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[Alix Fournier](#)*, [Steven L. Forman](#), [Connor Mayhack](#), Griffin Money

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Article

Perched Hydrologic Systems of the Monahans and the Kermit Dune Fields, Northern Chihuahuan Desert, West Texas, USA

Alix Fournier ^{1,*}, Steven L. Forman ¹, Connor Mayhack ¹ and Griffin Money ²

¹ Dept of Geosciences, Baylor University, Waco TX 76798 USA,

² Atlas Energy Solutions, Austin TX 78730

* Correspondence: Alix_Fournier1@Baylor.edu

Abstract: This study highlights the importance of quantifying groundwater resources for the Monahans and Kermit dune fields in the northern Chihuahuan Desert, West Texas USA as potential contributors to the regional Pecos Valley Aquifer (PVA). Sedimentary architecture models of these dune fields show perched aquifers with water tables 1-10m below the surface and southwestward groundwater flow sub-parallel to a Pleistocene/Pliocene aquitard. Sinkhole-like features into the top of the aquitard are infilled with the thickest occurrences of aeolian sand. Groundwater recharge occurs from the enhanced capture of precipitation on mostly bare active dunes where infiltration rates >250mm/hr. The deuterium and oxygen isotopic ratios for groundwater from the Kermit and Monahans dune fields show pronounced evaporative isotopic depletion and less isotopic variability than corresponding rainfall, particularly for deuterium values. Groundwater from a shallow central well in the Kermit dune field yielded contemporary ¹⁴C activity (Fm =1.02), indicating contributions from recent precipitation. In contrast, more evolved ¹⁴C values at the western margin (FM=0.84) and at 30m below the surface (FM=0.76), similar to proximal Fm values from the PVA (0.89-0.82), may indicate dissolution of older (> 100 ka) DIC from buried playa-lake sediments and carbonate-soils with groundwater flux to the southwest, and less direct atmospheric influence. The perched aquifers of the Monahans and Kermit dune fields contain water volumes > 0.1 km³ and may contribute up to 9% of the total annual recharge to the PVA.

Keywords: perched aquifer; West Texas; dune fields; Chihuahuan Desert; stable isotopes; radiocarbon; OSL dating.

1. Introduction

The Chihuahuan Desert in west Texas with distinctive active and tall dune fields and the widespread occurrence of sand sheets is one the most arid areas on the Southern High Plains (SHP) USA (Figure 1) [1–4]. Aridity has intensified in the late 20th and 21st centuries with a 10 to 50% decline in precipitation since 1979 [5–9]. This drying is regional with extended periods of stream intermittency with common no-flow conditions for tributary and major rivers concomitant with increased freshwater demand and decreased reservoir and groundwater storage [10–13]. A clear indication of current water supply limitations on the SHP is declining groundwater levels by up to 100 cm/yr. in the past seventy years for major aquifers, such as the Ogallala, Pecos Valley, Dockum and Edwards-Trinity Plateau [14–20]. Groundwater supply is predicted to decrease further by nearly 30% on the SHP with potentially higher drought frequency and intensity in the mid to late 21st century, which may have a detrimental impact on nearby cities and agricultural and energy production [21–23].

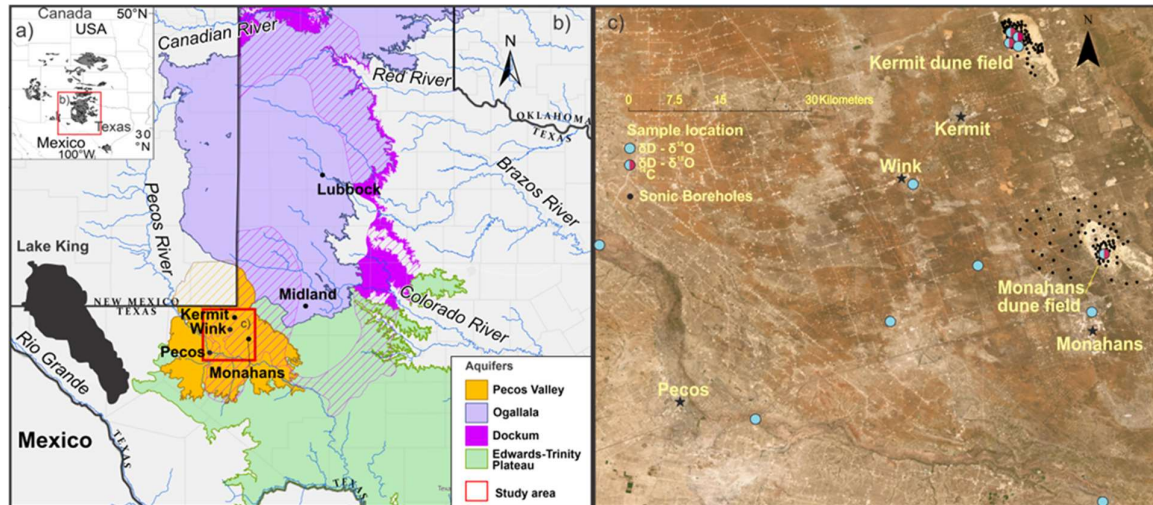


Figure 1. a) Location of the study area on the Southern High Plains with other Aeolian sand deposits (modified from Forman et al. [50]). b) Location of the study area relative to the major aquifers of Texas for Groundwater Management Areas 2, 3, and 7. c) Aerial Imagery of the Monahans and Kermit dune fields with location of Sonic Boreholes and water sampling sites in West Texas. Blue dots indicate sample sites for stable isotopes. Blue and red dots indicate sample sites for both stable isotopes and radiocarbon analyses.

The recharge for aquifers on the SHP occurs from precipitation, irrigation seepage, and cross-formational flow amongst aquifers [14,24–26]. Direct precipitation accounts for 1 to 8 % of the yearly contributions of aquifer volume in the arid areas, like The Pecos Valley Aquifer (PVA) in the Chihuahuan Desert of west Texas [27]. The PVA receives approximately 50% of yearly recharge, a volume of $55 \times 10^6 \text{ m}^3$ water, from cross flow from the Ogallala, Edward-Trinity Plateau, and Dockum aquifers. [26–28] However, additional recharge area may be afforded by unknown groundwater systems in the extensive dunes and sand sheets on the SHP [29,30].

Tall and extensive dune systems, including ergs, often host extensive aquifers or constitute preferential recharge pathways to unconfined aquifers [29,30]. Unsaturated-flow models dependent on antecedent conditions indicate that up to ~36 % of precipitation on unvegetated sand may directly recharge underlying unconfined aquifers [31,32]. Sand dunes and inter- and extra-dunal sand sheets with sparse vegetation often have relatively high infiltration rates $>250 \text{ mm/hr}$. which can convey water directly to an aquifer, limiting loss from evapotranspiration [1,2,29,31]. For example, the Badain Jaran Desert in China features the tallest dunes on Earth and hosts up to seventy-two groundwater-fed interdunal lakes [30,33–36]. The height, stability, and persistence of this Late Quaternary inland dune field may reflect a progressively rising groundwater table with ample supply and availability of aeolian sand [30]. The source of aquifer recharge for an extensive dune field in the Taklamakan Desert, China, is inferred to be principally from snowmelt infiltration into the dunes [37,38]. Other tall active dunes such as The Great Sand Dunes National Monument, Colorado, USA, near fluvial sand sources, show periodic interdunal wetlands reflecting an elevated water table, recharged mostly by snowmelt seeping through the dunes [39–41]. Also, the Nebraska Sand Hills, USA, a mostly vegetated and stabilized late Quaternary dune system, hosts numerous groundwater and precipitation-fed lakes and rivers and deranged drainages from dune-migration blockage [42–44]. This paleo-erg shows the prominence of an elevated water table, which has dampened response to historic droughts, such as the 1930s Dust Bowl Drought [45,46]. In contrast, aeolian systems in the Saharan, Sinai, and Negev deserts overlay the regional Nubian Sandstone Aquifer and other shallow Quaternary aquifers that are partially unconfined and receive limited recharge by infiltration from runoff and direct precipitation. This extensive aquifer system was apparently recharged during the last glacial period between ca. 14 and 50 ka [47,48].

This study focused on understanding perched hydrologic systems identified in large and active Monahans and Kermit dune fields situated between the Pecos River and the High Plains escarpment in the northern Chihuahuan Desert (Figure 1). A high groundwater table and the extension of the capillary fringe zone in major dune fields act as an agent for cohesion of aeolian strata, which contributes to dune field stability, height and may aid resistance to subsequent aeolian erosion [30,49]. Available evidence indicates that perched aquifers exist for large dune fields, such as the Monahans and Kermit, and possibly other aeolian systems and ergs across the SHP and the Chihuahuan Desert, with the Monahans system preserving surprisingly old sediments, >550 ka [50]. Oxygen-18 and deuterium isotopes ratios were determined on groundwater from the Monahans and Kermit dune fields, the Pecos Valley Aquifer, local rainfall, and the nearby Pecos River to infer flux and water source. The ^{14}C activity of dissolved inorganic carbon (DIC) was determined from groundwater for Kermit and Monahans dune fields and was integrated with prior data sets for SHP [51–53] to infer the potential flow direction of groundwater and eventual mixing with the Pecos Valley Aquifer (PVA).

