ESTIMATING THE IMPACTS OF GROUNDWATER PUMPING FOR HYDRAULIC FRACTURING ON FRESH AND BRACKISH WATER AQUIFERS IN THE PERMIAN BASIN OF WEST TEXAS

A Thesis

by

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Submitted to the Graduate and Professional School of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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December 2021

Major Subject: Water Management and Hydrological Science

ABSTRACT

This study evaluates the impacts of recent groundwater pumping for hydraulic fracturing (HF) on: 1) hydraulic heads; 2) gross water volumes going into and out of storage; and 3) gross water fluxes within and between the Dockum and lower Ogallala aquifers underneath the focus area in the Permian Basin, in west Texas. The focus area of the study is the properties of University Lands (UL). These impacts were first calculated for the past 9 years (2012-2020), and then forecasted for the next 30 years (2021-2050) utilizing a Groundwater Availability Model (GAM) developed by the Texas Water Development Board for the lower Ogallala and Dockum. The forecast assumes four different scenarios generated from two levels of two parameters: percent recycling of flowback water (0 and 30%) and anticipated pumping rates (low and high). Future pumping rates for HF supply will likely be influenced by global oil and gas prices and US domestic energy policy changes. The study area was divided into three regions managed by UL: Northern Midland Basin, Delaware and Central (D&C) Basins, and Southern Midland Basin. The locations of the Rig/Frack supply wells and HF oil production wells were collected from databases hosted by the Texas Water Development Board (TWDB), Texas Commission of Environmental Quality (TCEQ), FracFocus, and UL. The exact source of water supply for each HF event is unknown. Therefore, three approaches were developed to assign the water source for HF supply across known Rig/Frack supply wells within each region: 1) annual water demand for HF events was met by existing Rig/Frack supply wells screened in all underlying aquifers; 2) water demand for HF events was met by existing Rig/Frack supply wells screened in the Dockum aquifer; 3) the nearest water supply well to a HF event was assumed to supply all the water for that event. The second approach represents the official policy of UL for sourcing water from the Dockum aquifer. Water quality across the Pecos Valley, Edwards-Trinity (Plateau), and Dockum aquifers in the study area varies substantially, ranging from very fresh to saline and TDS varies from 10 to 10,000 mg/L. The simulations found that groundwater pumping for HF supply on UL properties has minor impacts on the water levels of the Dockum aquifer. The aquifers underneath UL can provide water for HF even if pumping remains high due to the large volumes of stored water within the aquifers. If pumping activity shifts to the Dockum aquifer exclusively, more water would flow downwards than upwards thereby protecting the high quality fresh water of the lower Ogallala from deteriorating.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professor Peter S. K. Knappett and Professor Hongbin Zhan of the Department of Geology and Geophysics, and Professor Mukul R. Bhatia of the Department of Geology and Geophysics and the Berg-Hughes Center.

All other work conducted for the thesis was completed by the student independently.

Funding Sources

Graduate study was supported by the Berg-Hughes Center for Petroleum & Sedimentary Systems and University Lands.

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NOMENCLATURE

ACRONYMS

API	American Petroleum Institute
D&C	Delaware and Central
DEM	Digital Elevation Model
EIA	United States Energy Information Administration
FID	Feature Identification
GAM	Groundwater Availability Model
GCDs	Groundwater Conservation Districts
GMAs	Groundwater Management Areas
GMS	Groundwater Modeling System
HF	Hydraulic Fracturing
PUF	Permanent University Fund
SDR	Submitted Drillers Report
TCEQ	Texas Commission of Environmental Quality
TDS	Total Dissolved Solids [mg/L]
TWDB	Texas Water Development Board
UL	University Lands
USGS	United States Geological Survey
US EPA	United States Environmental Protection Agency

NOMENCLATURE

SYMBOLOGY

ET	Evapotranspiration [cm/year]
K	Hydraulic Conductivity [m/day]
S	Storativity [-]
S_s	Specific Storage [m^{-1}]
S_y	Specific Yield [-]

