of WDNR 2016 suggests permitted amounts, not actual produced amounts). Orr and Krumenacher (2015) noted that facilities might need 250–500 gallons per minute of make-up water per million tons of sand production (130–260 gallons of water consumed per ton of sand produced) for closed-loop systems that recycle 90% of their water.

We were unable to find published numbers for water consumption for frac sand facilities in Texas; however, we were able to access limited information and compare it to Orr and Krumenacher's (2015) numbers. We list the estimates below from largest to smallest. Note that only one of the estimates (U.S. Silica) was explicitly normalized to tons of sand produced. For many of the other estimates, we 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. We first present the data in the units they were reported in and then end each bullet 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 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 2018b), 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 its consumptive water use at 370 gallons per minute (Osborne 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 400–600 gallons per minute (210 million–315 million gallons per year) of supply. 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 60–90 gallons per ton of sand.

- U.S. Silica reported that its 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 its 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, a number that is too low to operate a frac sand operation. At a minimum, the water lost to capillary forces before sand is dried is about 11 gallons of water per ton, and this does not account for water lost through adhesion to the fine particulates and other processes (Mace 2019).

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) 130–260 gallons per ton.

With the study area's dry climate and lack of available surface-water resources, local frac sand operations almost exclusively use groundwater. Local aquifers provide most of the water for frac sand production in the Permian Basin (Campbell 2018); municipal and private suppliers are also sources or future sources of water.

To assess water sources for frac sand facilities in the study area, we used the Texas Water Development Board's Groundwater Data Viewer (TWDB 2018b) to inspect submitted drillers reports. 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, but 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, but papers forms may take more than a year to be entered by Texas Water Development Board staff. For example, for Lonestar Prospects' West Texas Sand Plant, four well reports submitted in paper form in October 2017 were not entered into the database until late December 2018. Therefore, if a driller submitted paper forms for the wells it drilled, the wells may not be reflected in this study.

We identified a total of 230 production wells for the 16 sites that had production wells drilled at their locations. Drillers identified most production wells as industrial; however, drillers marked a few as irrigation wells (perhaps because they were intended for dust suppression). Because we did not see any agricultural irrigation associated with these wells from aerial photography, we included irrigation wells as production wells for the facilities. Several facilities also had test and monitor wells, which we did not include in the analysis. Test wells were generally plugged after boring, and monitor wells generally had small diameters consistent with monitoring rather than production purposes. Two sites did not have any wells in the state database, suggesting an off-site source of water or delay in reporting drillers reports.

Based on the depth of wells, which ranged from 80 to 1,199 feet deep (Table 4), and geologic structure (Meyer et al. 2012; Ewing et al. 2008; Mace 2019), 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 Basin (14 wells). The drillers for 10 wells did not report completion information, but given their depths, they are either completed in the Dockum Aquifer or both the Dockum and Pecos Valley aquifers. Seven facilities have wells completed in both aquifers either explicitly (screened in both) or non-explicitly (screened in the Dockum Aquifer but with the borehole annulus packed with gravel or sand across both formations).

The number of wells at individual facilities ranged from four to 29 (Table 4). For facilities solely reliant on the Pecos Valley Aquifer, the number of wells per facility ranges from eight to 14, whereas for facilities reliant exclusively on the Dockum Aquifer, the number of wells per facility ranges from four to 27 (Table 4). Nine—possibly 10—facilities have wells completed in both aquifers. Our results agree with Campbell (2018), who found that facilities have 10–15 wells pumping water from Pecos Valley and Dockum aquifers, and wells can be screened in both aquifers.

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 maintenance.

POTENTIAL IMPACTS FROM GROUNDWATER PRODUCTION

The Minnesota Environmental Quality Board (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 News (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."

Table 4. Number of production wells drilled at the facilities.

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

[a] Listed owner of wells drilled in area is Barr Engineering; we assumed these wells were all drilled for Unimin.

[b] "Upper" refers to wells completed in the shallower part of the Dockum Aquifer on-site and "lower" refers to the lower part. All other references to Dockum Aquifer in this table refer to the lower part.

[c] Listed owner of wells drilled in area is Hydro Logics; we assumed these wells were all drilled for Preferred Sands.

It was too soon at the time of our study to see possible impacts from pumping beneath frac sand facilities with available data collection. Because 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 its online database (TWDB 2018b). In areas without groundwater conservation districts or in districts that do not 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. Because most of the frac sand facilities went into operation during 2018, many of those measurements were not available at the time of our work. However, even with the Texas Water Development Board's measurements, the monitor wells may not be in the right place to accurately assess effects.