1.1. Hydrogeologic Setting

The towns of Monahans and Kermit, TX, within 15 km of the associated dune fields, have mean annual temperature (MAT) between 1959 and 2023 $\sim 18^\circ\text{C}$, with winter and summer means of 28°C and 8.5°C , respectively [4]. Of note is that the MAT has increased by about 2°C between 1959 and 2023 (Figure 2). The mean annual precipitation (MAP) is ~ 300 mm with average annual potential evapotranspiration (ET_o) of ~ 1800 mm between 1972 – 2024 for the nearby town of Midland [3], and modeled evapotranspiration from Open ET [54] ~ 350 mm between 2016–2023 on the Kermit and Monahans dune fields. About 70% of precipitation is delivered with thunderstorms between May and October and often coincident with peak temperatures in July and August (Figure 2). The MAP has increased by 30% between 1959 and 1980 and subsequently decreased by 7% between 1980 and 2022 (Figure 2). This increase in MAT and decrease in MAP in the past 40 years is consistent with aridification trends on the SHP [5,7].

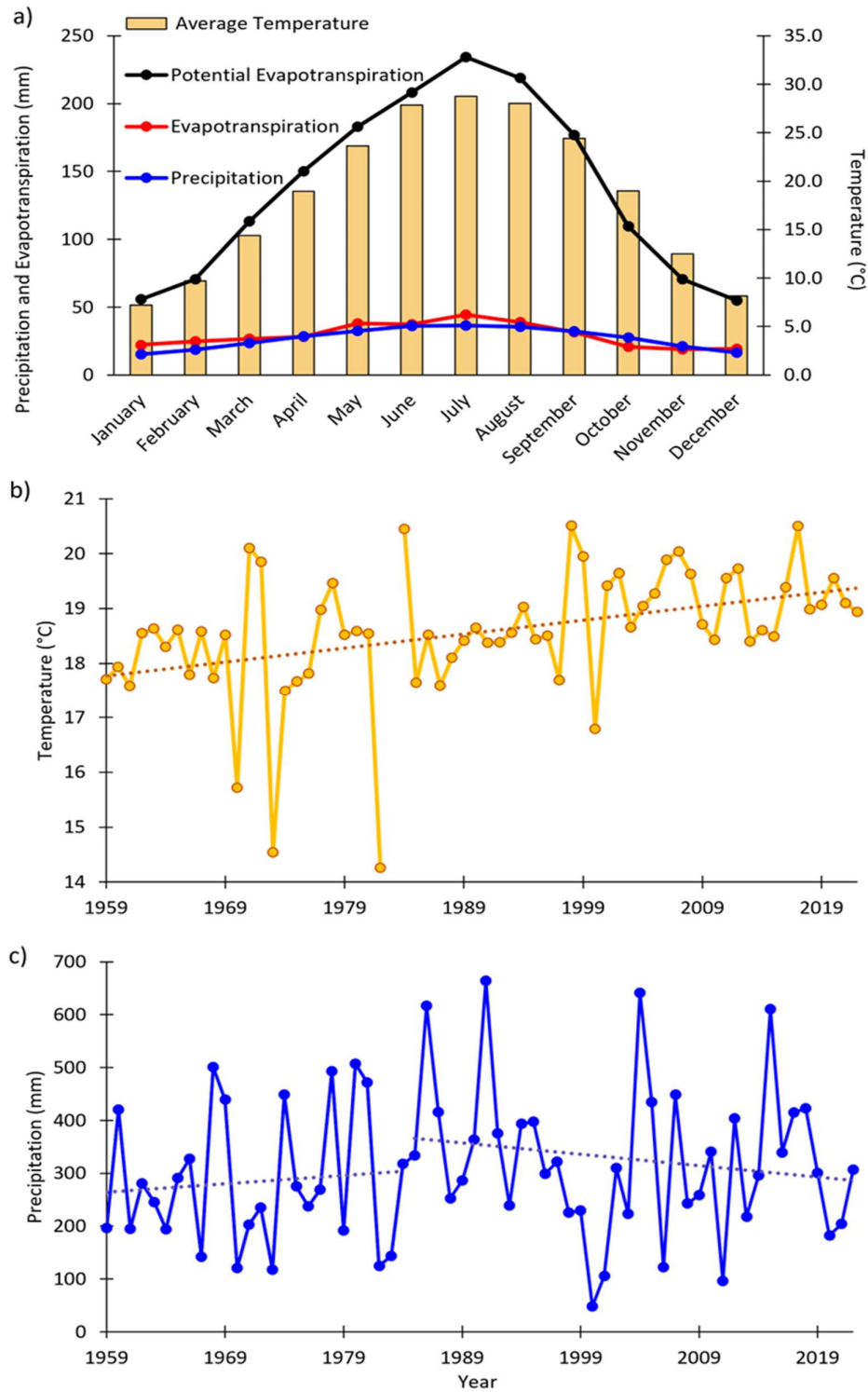


Figure 2. a) Average monthly temperatures and precipitation recorded by weather stations USC00415999, USW00003047, and USC00414775 in Monahans and Kermit, TX, over the period 1959-2022 [4], 52-year average potential evapotranspiration calculated for the town of Midland, TX [3], and modeled evapotranspiration for 2016-2023 [54]. b) Evolution of the mean annual temperature (MAT) in Kermit and Monahans for the period 1959-2022 [4]. c) Evolution of the mean annual precipitation (MAP) in Kermit and Monahans for the period 1959-2022 [4].

Multiple coring and boring campaigns across the Monahans and Kermit dune fields revealed a shallow water table <1 to 10 m from the surface. On occasion, the water table coincides with the surface in interdunal areas, creating ephemeral ponds. One pond in the Monahans State Park persisted for several years in the 1980s [20,55–57].

The Pecos Valley Aquifer (PVA) is a regional groundwater resource found approximately 30 m below the Monahans and Kermit dune fields and the adjacent sand sheet area [20,57,58]. This aquifer occurs within Cenozoic-age alluvium that infills two main subsurface basins, the Pecos and the Monument Draw troughs [27]. The PVA is wholly unconfined with an inferred area of 17,700 km², a maximum thickness of 460 m in the Pecos Trough, and a mean saturated thickness of 137 m [28]. The static water level ranges between 4 and 110 m for the aquifer's southeastern part and at the Pecos Trough center, respectively. Thus, there appears to be a stratigraphic separation between the PVA and the identified perched ground water systems in the Monahans and Kermit dune fields (Figure 3), the topic of this paper.