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1. INTRODUCTION

The Permian Basin of west Texas is one of the largest sources of trapped oil in the world, with approximately 9 to 10 stacked reservoirs within a maximum total thickness of approximately 3,000 m (10,000 ft) (Scanlon, 2017). There are two unconventional basins (Delaware and Midland) and one conventional basin platform (Central). Unconventional oil extraction involves the hydraulic fracturing (HF) method for extracting oil from low permeability, petroleum-bearing rocks (tight sandstones, shale). This is achieved by injecting water, sand, and chemicals under high pressure into a perforated, horizontal segment of the well to increase the permeability by fracturing the rock, and then extracting the oil that infiltrates into the newly connected fractures. Hydraulic fracturing has greatly increased U.S. oil production, but it requires large volumes of water, which is a non-renewable resource in arid regions (Scanlon, 2014).

The large volumes of water needed for HF within the UL regions equal approximately 2.38×10^6 m^3 (2.00×10^7 bbl) of water annually. The publicly available FracFocus database reports the water volumes used for each HF event, but does not specify the source of the water. Indeed, in the Permian Basin, the source of the water used for a single HF event is typically unknown even by the HF operators (Jim Buice, personal communication, February 12, 2021). This is problematic for assessing the impacts of that water use as there are several aquifers underneath UL acreage. One approach to assign a water source for each HF event is to assume that the water is sourced from the nearest Rig/Frack supply well (Obkirchner, 2019). This assumption is partially supported by its cost-effectiveness since transportation costs would be minimized. Transportation costs, however, are not the only factor. For example, farmers who own groundwater rights are commonly willing to sell their water to HF water supply contractors (Richard Brantley, personal communication, August 11, 2020). Despite the apparent economy of sourcing water from the nearest water production well, that assumption is not the most representative of water sourcing for HF on UL properties (Jim Buice, personal communication, February 12, 2021). Out of the 3,112 water supply wells in the UL database, 1,520 (49%) are designated as Rig/Frack supply wells providing water for oil & gas operations during the time period from 2012 to 2020. Therefore, a more representative scenario of water sources is needed that is useful across all years studied (2012 to 2020). After meeting with UL hydrogeologists (Jim Buice and Steven Brite) and Senior Executives (Richard Brantley, John Tackett, and Maryam Schellstede), four aquifers were selected for study in the Permian Basin based on their potential use for HF supply, and the sensitivity of stakeholders in the region to changes in water quantity or quality. These aquifers are: the Pecos Valley (major aquifer), the Edwards-Trinity (Plateau) (major aquifer), the lower Ogallala (major aquifer), and the Dockum (minor aquifer). The Pecos Valley, Edwards-Trinity (Plateau), and particularly the Dockum have played a significant role in supplying water for HF on UL properties.

1.1 Objectives

1) Assess the approximate spatial distributions of various indicators of groundwater quality that are relevant for HF supply on UL properties. This was achieved by creating 3-dimensional (3-D) groundwater quality maps that describe the spatial distribution of fresh, brackish, and saline water as well as the distribution of concentrations of specific ions (Na, Ca, Cl, SO_4) in the Pecos Valley, Edwards-Trinity (Plateau), and Dockum aquifers. The lower Ogallala was left out of this assessment because UL does not approve applications to pump from this aquifer for HF supply to conserve its diminishing fresh water from further depletion.
2) Assess the impacts of pumping for HF supply by UL operators during the time period from 2012 to 2020 on: a) hydraulic heads; b) gross water volumes that enter and leave storage; and c) volumetric fluxes within and between the hydraulically connected Dockum and lower Ogallala aquifers within the Northern Midland Basin, Delaware & Central Basins, and Southern Midland Basin regions.
3) Forecast the future impacts of pumping for HF supply by building on the calibration period for which there was HF supply pumping data (2012 to 2020). The uncertainty in future pumping rates was dealt with by utilizing a 2^2 factorial experiment where percent recycling and overall water demand for HF are tested at two levels. The two levels of reuse/recycling were 0 and 30%. The two levels of water demand for HF supply were "low" (2014) rates and "high" (2018) through 2050.