COMPARISON TO OTHER WATER USES

Other pumping may make it difficult to assess the effects of frac sand facilities without purpose-built monitoring. With at least 53.8 million tons per year of production capacity possibly needing 60–250 gallons of water per ton of sand production, frac sand facilities may be pumping 10,000–40,000 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 for other uses in Crane, Ector, Ward, and Winkler counties, 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 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 Shinnery Sands rest 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 et al. 2017). In the Central Basin Platform, 96–152 non-conventional (fracking) horizontal wells were drilled per year in 2012–2015, as compared to 1,256 wells drilled in the Midland Basin (Scanlon et al. 2017 Table S3b). With an average of about 80 acre-feet of water used to frac an oil well in the Permian Basin (Kondash et al. 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 et al. 2017 Table S3a). If half of those were drilled in the Central Basin Platform—and assuming water use of 300,000–600,000 gallons per well for drilling (Mielke et al. 2010)—water use for conventional drilling could range from 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 are currently focused. Furthermore, drilling intensity in the Central Basin Platform has generally been away from the Monahans-Mescalero Shinnery Sands (Scanlon et al. 2017 Figure 1).

Summing the above pumping estimates results in a range of 42,900–77,000 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 2) sums to 118,702 acre-feet per year. Therefore, the combined four counties' uses—including those for frac sand facilities—are below the estimated groundwater availability with the ability to accommodate additional pumping.

WATER-LEVEL TRENDS

Some published information is available on water-level impacts for 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 had seen some small decreases in the water table and had one well with a water-level decline of over 70 feet in the previous year. Using measurements made by the Texas Water Development Board as part of its annual water-level monitoring activities, Mace (2019) did not find any declines associated with frac sand mining; however, the wells were too distant from the mines to detect any changes as of December 2018.

CROSS-FORMATIONAL FLOW THROUGH MULTI-SCREENED WELLS

A total of 32 wells were screened in both the Pecos Valley and Dockum aquifers, and one well was screened in the Pecos Valley Aquifer, Dockum Aquifer, and upper part of the Permian rocks. Given the greater hydraulic head in the Pecos Valley Aquifer compared to the Dockum Aquifer, there is the potential for cross-formational flow from the Pecos Valley Aquifer to the Dockum Aquifer. While a well with multiple completions will produce from multiple formations during production (as

Table 5. Simulated water-level declines in the Pecos Valley and Dockum aquifers for single wells and hypothetical well fields.

Years of pumping	Water-level decline at well site (feet)	Radius of influence to 5-foot water-level decline (feet)	Radius of influence to 1-foot water-level decline (feet)
***Scenario 1:** Single well pumping 40 gallons per minute in the Pecos Valley Aquifer*			
1	18	100	1,000
10	20	300	3,000
***Scenario 2:** Twelve wells pumping 40 gallons per minute in the Pecos Valley Aquifer*			
1	25	550	2,100
10	47	4,000	9,000
***Scenario 3:** Single well pumping 70 gallons per minute in the Dockum Aquifer*			
1	124	16,000	23,000
10	136	51,000	74,000
***Scenario 4:** Seven wells pumping 70 gallons per minute in the Dockum Aquifer*			
1	272	40,000	65,000
10	360	130,000	-

long as the production head is lower than the head in any of the screened formations), once the well is no longer producing, groundwater will flow into the borehole from formation with higher heads into formations with lower heads. In the case of the dual completed wells, groundwater from the Pecos Valley Aquifer will flow through the borehole to the Dockum Aquifer. Such well completions should be discouraged because these wells are likely to affect water resources for remaining users as long as the well connection exists.

PROJECTIONS OF WELL-SITE WATER-LEVEL DECLINES

We developed two simple, interpretive groundwater models to project water-level declines in well clusters completed in the Pecos Valley and Dockum aquifers. 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 we lacked specifics on the facilities, we 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 general sense of how area aquifers might respond to pumping. An assessment of specific impacts at specific sites requires site-specific information that was not publicly available.

Based on the hydrogeologic data for the study area (Mace 2019), the type case for the Pecos Valley Aquifer had 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 produced 3.6 million tons of sand per year and had 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. We chose 70 gallons of water per ton of sand, which is on the low end of the range we reported earlier, both because this rate was reported by U.S. Silica and because this type case would not support much higher amounts of pumping over 10 years.