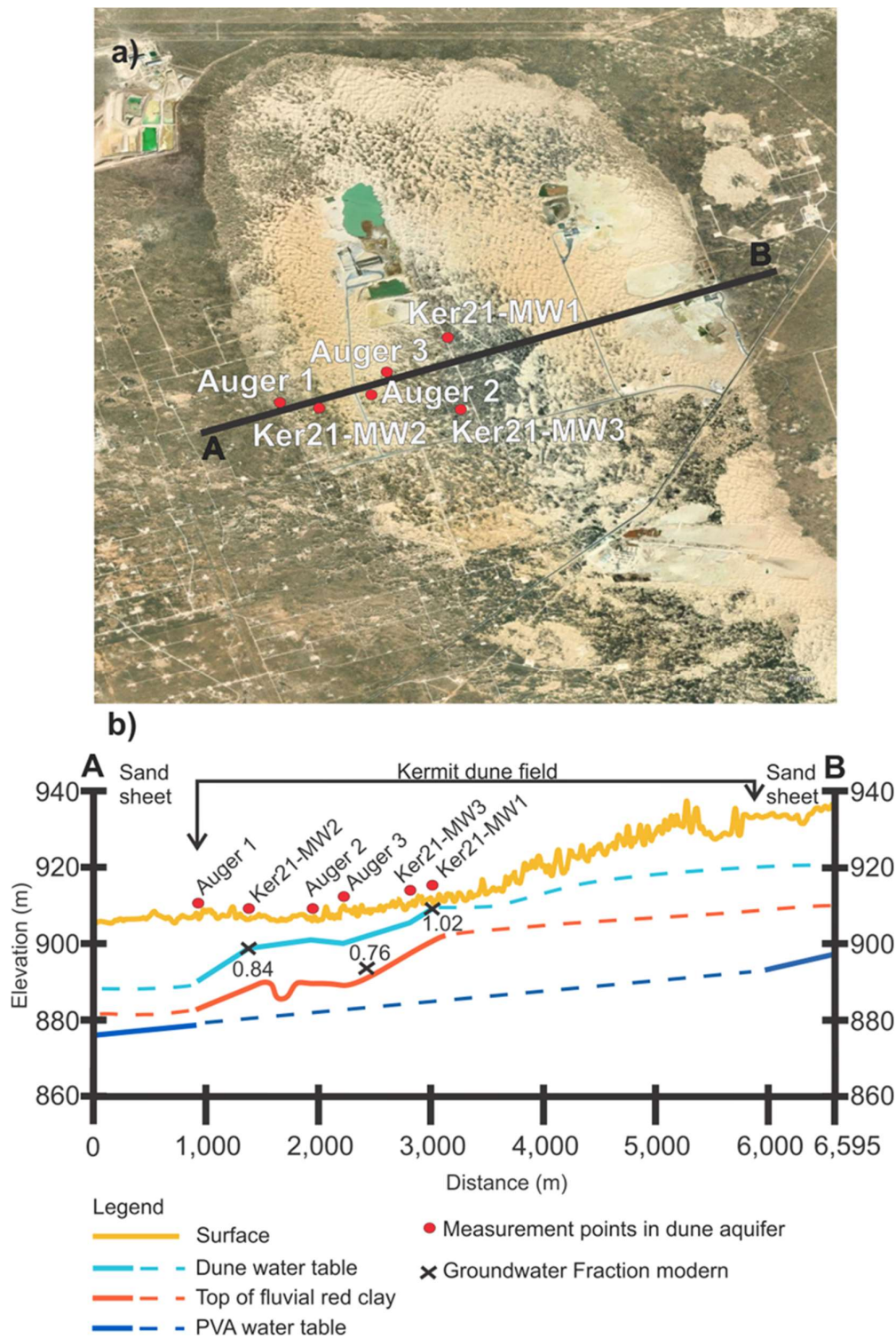


Figure 3. a) Location of the cross-section AB in Kermit dune field with points of water table measurement. b) For cross-section AB: elevation profile from The National Map – USGS 1/9 arc-second DEM (yellow), dune field water table elevation profile (light blue), red fluvial clay aquitard elevation profile (red), PVA water table elevation profile (dark blue), and dunes groundwater Fraction moderns (black cross). Solid lines indicate physical measurements from LiDAR, auger and monitoring wells, borings, and Texas Water Development Board (twdb.texas.gov) well records respectively. Dashed lines represent hypothetical continuations of the elevation profiles.

1.2. Geomorphic and Stratigraphic Context

The Kermit and Monahans dune fields are tall, active dune fields, rising 15 to 20 m above the surrounding sand sheet (TessaDEM 2023), limited to the east by the High Plains escarpment [59–61]. These high dune fields show barchanoid ridges and reverse dunes, interdunal sand sheets and numerous active blow outs. Lower and central areas of the dune fields show dense vegetation cover of shrubs and grasses, that is being buried by contemporary aeolian activity. Most dune crests lack vegetation cover and actively migrate when wind speeds exceed threshold velocities of > 6 to 10 m/s [62].

Recent sediment core-based studies and stratigraphic modeling for the Monahans dune field defined the geometry for three major aeolian chronostratigraphic units (Figure 4; Table S2) [50,63,64], intercalated with at least six buried soils, and assumed to be broadly correlative with the Blackwater Draw Formation or time equivalents, such as the Mescalero Sands in New Mexico [50,65,66]. The lowest-most unit, underlying the aeolian sand in the Monahans and Kermit dune fields, is an alluvial red gravelly clay unit, with an inferred basal age of early Pleistocene/Pliocene that reflects fluvial activity and pedogenesis prior to dune field formation [50,67]. This basal red clay unit, identified at depths below the Monahans and Kermit dune fields and in the nearby sand sheet area, slopes northeast to southwest with 5 to 15 m deep oval sinkhole-like features [50,67,68]. Geophysical surveys of the Monahans dune field indicate a thickness of 10-15 m for this basal red clay unit [68].

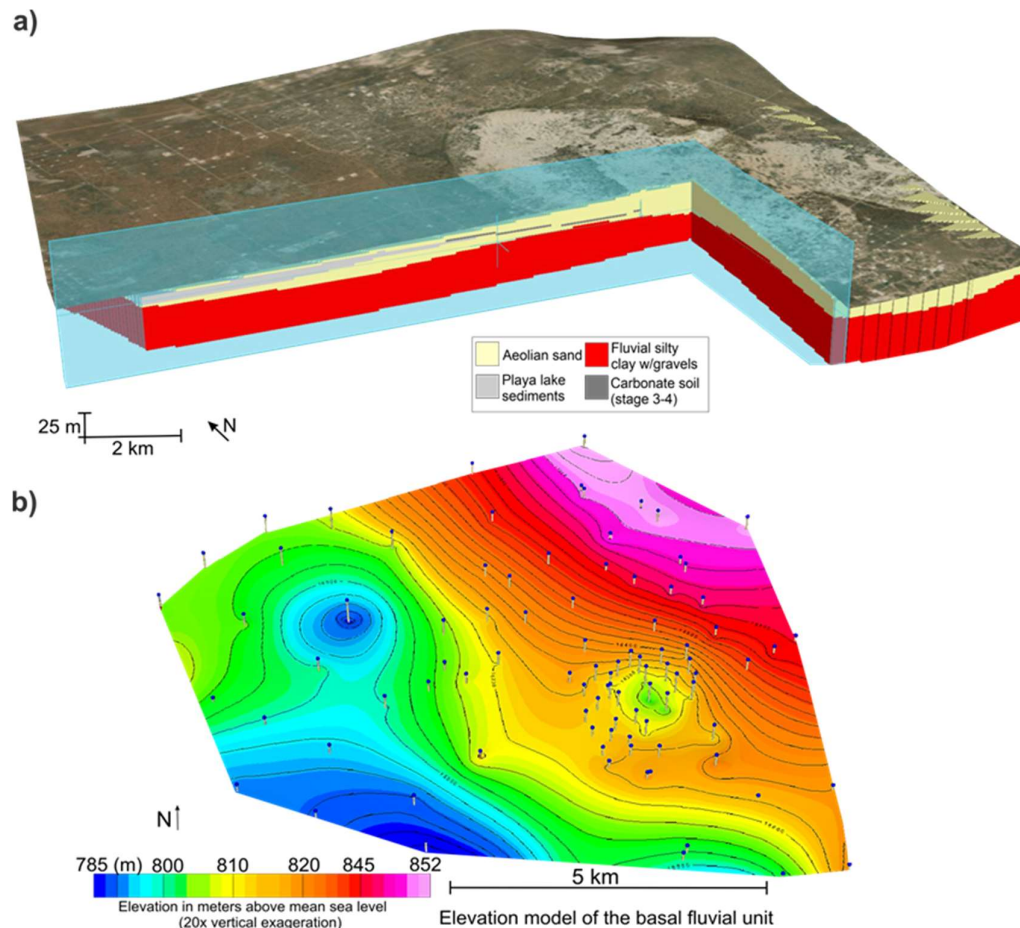


Figure 4. a) 3D model of the internal stratigraphy of the Monahans dune field with cross-section views, and b) elevation model of the basal clay unit with contours in meters above sea level [63].

Aeolian sand deposits, intercalated with at least two paleosols, infilled sinkhole-like features within the basal red clay and buried this older surface by up to 30 m of aeolian sand. The greatest thickness of this aeolian sand coincides with the 5 to 15 m deep sinkhole like features [67]. This

complex aeolian unit has an inferred basal age of early Pleistocene, ca. 2 to 1 ma, and an upper boundary within late MOIS Stage 5, at ca. 100 to 75 ka, the latter assessment based on OSL ages [50]. The upper limit of this aeolian complex is well demarcated by a singular or composite paleosol with stage 3 to 4 carbonate morphologies and/or argillic horizons and may be wholly or partially correlative with the Mescalero Paleosol in adjacent New Mexico [69]. Overlying this paleosol is the youngest aeolian sand deposit with a basal age of 65 to 50 ka and includes recent late Holocene aeolian sand deposits at the surface [50]. The basal boundary of the third unit, a medium to fine aeolian sand, is at the paleosol complex, and spans from ca. 65 ka to contemporary aeolian activity [50].

Quaternary paleoclimatic studies indicate that the wettest conditions in the southwestern U.S. has been associated with the southward expansion of the Laurentide ice sheet steering storm-tracks across the southwestern USA bringing cooler temperatures, reduced evapotranspiration and an increase in winter precipitation [50,70–72]. Case-in-point, a period of limited aeolian sand deposition with pronounced pedogenesis in the Monahans dune field occurred ca. 26 to 12 ka, contemporaneous with high stands of the nearby Pleistocene Lake King [62,67,70]. Other potential pluvial episodes between ca. 350 and 195 ka adjacent to the Monahans dune field were identified by crayfish burrows, stromatolites, and mud cracks, and indicate hydrologic excess during an extended (> 20 ka) interglacial period, such as marine oxygen isotope stage (MOIS) 7 [50,73]. Recent climate modeling of warmest conditions during the last interglacial ca. 135 to 125 ka indicates a precipitation dipole with drier states in Arizona, and wetter conditions in West Texas and adjacent areas in New Mexico associated with an increased flux of low-level moisture from the Gulf of Mexico [74]. Thus, the wettest intervals in West Texas spanning ca. 10 to 30 ka appeared to have occurred during glacial periods. However, wetter climates may have prevailed for ca. 5 to 10 ka intervals during the warmest interglacial conditions in MOIS 5, 7, 9 and 11, with an inferred strengthening of the summer monsoon, enhanced by evaporative sources from the Gulf of Mexico [50,74–76].