1.2 Workflow

There were twelve scenarios explored in this study. These different scenarios were derived from the first two water source assignment approaches listed in the abstract.

This section explains the difference between the scenarios derived from the two major approaches and assigns a case identification to each scenario. Water suppliers for HF do not report where their water was sourced from, so we had to make the following assumptions. First, each region in UL’s acreage was solely supplied by Rig/Frack supply wells within that region. Then, we annualized the total groundwater pumped for HF across that region (Fig. 1).

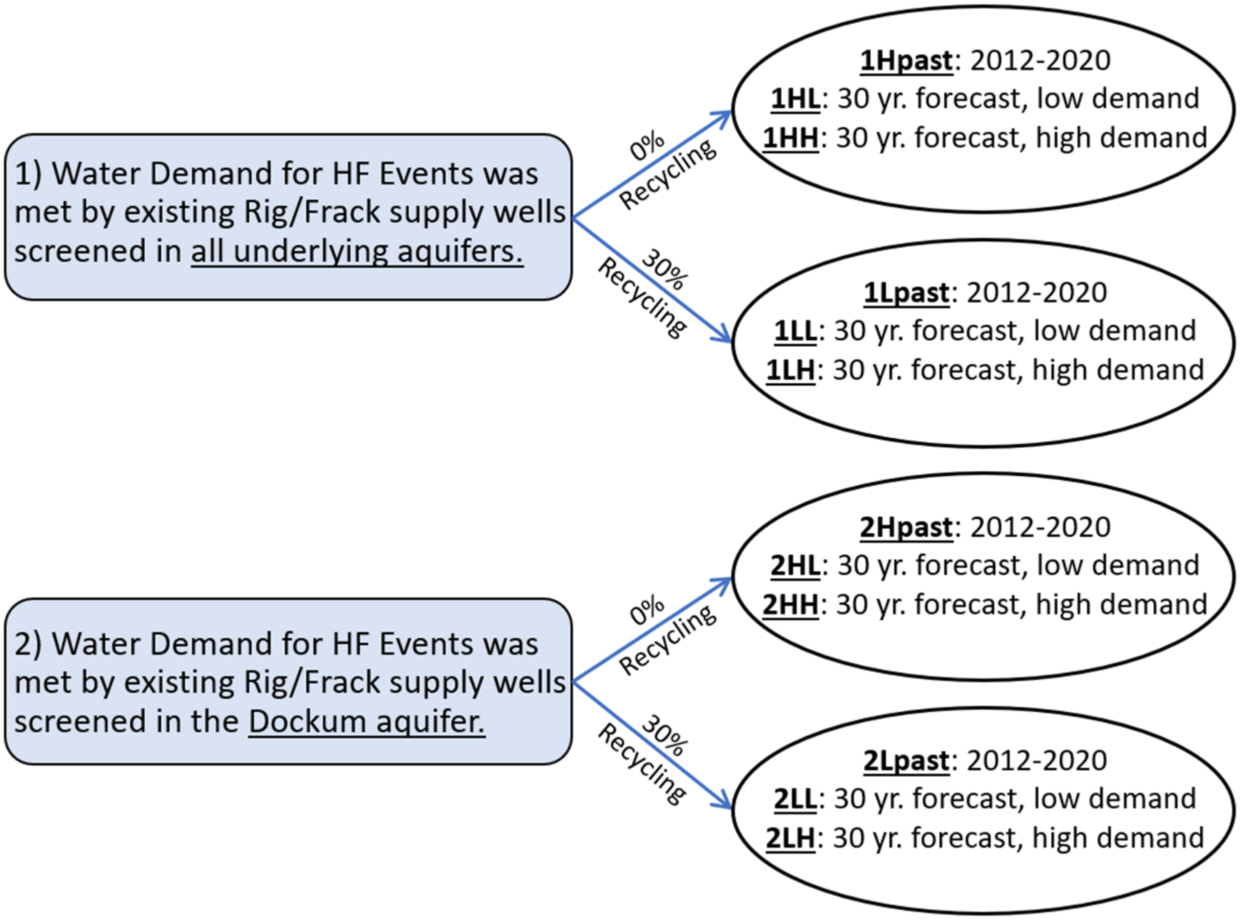


Figure 1: Workflow describing the different scenarios explored in this study. The number represents the water sourcing approach. The first letter represents the effect on pumping from the two recycling scenarios: L is for low pumping, when there is 30% recycling; and H is for high pumping, when there is 0% recycling. The second letter represents the effect on pumping from the two forecast scenarios: L is for low pumping, when 2014 pumping rates are assumed; and H is for high pumping, when 2018 pumping rates are assumed.