The type case for the Dockum Aquifer included 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 had seven wells with 8-inch diameters spaced 2,000 feet apart pumping 70 gallons per minute per well (again assuming a facility that produced 3.6 million tons per year pumping 70 gallons of water per ton of sand).

To model these type cases, we 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. We then then developed simple numerical groundwater flow models using MODFLOW-2000 (Harbaugh et al. 2000) through Groundwater Vistas (Rumbaugh and Rumbaugh 2017) with lateral boundaries placed distantly enough to have no impact on drawdowns caused by the well fields. To verify the numerical groundwater model, we compared its results for a single well to the results from Theis (1935). For the numerical groundwater flow model, we 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.

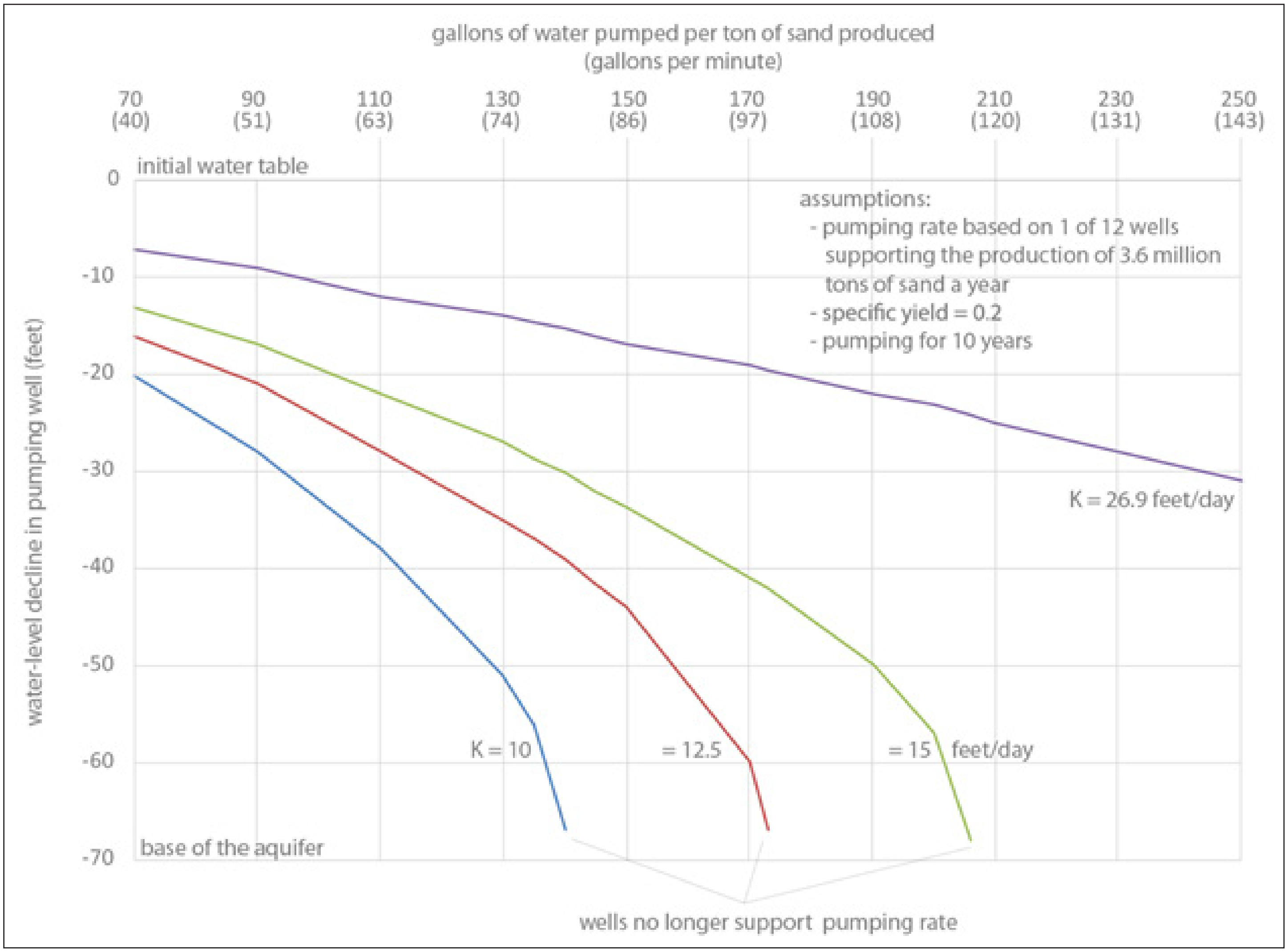

Figure 5. Sensitivity analysis of pumping rate and hydraulic conductivity on water-level declines in a single well in the Pecos Valley Aquifer after pumping 10 years.