2. Materials and Methods

2.1. Stratigraphic Modeling of the Kermit Dune Field and Estimation of Recharge Contribution to the PVA

The stratigraphic architecture of the Kermit dune field was determined from data for eighty-two sonic boreholes drilled in 2017, 2018, and 2021 (Figure 1). Most of these boreholes penetrated through the aeolian sand sequence into the basal, red gravelly-clay. The lithology of sediments retrieved by sonic drilling was continuously logged, and one author (A.F.) observed and logged sediments during active retrieval of borings in 2021. The lithologic data was separated into three units: basal alluvial clay with gravel, carbonate and clay-rich pedogenic complex, and fine to medium aeolian sands (Figure 5). The drillers also recorded the depth to water table, which is the basis for depth inferences for the unsaturated layer, saturated layer, and the basal red clay aquitard (Table S1). Geoprobe cores from the Monahans [50,64] and the Kermit dune field from this study confirm the upper lithostratigraphic units including aeolian sands and carbonate-rich pedogenic complex (Figures 4 and 5).

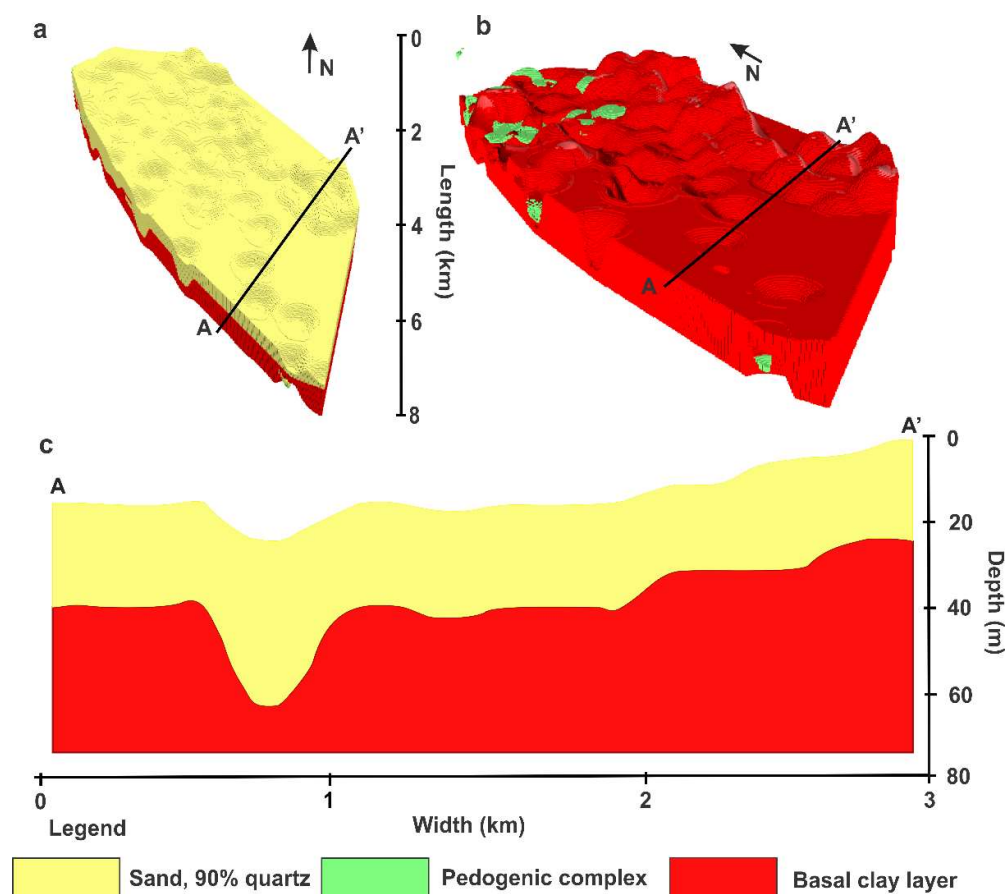


Figure 3. a) Bird view of the 3D model of the Kermit dune field, showing sand infilling on the basal red clay unit. b) Bird view of the basal red clay and pedogenic complexes below the eolian sand infill in the Kermit dune field. c) Cross-section A-A' across the Kermit dune field.

The lithostratigraphic and hydrologic data from borings and Geoprobe cores for the Kermit dune field is the basis for calculating isosurfaces and voxel-based 3D block models using Geosoft Target software (Figures 5 and 6; Version 2021.2.1 <https://www.sequent.com/products-solutions/geosoft-target/>). Boreholes were georeferenced with depths determined to major composite unit contacts and boundaries, including the depth to the aeolian sand base, to the interstratified rubified, carbonate-dominated, paleosol complexes with a thickness exceeding 1 m, and to the subjacent basal red-clay alluvial deposit. Isosurfaces were produced for each unit boundary applying a minimum curvature model to interpolate amongst boreholes. A 3D visualization of the subsurface was modeled by populating the model area amongst isosurfaces with 4 m³ voxel resolution for over 65% of the Kermit dune field (Figures 5 and 6). Smaller voxels can yield finer resolutions, however, the use of voxels < 1 m³ exceeds the sampling density of the minimum curvature method and may return anomalous stratigraphic associations. The distribution and density of borehole data for the Kermit dune field (Figure 1) yields a higher resolution architectural model compared to the Monahans dune field (Figure 4).

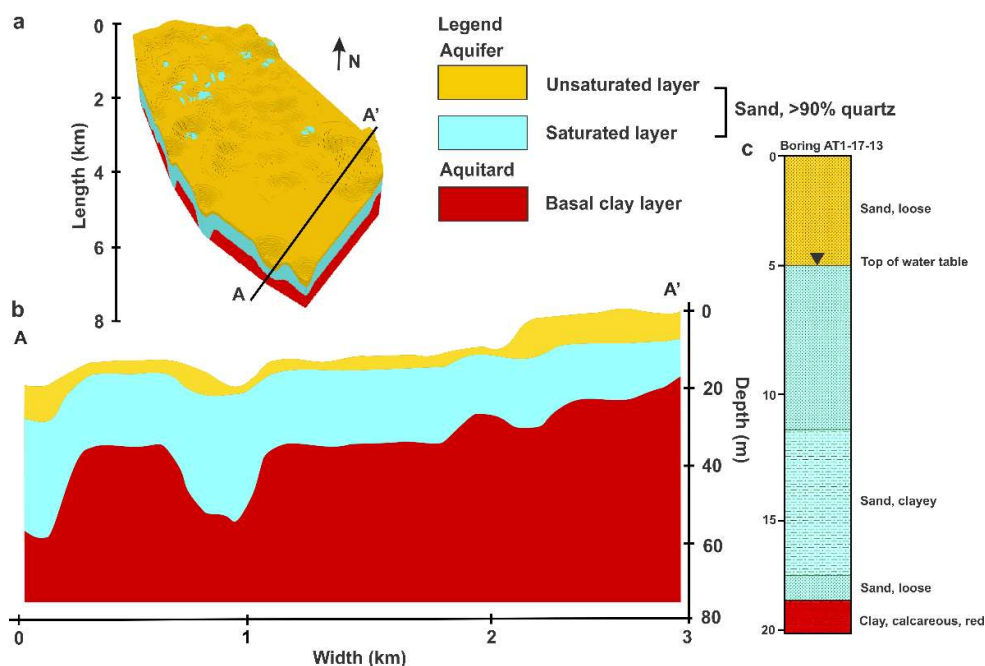


Figure 4. a) Top view of the 3D model of Kermit dune field. b) Cross-section of the Kermit dune field, with three layers: the top unsaturated layer, the saturated layer or aquifer, and the basal clay aquitard. c) Example of borehole log AT1-17-13 used to create the 3D model.

The recharge contribution of the Kermit and Monahans dunal aquifers to the Pecos Valley Aquifer (PVA) was evaluated according to the soil water balance method [76] annually between 2021 and 2023:

$$R_i = P - E_o + \Delta W - R_o,$$

Where,

R_i = recharge in the Pecos Valley Aquifer

P = precipitation on the Kermit dune field [4]

E_o = actual evapotranspiration on the Kermit dune field, from Open ET [54]

ΔW = change in soil water storage, here it corresponds to the annual water level change measured in monitoring wells 2 and 3 on the Kermit dune field [77]

R_o = run – off. On the Kermit dune field, run-off is considered null.

The resulting recharge from the Kermit dune field to the PVA R_i is compared to the estimated total annual recharge in the PVA, 0.112 km^3 [27,28]. Water pumping from local mines is not publicly accessible, therefore it is assumed to be negligible for the purpose of this study.

2.2. Chronostratigraphy of Aeolian Sands by Optically Stimulated Luminescence (OSL) Dating

Three Geoprobe cores of sediment, Ker21-2, Ker21-5, and Ker21-7 (Figure 7), from monitoring well locations 1, 2, and 3, were retrieved from the Kermit dune field. These cores were logged for sedimentologic and pedologic details, including Munsell colors to discern lithologic units. In turn, the cores were analyzed for granulometry by a Malvern Mastersizer 3000 (Figure 7). Age of lithologic units are provided by optically stimulated luminescence (OSL) dating using single aliquot regeneration (SAR) and thermal transfer (TT) protocols on quartz grains size $150\text{-}250 \mu\text{m}$, following analytical approaches of Forman et al. [50].