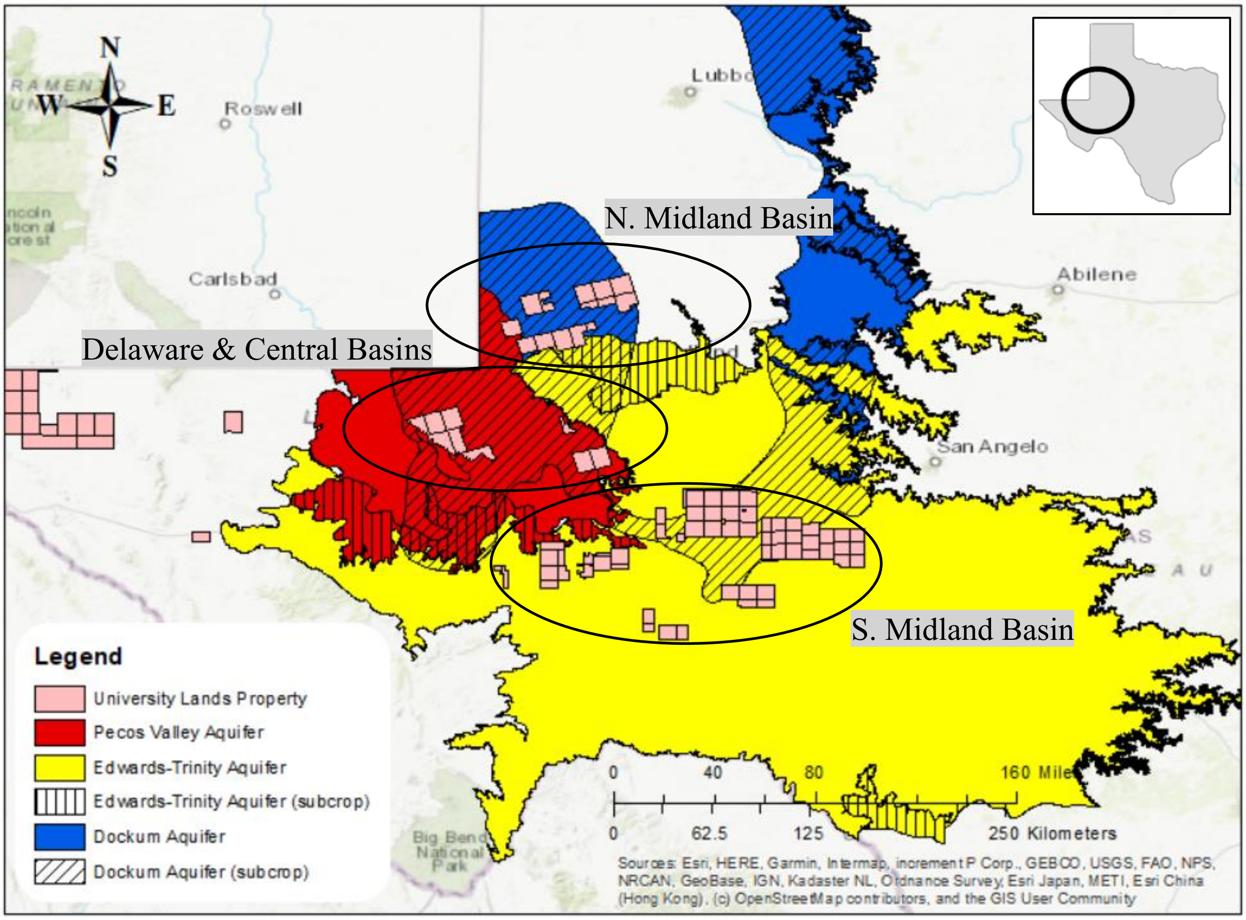
2. STUDY AREA & LITERATURE REVIEW

2.1 Permian Basin Regional Overview

2.1.1 University Lands' Groundwater Management

University Lands manages the surface and mineral economic interests of 4,856 km^2 ($1.20x10^6$ ac) of land in the Permian Basin of west Texas for the benefit of the Permanent University Fund (PUF). The PUF is one of the largest university endowments in the United States and benefits the students of more than twenty educational and health institutions across both Texas A&M University System and The University of Texas System. University Lands works with over 250 oil and gas companies, operates 3,500 leases (schools, wind farms, ranching & livestock, wineries, groundwater sales, etc.), and their 9,000 wells currently produce over $2.2x10^5$ bbl of oil equivalent per day (UL, 2021).

Out of all the water being sourced across the UL properties, approximately 90% of it is used within UL properties. University Lands plays a key role in managing groundwater in west Texas and is actively working to monitor and conserve water use for the long-term. Hydraulic fracturing began in 2008 in the region. This new industrial activity introduced a new competitor for groundwater resources. In these early years of HF development, operators were not required to ask for permission to drill wells to pump water (Jim Buice, personal communication, February 12, 2021). Hydraulic fracturing companies would therefore drill their own wells to self-supply. In 2011/12 much of the southwest, and U.S., suffered through a drought (Nielsen-Gammon, 2012), especially in south Midland