For the modeling results presented below, we 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 for 1 year and 10 years (Table 5). We then present a sensitivity analysis on a single well pumping for 10 years, where we plot water-level declines at the well for different pumping rates and hydraulic conductivities. We 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. In the case of the Pecos Valley Aquifer, this analysis helps establish a physical bound on how much water can be pumped from the aquifer and thus how much water may be being pumped for frac sand facilities.

After that, we present results from the numerical model where all the wells are included, 12 for the Pecos Valley Aquifer and seven for the Dockum Aquifer, first for 1 year of pumping and then for 10 years of pumping (Table 5). These are the simulations that show the water-level declines around the frac sand facility type cases. As a sensitivity analysis on the numerical model, we 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). We did this for both the 1-year and 10-years simulation periods.

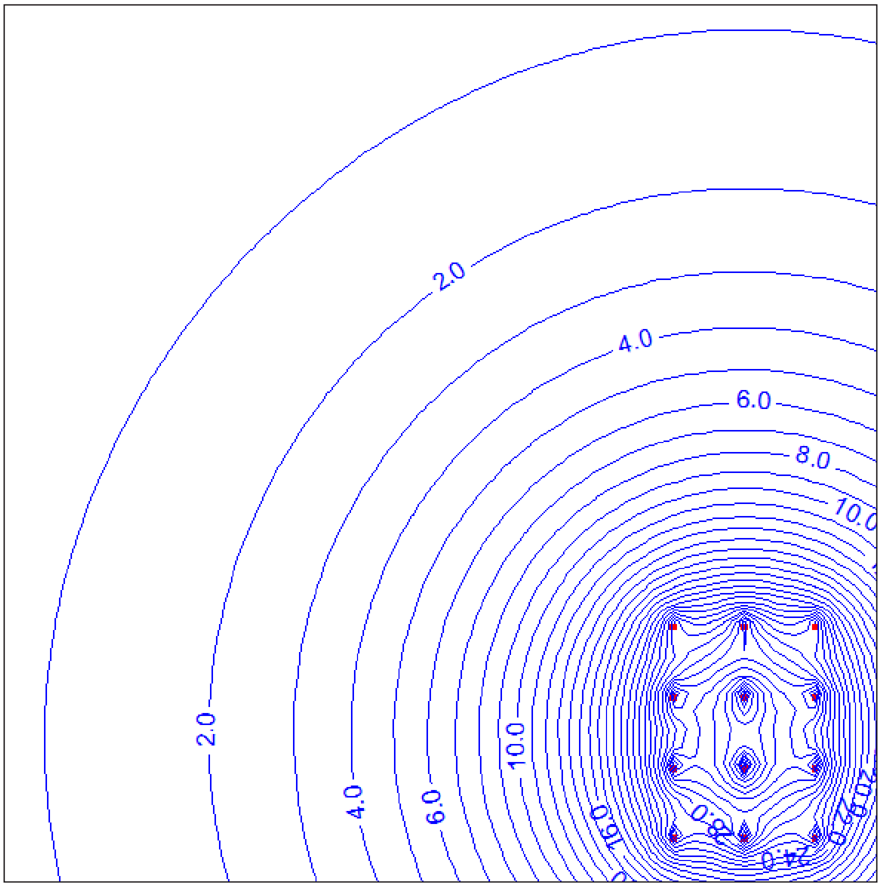

Figure 6. Water-level declines at a 1-foot interval around a hypothetical well field in the Pecos Valley Aquifer after pumping for 10 years. The wells (red squares) are spaced 1,000 feet apart.

MODELING RESULTS FOR THE PECOS VALLEY AQUIFER

For a single well pumping 40 gallons per minute in the Pecos Valley Aquifer, there would be about 18 feet of water-level decline after 1 year of pumping and 20 feet after 10 years of pumping (Table 5). After 10 years of pumping, the distances to the 5-foot and 1-foot water-level declines are 300 feet and 3,000 feet, respectively (Table 5).