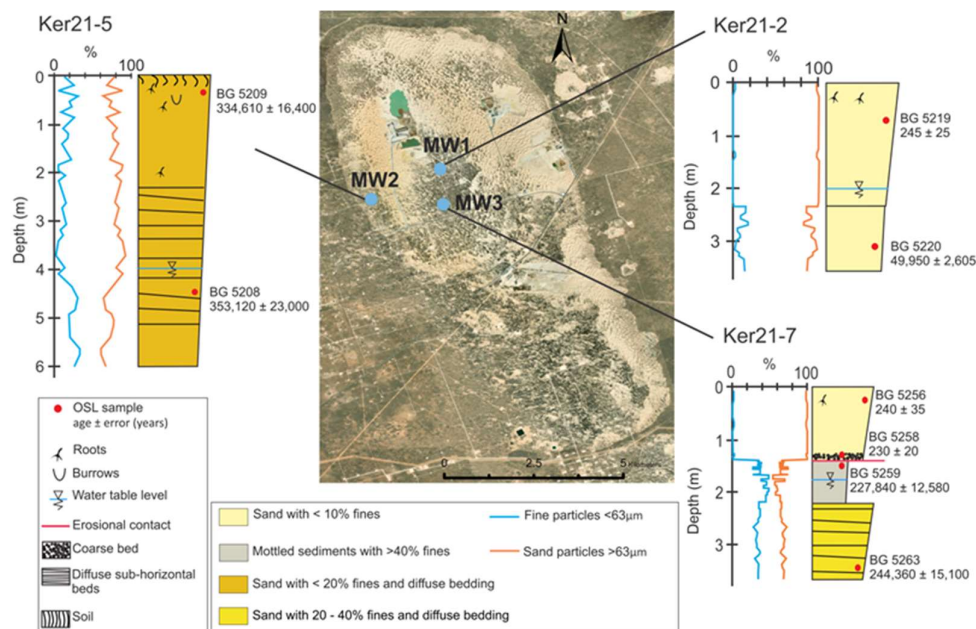


Figure 5. Location of the cores Ker21-2, Ker21-5, and Ker21-7 on the Kermit dune field, with lithostratigraphic columns, particle size profiles, water table depth, and OSL ages. The core sites were used to install monitoring wells 1, 2 and 3 (MW#).

2.3. Deuterium and Oxygen Isotopic Analysis of Ground and Surface Waters

The deuterium ($2\text{H}/1\text{H}$) and oxygen ($^{18}\text{O}/^{16}\text{O}$) isotopic ratios were determined for forty-three water samples at the Stable Isotope Laboratory, Baylor University. Specifically, multiple water samples were taken from three monitoring wells in the Kermit dune field, thirteen water production wells associated with proppant mining at Atlas Energy Solutions' Kermit and Monahans facilities, three local rainwater events, two public-use wells in the nearby towns of Monahans and Wink, TX, and the Pecos River near Grandfalls, Mentone, and Pecos, TX (Figure 1). Samples were collected carefully into 10 mL vials with the vials filled after triplicate overflow and sealed with no air gap. The vials were kept in an ice chest prior to analyses to avoid evaporation. The resultant δD vs $\delta^{18}\text{O}$ isotopic ratios for aquifers associated with Kermit and Monahans dune fields were compared to the global meteoritic water line [78–80], and pre-existing isotopic data for the Pecos Valley Aquifer [53], the Pecos River [52], and the Chihuahuah Desert [51], to investigate the potential sources of water, mixing and derivations (Table S3).

2.4. Determining Radiocarbon Activity of Groundwater

Three water samples from the Kermit dune field and one from the Monahans dune field (Figure 1) were analyzed for radiocarbon activity or Fraction modern (Fm) on dissolved inorganic carbon (DIC) at the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility at the Woods Hole Oceanographic Institution (WHOI), MA. Samples were collected in 1 L Nalgene bottles, filled after triplicate overflow, sealed with no air gap, and stored in an ice chest. The spatial variation of apparent DIC ^{14}C activity for the Kermit and Monahans dune field was compared to previously acquired ^{14}C DIC for the Pecos Valley Aquifer [53] to evaluate spatial variations in ^{14}C DIC activity and infer recharge and flow patterns. Older sources of DIC (> 100 ka old) within the stratigraphy of these dune fields such as CaCO_3 -bearing playa lake sediments and paleosols [50,77] may exchange with groundwater and artificially increase the apparent ages [81].

3. Results

Most borehole logs record the depth to the water table in the Kermit dune field, which is the basis for a simplified 3D-model of the saturated zone with an area of ~23 km² (Figure 6). The top of the saturated zone appears to be broadly subparallel with the basal red clay aquitard, and groundwater flows apparently from northeast to southwest with a gradient of 8 m/km, which increases toward the steep, western edge of the dune field. The saturated zone for model calculation for this study occurs in a relatively homogeneous well-sorted medium to fine sand with a porosity of ~30 % [29]. The total estimated volume of the saturated layer for the Kermit dune field is ~0.22 km³ derived from this model. The groundwater estimated volume of the Kermit and Monahans dune fields is 0.13 km³ and 0.19 km³ respectively, derived from the simplified model representation of the stratigraphy and groundwater table.

Sediment core, Ker21-7, from monitoring well 3 site contains a discontinuous but significant record on past variability in environmental conditions (Figure 7, Table 1). A conspicuous 1 m-thick grey, mottled older sandy loam deposit, containing >30% fines, with a bounding TT-OSL age of ca. 227 ± 12.6 ka (BG5259), occurs at 1.33 m depth in this core and is interpreted as an ephemeral interdunal lake deposit. The OSL age for this inferred interdunal sediments in the Kermit dune field is correlative to a pluvial lake interval documented at the margin of the Monahans dune field bounded by TT-OSL ages of 233 ± 14.5 ka (BG4765TT) and 196 ± 10.9 ka (BG4761TT) [50]. The lacustrine sediments in the Kermit dune field were eroded and truncated by emplacement of near surface well-sorted aeolian sand, with < 5% fines and quartz grains yielded an OSL age of 230 ± 20 yr. (BG5258).

Table 1. Single Aliquot Regeneration (SAR) and thermal transfer (TT-OSL) optically-stimulated luminescence ages on quartz grains from aeolian sediments from the Kermit dune field, west Texas.

Field number/ Depth (m)	BG Lab number	Aliquo ts ^b	Gra in size (μm)	Equival Dose (De) (Gv) ^c	Over- dispersi on (%) ^d	U (ppm) ^e	Th (ppm) ^e	K ₂ O (%) ^e	Rb (ppm) ^e	H ₂ 0 (%) ^e	Cosmic Dose rate (mGray/ yr) ^f	Dose Rate (mGray/ yr)	SAR- or TT (t)
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													OSL age (yr) ^g
KER 21- 2A/0.69	5219	29/40	150- 250	0.11 ± 0.01	90 ± 12	0.29 ± 0.01	0.82 ± 0.01	0.14 ± 0.01	5.3 ±5 ± 0.1 2	0.212 ± 0.021	0.44 ± 0.02	245 ± 25	
KER 21- 2C/3.10	5220	56/59	150- 250	26.65 ± 0.92	22 ± 2	0.72 ± 0.01	1.37 ± 0.01	0.27 ± 0.01	10.2 30 ± 0.1± 3	0.176 ± 0.018	0.53 ± 0.02	49,95 0 ± 2605	
KER21- 5A/0.30	5209TT	20/20	150- 250	177.31 ± 10.56	25 ± 4	0.43 ± 0.01	2.15 ± 0.01	0.32 ± 0.01	14.8 5 ± ± 0.1 2	0.274 ± 0.027	0.76 ± 0.03	334,6 10 ± 16,40 0 ^h	
KER21- 5D/4.40	5208TT ^a	18/20	150- 250	233.69 ± 11.88	19 ± 3	0.58 ± 0.01	2.43 ± 0.01	0.47 ± 0.01	19.8 30 ± 0.1± 3	0.154 ± 0.016	0.66 ± 0.03	353,1 20 ± 23,00 0 ^h	
KER21- 7A/0.43	5266	27/35	150- 250	0.11 ± 0.02	67 ± 10	0.46 ± 0.01	0.78 ± 0.01	0.02 ± 0.01	0.8 ±5 ± 0.1 2	0.261 ± 0.026	0.43 ± 0.03	240 ± 35	
KER21- 7A/1.03	5257	33/40	150- 250	0.12 ± 0.02	79 ± 10	0.33 ± 0.01	0.68 ± 0.01	0.15 ± 0.01	5.7 ±5 ± 0.1 2	0.219 ± 0.022	0.45 ± 0.02	245 ± 40	
KER21- 7B/1.30	5258	29/35	150- 250	0.10 ± 0.01	64 ± 9	0.33 ± 0.01	0.76 ± 0.01	0.13 ± 0.01	5.2 ±7 ± 0.1 2	0.214 ± 0.021	0.43 ± 0.02	230 ± 20	
KER21- 7B/1.33	5259TT ^a	18/20	150- 250	183.19 ± 8.05	16 ± 3	0.44 ± 0.01	2.06 ± 0.01	0.48 ± 0.01	17.6 7 ± ± 0.1 2	0.213 ± 0.021	0.80 ± 0.03	227,8 40 ± 12,58 0 ^h	
KER21- 7C/3.54	5263TT ^a	20/20	150- 250	142.90 ± 7.10	20 ± 3	0.43 ± 0.01	2.21 ± 0.01	0.38 ± 0.01	17.1 30 ± 0.1± 3	0.168 ± 0.017	0.58 ± 0.02	244,3 60 ± 15,10 0 ^h	