Basin. As the iconic windmill pumps that supply drinking water to cattle were going dry, the ranchers noticed that "frack pits" (pools to store water for HF) contained a lot of water. Under these circumstances, the unconventional oil and gas industry came under scrutiny for how they were sourcing, using and disposing of this water. In response, UL developed their own groundwater management plan (UL, 2012). This plan required operators to apply for a permit to drill, and a separate application to pump. These applications needed to be endorsed by a certified Professional Geologist and Professional Engineer. The information for the application included cement type, geophysical logs (resistivity and natural gamma), pumping test results, water quality (TDS), screened interval(s), well depth, proposed use, aquifer, GPS coordinates, well yield, casing type, etc. The drillers use geophysical logs along with drill cuttings to determine the most water-producing depths to screen the wells. Starting in 2012, UL advised HF operators and HF water supply contractors to source their water from the Dockum aquifer to conserve the overlying freshwater of the lower Ogallala, the Edwards-Trinity (Plateau), and the Pecos Valley for ranchers. Owing to their proximity, the three aquifers that provide substantial amounts of water for HF on UL properties are the Pecos Valley, Edwards-Trinity (Plateau), and Dockum aquifers (Fig. 2).



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 2: UL regions and the aquifers (top to bottom: Pecos Valley, Edwards-Trinity (Plateau), and Dockum) that provide significant amounts of water for HF.