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 5). If the hydraulic conductivity is 15 feet per day, a single well can support upwards of 115 gallons per minute of pumping for 10 years before going dry (Figure 5). At the highest reported hydraulic conductivity of 26.9 feet per day (Anaya and Jones 2009), a single well could support more than 140 gallons per minute of pumping without depleting more than half of the saturated thickness at the well (Figure 5).

For a well field of 12 wells arranged in a three-by-four pattern (Figure 6) in the Pecos Valley Aquifer with each well pumping 40 gallons per minute, there would be about 25 feet of water-level decline after 1 year of pumping and 47 feet after 10 years of pumping in the center of the well field (Table 5). After 10 years of pumping the well field, the distances to the 5-foot and 1-foot water-level declines were 4,000 feet and 9,000 feet, respectively (Table 5).

We increased the pumping rate for all of the wells in the well field 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. We also increased the pumping rate to identify when the 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. This simulation and the reported use by U.S. Silica are why we used 70 gallons of water consumed per ton of sand produced for the Pecos Valley Aquifer type case.

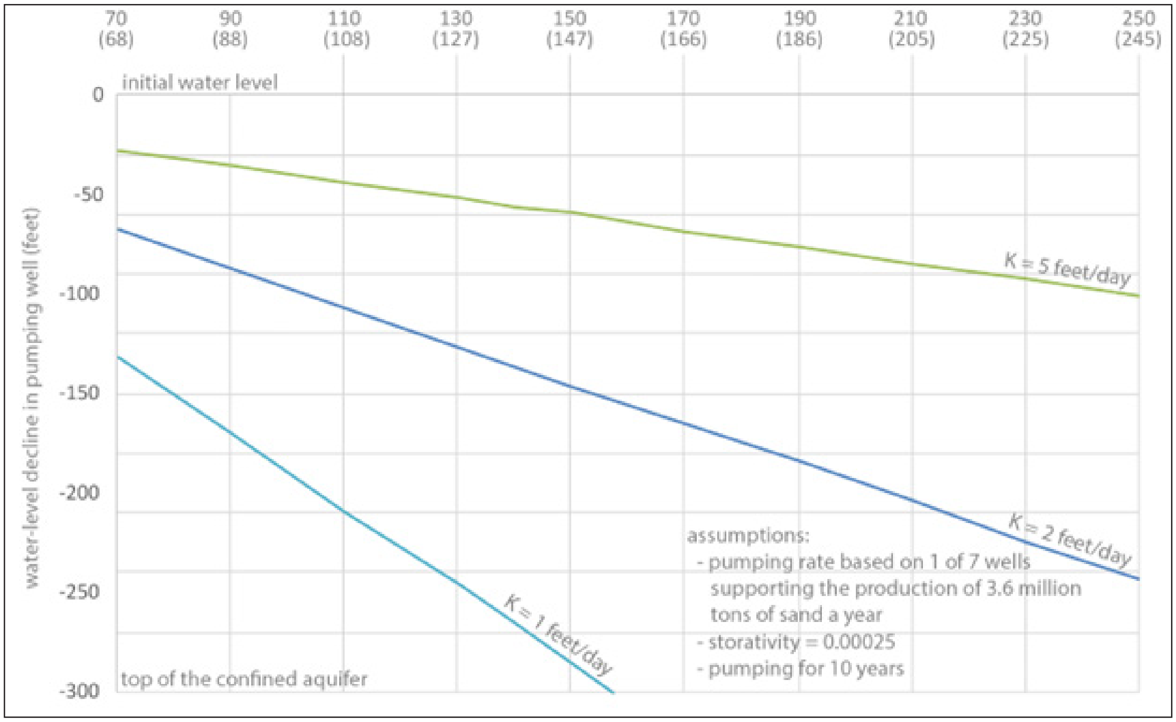

Figure 7. Sensitivity analysis of pumping rate and hydraulic conductivity on water-level declines in a single well in the Dockum Aquifer after pumping 10 years.

MODELING RESULTS FOR THE DOCKUM AQUIFER

For a single well pumping 70 gallons per minute in the lower part of the Dockum Aquifer, there would be about 136 feet of water-level decline after 10 years of pumping (Table 5). A single well in the Dockum Aquifer with a hydraulic conductivity of 1 foot 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). If the hydraulic conductivity is 2 feet per day, a single well can support more than 250 gallons per minute of pumping (Figure 7). At the highest reported hydraulic conductivity of 5 feet per day, a single well could support considerably more than 250 gallons per minute of pumping while depleting about a third of the artesian pressure head (Figure 7).