^a Equivalent dose determined by thermal transfer protocols on quartz grains as outlined in Forman et al. [50]. ^b Aliquots measured and used to define De population by Central Age or Minimum Age Model [85]. ^c Equivalent dose calculated on a pure quartz fraction with ultra-small aliquots with 20-80 grains/aliquot and analyzed under blue-light excitation (470 ± 20 nm) by Single Aliquot Regeneration protocols (SAR) [86,87]. Equivalent dose (De) was calculated by the Central Age or Minimum Age model when overdispersion values are < 20% (at two sigma) and > 20% (at two sigma) and assuming a normal data distribution [85,88]. ^d Overdispersion values reflects precision beyond instrumental errors; values of ≤ 20% (at 1 sigma limit) indicate low dispersion in equivalent dose values and defines a unimodal distribution. Values > 20% are associated with mixed equivalent dose signature reflecting multiple grain populations or partial solar resetting. ^e U, Th, Rb and K content analyzed by inductively coupled plasma-mass spectrometry by ALS Laboratories, Reno, NV. ^f Includes a cosmic dose rate calculated from parameters in Prescott and Hutton [89] and includes soft components [88]. ^g Systematic and random errors calculated in a quadrature at one standard deviation by the Luminescence Dating and Age Calculator (LDAC) at <https://www.baylor.edu/geosciences/index.php?id=962356> [88]. Datum year is AD 2010. ^h OSL Ages determined on quart grains by TT-OSL protocols [50]. OSL ages determined at Geoluminescence Dating Research Laboratory, Dept. of Geosciences, Baylor University, Waco, TX, USA.

Sediment core, Ker21-5, at monitoring well 2 site, is close to the western edge of the dune field, with the water table 4 m from the surface (Figure 7). This core contains homogeneous sandy sediments with <20 % fines and yielded TT-OSL ages of 334 ± 16.4 ka (BG5209) and 353 ± 23 ka (BG5208); a similar age, 347 ± 21 ka (BG4760) was reported for one aeolian unit in the Monahans dune field [50]. These older sediments are unearthed near the sloping western edge of Kermit dune field and may indicate net surface erosion.

3.3. Deuterium and Oxygen Isotopic Signature of the Kermit and Monahans Dune Field Aquifers

The deuterium (δD) and oxygen ($\delta^{18}O$) isotopic ratios of the PVA, the Pecos River, the Chihuahuan Desert and local precipitation reflect the dominance of evaporation processes in this hot semiarid environment [51–53,78,90]. The δD (-33.50 to -38.24 ‰), and $\delta^{18}O$ (-4.07 to -5.85 ‰) ratios for ground water from the Kermit and Monahans dune fields yield similar values with considerably less variability than other isotopic data sets from the Chihuahuan Desert (Figure 8). These isotopic ratios for groundwater from the Monahans and Kermit dune fields show a surprising similarity potentially reflecting a common water source, consistent aeolian sedimentary architectural context, with the water table perched above the Pleistocene/Pliocene basal red clay aquitard.

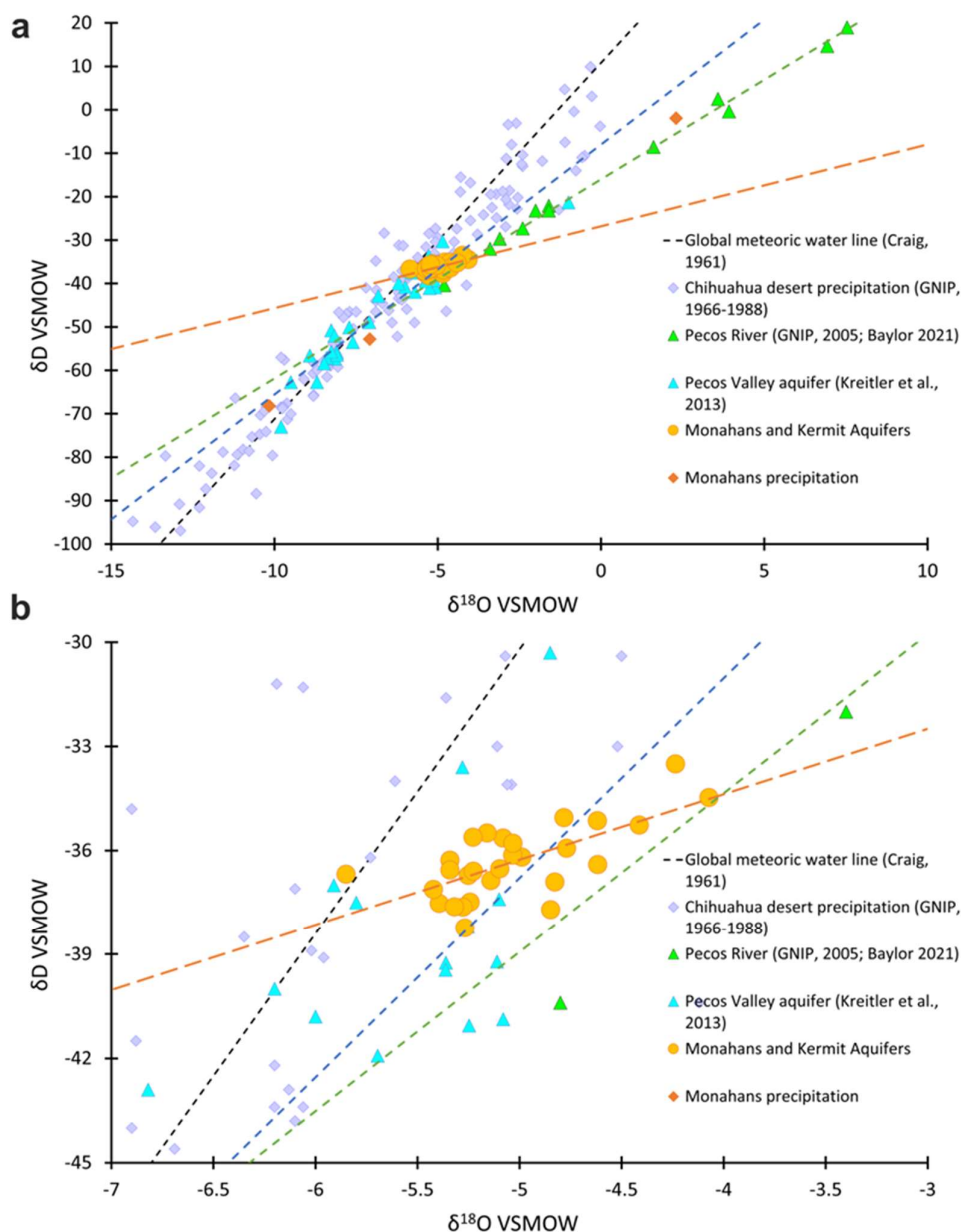


Figure 6. a) δD and $\delta^{18}O$ isotopic ratios for the Kermit and Monahans dune fields, compared to local precipitation, groundwater from the Pecos Valley Aquifer [53], the Pecos River [52], Chihuahuan Desert precipitation [51] and the Global Meteoric Water Line [78]. B) Close-up on the Kermit and Monahans dune field's data points.

The δD and $\delta^{18}O$ values for Chihuahuan Desert precipitation [51] display substantial variability with no apparent seasonal trend similar to isotopic values for precipitation events in proximity to the

Monahans and Kermit dune fields (Figure 9, Table S3). The PVA shows a range of δD and $\delta^{18}O$ values from -73 to -21.30 ‰ and from -9.80 to -1 ‰ respectively. However, these isotopic values for the PVA are more negative than local precipitation, suggesting limited recharge from modern precipitation [53]. The δD and $\delta^{18}O$ values for the Pecos River are enriched with distance from the headwaters in the Sangre de Cristo Mountains, NM, reflecting a snowmelt source or, an abundance of elevational recycled moisture [52]. In contrast, the Pecos River water near Pecos, TX, shows enriched, evaporation-influenced δD and $\delta^{18}O$ values, with up to 33% of stream volume lost through evaporation [52].

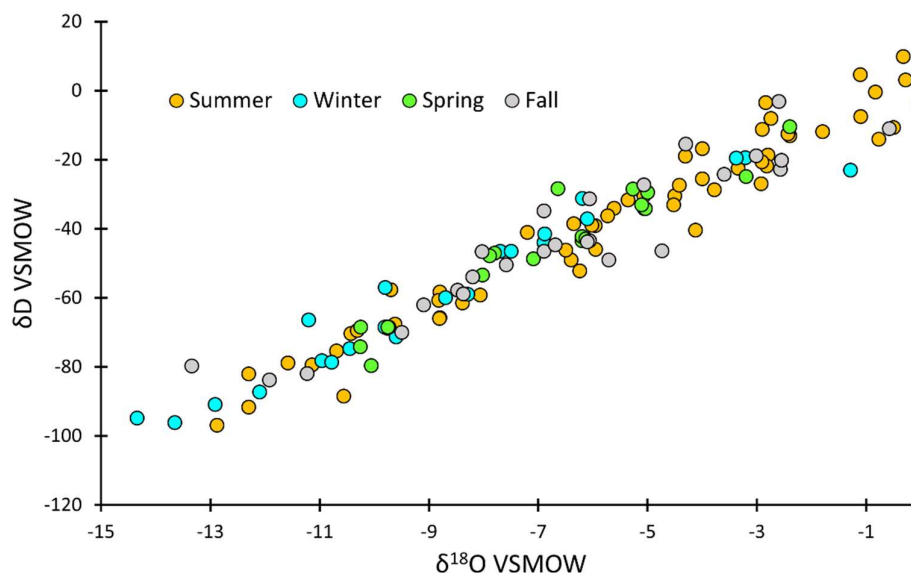


Figure 7. δD and $\delta^{18}O$ isotopic ratios for the Chihuahua Desert precipitation measured in a single station in the city of Chihuahua, Mexico, between June 1962 and November 1988 [51]. The data is color coded per season: summer (yellow), fall (grey), winter (blue), and spring (green).

3.4. Radiocarbon Variations of Groundwater

The radiocarbon assays for groundwater are expressed as Fraction modern (F_m) (Figure 10, Table 2), a measure of ^{14}C activity in the water sample relative to activity of ^{14}C in 1950 atmospheric CO_2 [91]. F_m may be related to potential water sources with low $F_m < 0.02$, close to ^{14}C measurement limit of about 40 to 50 ka reflecting isolation from atmospheric sources, and high $F_m > 0.95$ reflecting ages closer to the radiocarbon datum year of ca. 1950 [92–94]. The PVA yields F_m of 0.01 to 0.89, with the lowest values in the Pecos Trough and highest values in the Monument Draw Trough. Furthermore, ^{14}C F_m in the north and east of the Monument Draw Trough appear to gradually increase towards the Pecos River [53].

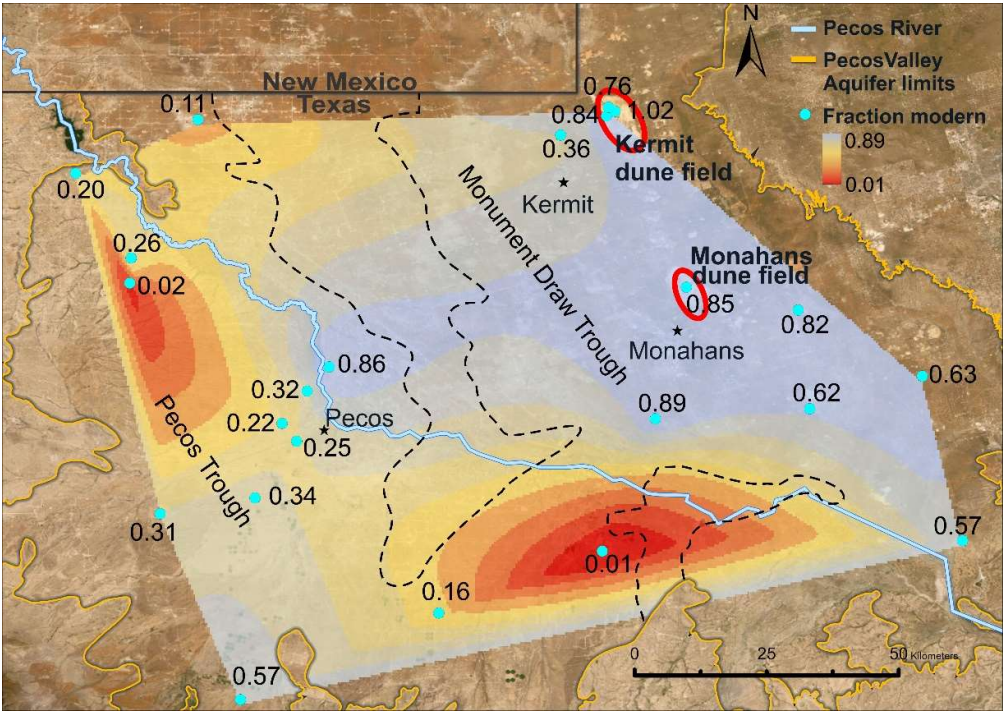


Figure 8. ¹⁴C Fraction modern measured in MW1, MW2, a production well in Kermit dune field, and a production well in Monahans dune field, integrated with data from Kreitler et al. [53].

Table 2. Fraction Modern and associated ¹⁴C age (calendar) for four samples from the Monahans and Kermit dune fields aquifers.

Sample ID	Latitude	Longitude	Fraction Modern	¹⁴ C age (ca.)	Date
Ker21-MW1	31.960283	-103.001811	1.0234	2017	6/16/2022
Ker21-MW2	31.951562	-103.016855	0.8440	-1360	10/13/2022
Monahans pump well	31.661111	-102.875556	0.8531	-1280	10/13/2022
Kermit pump well	31.967375	-103.010178	0.7605	-2200	10/13/2022

The Fm of groundwater from the Monahans and Kermit dune fields indicates recharge from contemporary water sources and the incorporation of older carbon with transit through the dune field aquifer, most likely from dissolution of CaCO₃ dominated paleo-playa lake sediments and buried soils (Figure 7) [50]. Groundwater samples from Kermit and Monahans dune fields yielded ¹⁴C Fm of 0.76 – 1.0, similar to nearby PVA Fm values (0.89-0.82). The lowest Fm values (0.84-0.76) were from monitoring well 3, near the western descending slope of the Kermit dune field, and a water well pumping ~25 m deep in the center of the dune field. In contrast, the highest Fm value (1.02) for groundwater derived from the topographically higher Kermit dune field interior where the aquifer is shallower (1-2 m deep), reflecting primarily meteoric sources (Figure 3).

4. Discussion

4.1. Pleistocene – Holocene Dune Field Evolution

This study highlighted the similarities between the Monahans and Kermit dune fields’ internal sedimentary architecture, chronology and water isotopic signature. Both dune fields show a shallow 1 to 10 m deep perched water table above a red gravelly-clay aquitard with sinkhole-like features [77]. The thickest aeolian sands occur in these sinkhole-like features, which shows no surface expression in the present topography [50,77]. The oldest OSL ages on quartz grains of ca. 560 to 540 ka were retrieved from continuous Geoprobe cores on the sand sheet, immediately west of Monahans

dune field [50] and approximately 5 to 10 m above the basal red clay unit [63]. Previously, the deposition of aeolian sand in the Monahans dune field was inferred to commenced ca. 2.6 ma, based on an inferred correlation to the base of the Blackwater Draw Formation [50]. However, the onset of aeolian deposition for the Monahans and Kermit aeolian systems may be linked to changes in flow direction of the Pecos River ca. 2.0 to 0.8 ma ago from northwest to south-southwest after headward fluvial erosion of the Stockton Plateau [66]. Thus, this erosion event may have captured the northerly flowing, a precursor of the modern Pecos River, resulting in a flow direction reversal and eastward avulsion [66], in proximity to current locations of the Monahans and Kermit dune fields. Geochemical analysis indicates that the dune grains may ultimately be derived from fluvial erosion of upper Triassic Chinle Formation and local aeolian reworking of Pleistocene Blackwater Draw Formation [50,60,95].

OSL dating for aeolian sediment cores from the Kermit dune field recognize two aeolian deposition phases (ADP) that coincide with Monahans ADP at ca. 353-334 ka, and 65-30 ka, possibly corresponding to marine oxygen isotope stages (MOIS) 10 and 3-4 during transitions from glacial to interglacial and stadial periods [50]. In contrast, there is compelling evidence of higher-than-modern water static levels for the Monahans and Kermit dune fields, with lacustrine sediments yielding OSL ages of ca. 233 ± 14.5 ka and 196 ± 10.9 ka in the Monahans dune field [50] and ca. 227 ± 12.6 ka in the Kermit dune field. These OSL ages reflect two pluvial episodes corresponding to the onset (240-214 ka) and termination (206-186 ka) of interglacial episode MOIS 7 (186 to 240 ka) [50,96]. Climate models for MOIS 7 indicate a positive water budget with enhanced rainfall in southwestern Texas possibly reflecting increased moisture from the Gulf of Mexico with North American Monsoon precipitation rates estimated at ~ 4 mm/day [96,97]. Pluvial conditions may have prevailed during the warmest intervals of interglacial such as MOIS 5 and possibly 7 [50,74,98]. Wetter conditions also prevailed during the Last Glacial Maximum ca. 25 to 15 ka, with formation of pluvial Lake King in the adjacent Rio Grande catchment [50,70].

OSL ages for near surface sediments in the Kermit dune field indicate recent aeolian activity, 1760 CE, just prior to European settlement. This aeolian activity may correspond with periods of drought in the Trans-Pecos region and the Sangre de Cristo Mountains assessed from tree ring records, and decreased flood frequency in the Mississippi River, around 250 ± 30 years ago [13,99,100]. This upper aeolian deposition phase may be coincident with formation of the coppice and parabolic dune fields of the Mescalero sand sheet at ca. 300 years BP in adjacent New Mexico [69].