With a well field of seven wells arranged in a two-by-three pattern with a single well on top, each pumping 70 gallons per minute in the Dockum Aquifer, the distance from an outer well in the well field to the 5-foot water-level decline contour after one year of pumping is about 40,000 feet (7.5 miles; Table 5, Figure 8). Using superposition and the Theis (1935) equation, 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, the distance from an outer well in the well field to the 5-foot water-level decline line is about 130,000 feet (24.6 miles; Table 5). 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 after 10 years of operation.

Using the MODFLOW model, we increased the pumping rate to identify when the 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.

While the modeling provides an indication of what might happen around a well and at a well field, it does have its limitations. This is especially true in the case of the Dockum Aquifer, once available artesian head is exhausted, and the aquifer at the well transitions to unconfined conditions. Once this condition is reached, well yields could be severely impacted in the

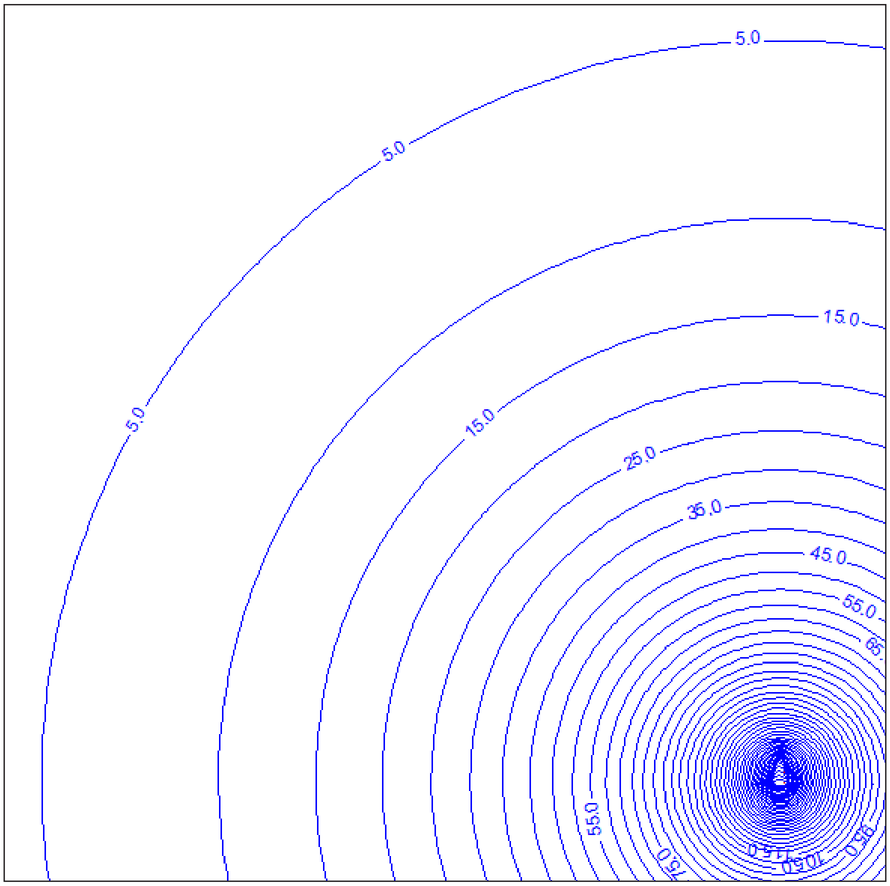

Figure 8. Water-level declines at a 5-foot interval around a hypothetical well field in the Dockum Aquifer after pumping for 10 years. The distance from the 5-foot contour to the well field in the lower right is about 130,000 feet (about 25 miles).

Dockum Aquifer due to decreasing saturated thickness and air impingement. In the unconfined Pecos Valley Aquifer, well yields will also decline as the saturated thickness decreases. At some point, the economics of drilling more wells to replace declining well yields will become prohibitive. When saturated thicknesses decline significantly, the numerical model will overpredict well yields.

RECOMMENDATIONS

We 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 in the public domain. If the State of Texas wishes to have a better understanding of potential effects of pumping at these facilities, then requiring the reporting of this information is critical. 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.

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