4.2. Groundwater Recharge

The Kermit and Monahans dune fields, and possibly other dune systems on the Southern Great Plains, host significant perched aquifers, with volumes > 0.1 km³. Stable isotopic ratios (D/H and $^{18}\text{O}/^{16}\text{O}$) on groundwater indicate recharge of the dune field aquifers from contemporary precipitation, particularly when precipitation exceeds evapotranspiration, such as in 2022. Average precipitation and evapotranspiration for the Kermit dune field in 2022, obtained from OpenET [54], were respectively 307.8 mm and 295.7 mm, thus there may be a small net recharge of 12.1 mm/yr during years with average rainfall. The isotopic signature of water derived from aquifers for Kermit and Monahans dune fields was distinct for water from the PVA and the Pecos River. However, the stable D and ^{18}O isotopic values for dune field groundwater resembles local and Chihuahuan Desert precipitation, though more evaporatively enriched (Figure 8). Precipitation is the only water source to maintain groundwater resources in these dune systems. Water table measurements in the Kermit Dunal Aquifer (KDA) from three monitoring wells and a northeast to southwest transect of auger holes show the top of the water table at 1 to 10 m below the surface [77]. Net groundwater flow is down elevation towards the southwest and subparallel to the basal red gravely clay paleosurface at 30-40 m depth (Figure 3).

The ^{14}C fraction modern (Fm) on dissolved inorganic carbon (DIC) may inform on flow path and mixing within an aquifer [101–105]. In the KDA, groundwater from a shallow central well (Monitoring well 1) yielded a post-1950 Fm (1.02), which indicated exchange(s) with meteoric sources. Whereas groundwater from the western edge of the dune field (Monitoring well 2) yielded

a $\delta^{13}\text{C}$ of 0.84 possibly reflecting additions of older DIC with water flux through the subsurface interacting with buried, older (>100 ka old) playa lake or buried pedogenic carbonate (Figure 7) [50] and less pure meteoric source. This variation in stable isotopes of groundwater may indicate recharge most likely occurs from the enhanced capture of precipitation on central bare active dunes of Kermit dune field where infiltration rates are higher, >250 mm/hr, compared to nearly flat vegetated relief of the adjacent sand sheet [29,31]. The observed vertical gradient in $\delta^{13}\text{C}$ in the KDA, ranges from 1.02 (post-1950) in shallow >1 m deep groundwater to 0.76 at 30 m deep, may reflect local mine pumping enhancing vertical mixing of groundwater of various recharge times and DIC sources.

Interdunal lake sediments yielded OSL ages of ca. 196 ± 10.9 , 227 ± 12.6 , and 233 ± 14.5 ka which indicated the occurrence of significant pluvial conditions for west Texas dune fields during MOIS 7, with ground water levels at least 1 m higher than current conditions. Periods of higher water table during glacials and peak interglacial periods occurred in past ca. 1 to 2 Ma and added to the stability of the dune field through capillary groundwater rise. These wet periods with pluvial lake formation and concurrent soil formation for 10^3 to 10^4 years aid in vertical accretion and stability of the dune field [50]. Conversely, diminution in groundwater levels associated with drier conditions and less vegetation cover increases the availability and supply of sand for transport and redeposition across the dune field, with threshold wind speeds > 6 m/s [62,106–108]. The identification of a common aeolian sand unit that yielded OSL ages of ca. 250 year in cores Ker21-2 and Ker21-7 reflects a contemporary period of active aeolian deposition.

4.3. Potential Connection to the Pecos Valley Aquifer

The Monahans and Kermit Dunal Aquifers (MDA, KDA) appear to be semi-independent groundwater systems that may contribute recharge for the Pecos Valley Aquifer. Despite limited reported recharge from precipitation for the PVA [27], infiltration rates in arid environments are higher on bare sandy soils such as active dunes and playa lakes, that can represent important recharge points to major underlying aquifers like the adjacent Ogallala Aquifer [29,109–112]. Groundwater in the KDA and MDA appears to flow from the NE to SW consistent with the groundwater flow direction in the Monument Draw trough of the PVA [27,53]. Also, $\delta^{13}\text{C}$ values (1.02–0.76) from the KDA and MDA are consistent with eastern most $\delta^{13}\text{C}$ values for the PVA (0.89–0.62), indicating a less evolved $\delta^{13}\text{C}$ source water from these dune fields. A water balance calculation with groundwater monitoring data [77] and evapotranspiration and precipitation data from OpenET [54] indicates that recharge from the KDA to the PVA could be up to 0.01 km^3 per year or 9% of the 0.112 km^3 estimated total annual recharge in the PVA [27,28]. The Monahans dune field may provide similar magnitude recharge.

5. Conclusions

The Kermit and Monahans dune fields rise 10 to 15 m from the surrounding sand sheet environment in far western Texas. The 30 to 40 m thick aeolian strata are at least 550 ka old and are intercalated with up to six paleosols and pluvial lake sediments reflecting hydrologic excess during glacial and peak interglacial conditions, e.g., MOIS 2 and MOIS 7. However, the formation age of these dune systems is unknown with plausible hypotheses as correlative to the Pleistocene (ca. 2.6 ma) Blackwater Draw Formation or with initiation of the southward flow of the Pecos River ca. 2.0 to 0.8 ma [66,113]. These dune fields host significant groundwater resources for this semi-arid environment, with volumes > 0.1 km^3 , which has not been recognized previously. The water table within the dune fields is usually 1 to 10 m below the surface, with rare interdunal lakes and wetlands and with net groundwater flow down elevation towards the southwest and subparallel to a basal, red, gravely clay, aquitard paleosurface. Sinkhole-like features, 5 to 15 m deep at the top of basal red clay, are infilled with the thickest occurrence of aeolian sand but are not reflected at the surface.

The deuterium ($\delta^2\text{H}$) and oxygen ($\delta^{18}\text{O}$) isotopic ratios for groundwater from the Kermit and Monahans dune fields show characteristic isotopic depletion, below the meteoric water line, reflecting the dominance of evaporation, similar to stable isotopes of precipitation from the Chihuahuan Desert [51–53,78,90]. However, groundwater from dunal sources show considerably less

isotopic variability than Chihuahuan Desert rainfall, particularly for deuterium values, which defines a δD to $\delta^{18}O$ function oblique to the meteoric water line (Figure 8).

The ^{14}C fraction modern (Fm) on dissolved inorganic carbon (DIC) for dune derived groundwater yielded insights on sources of water, flux, and potential mixing. Groundwater from a shallow central well in the Kermit dune field yielded contemporary Fm (1.02), which indicated exchange with recent atmospheric ^{14}C sources. However, groundwater from the elevationally lower western edge of the dune field gave a more evolved Fm of 0.84 possibly reflecting DIC from older (>100 ka) carbonate-bearing playa lake deposits and buried soils within the aeolian stratigraphy of these dune fields [50]. Groundwater recharge occurs with the enhanced capture of precipitation on mostly bare, high surface area of active dunes of Kermit dune field where infiltration rates are higher, >250 mm/hr, compared to nearly flat vegetated relief of the adjacent sand sheet [29,31].

The perched aquifers of the Monahans and Kermit dune fields may contribute up to 9% of the total annual recharge to the regionally Pecos Valley Aquifer (PVA). However, recent mining activities [20,57] and increasing aridity since the 1980s [5,6] have led to exposure of the water table and enhanced evaporation, creating a moisture deficit that could reduce recharge and deplete the Kermit and Monahans dunal aquifers. This study highlights the importance of dune field systems as potential contributors to regional groundwater resources, particularly in arid and semi-arid regions. Understanding the recharge dynamics, flow patterns, and climatic controls on these perched aquifer systems is crucial for sustainable water resource management in the face of increasing water demands and climate change.

Supplementary Materials: : The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Table S1: AT1 – Kermit dune field borings – Atlas Sand – June-July 2017, February-March 2019 and September 2021; Table S2: AT2 – Monahans dune field borings – Atlas Sand – June 2017 and March 2018; Table S3: δD and $\delta^{18}O$ isotopic ratios for the Kermit and Monahans dune fields collected from three piezometers in Kermit dune field and thirteen production wells from the Kermit and Monahans Atlas mines, as well as for the Pecos Valley Aquifer from the towns of Wink and Monahans TX, for the Pecos River samples collected between Mentone and Grandfalls TX, and for precipitation in Monahans TX; Table S4: Estimation of the recharge contribution from the Monahans and Kermit dune fields to the Pecos Valley Aquifer.

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Data Availability Statement: The original contributions presented in the study are included in the article or supplementary material, further inquiries can be directed to the corresponding authors. Stable Isotopes (D, ^{18}O) datasets for the Chihuahuan Desert [51] and the Pecos River [52] are publicly available through the International Atomic Energy Agency (IAEA) – Water Isotope System for Data Analysis, Visualization and Electronic Retrieval (WISER) portal as part of the Global Network of Isotopes in Precipitation (GNIP) and Global Network of Isotopes in Rivers (GNIR): <https://nucleus.iaea.org/wiser>. Stable Isotopes (D, ^{18}O) and Radiocarbon datasets for the Pecos Valley Aquifer [53] are available on demand through the contact form of the Texas Water Development Board: twdb.texas.gov.

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