2.2 Regional Geology and Hydrogeology

2.2.1 Geology

The Permian Basin contains one of world's largest deposit of trapped oil, which is about 3 km thick (Scanlon, 2017). The basin is comprised of evaporite deposits, low energy marine shelf carbonates, and shelf edge reefs prograding into the basin. This sequences of organic rich shales, siltstones, limestones, and sandstones filled in deeper parts of basin and then were trapped during the late-Paleozoic by an evaporite layer known as the Salado Formation (Wang, 2019). The initiation of Dockum Group sedimentation was the result of a shift from an arid Permian climate toward a more humid Triassic climate (Asquith and Cramer, 1975). Triassic-age sediments of the Dockum Group accumulated in pre-existing late-Paleozoic structural basins including the Midland Basin, and Delaware Basin, which are separated by the uplifted Central Basin Platform (Ewing, et. al., 2008). Formations in the Dockum Group, from bottom to top, include the lowermost Santa Rosa Formation (sandstone and conglomerate beds), the overlying Tecovas Formation (mudstones and siltstones), the overlying Trujillo Sandstone (cross-bedded sandstones and conglomerates), and the uppermost Cooper Canyon Formation (mudstone with some siltstone, sandstone, and conglomerate) (Ewing, et. al., 2008). The Dockum Group is confined in the study area between older underlying Permian-age formations and younger overlying formations such as the Cretaceous-age Edwards-Trinity (Plateau), Tertiary-age Ogallala Formation, the Quaternary-age Pecos Valley Alluvium, as well as modern day soils.

2.2.2 Hydrogeology

2.2.2.1 Pecos Valley Alluvial Aquifer

The Pecos Valley aquifer is a major unconfined aquifer, covering $1.77\text{x}10^4$ km^2 (6,829 mi^2) (Fig. 3). It is comprised of alluvial (river), lacustrine (ancient lake), and eolian (wind) deposits of Tertiary and Quaternary age. Some of these deposits correlate with the Ogallala aquifer (Hawley et. al., 1976). The thickness of the sediment fill reaches 457 m (1,500 ft), and there is an average saturated thickness of about 76 m (250 ft) (Bruun et. al., 2016). Recharge to the aquifer is estimated at $1.11\text{x}10^8$ m^3/ year ($8.98\text{x}10^4$ ac-ft/year). Recharge is generally higher southwest of the Pecos River, and the groundwater generally flows northeast towards the river (Anaya and Jones, 2009). The hydraulic conductivity (K) ranges from 1.2 – 6.1 m/day (4 – 20 ft/day). Specific yield (S_y) and Specific Storage (S_s) are approximately 0.2 and $6.1\text{x}10^{-5}$ m^{-1}, respectively. These values were obtained from pumping tests and bailing tests and are reported in TWDB and TCEQ databases and were used in the calibrated GAM (Anaya and Jones, 2009).

Total storage in the Pecos Valley is approximately $3.98x10^{11}$ m^3 ($3.23x10^8$ ac-ft), with a recoverable storage between $9.98x10^{10}$ and $2.99x10^{11}$ m^3 ($8.09x10^7$ and $2.43x10^8$ ac-ft) (Bruun et. al., 2016). These values are estimated by multiplying the volume of aquifer times the S_y (or storativity (S) for unconfined aquifers). Texas Administrative Code Rule §356.10 defines the total estimated recoverable storage as 25 to 75 percent of the estimated total volume of groundwater within an aquifer. The water quality is highly variable in the Pecos Valley, with lower TDS (0 – 3,000 mg/L) in the east, and higher TDS (3,000 – 10,000 mg/L) in the west and the south. In the east, arsenic and fluoride concentrations decrease with depth, but radionuclides generally exceed United Stated Environmental Protection Agency (US EPA) drinking water standards (15 pCi/L) (Reedy et. al., 2011). The water is generally hard (high calcium content), with chloride and sulfate concentrations that exceed secondary US EPA drinking water standards of 250 mg/L which is the same for both ions (Bruun et. al., 2016).

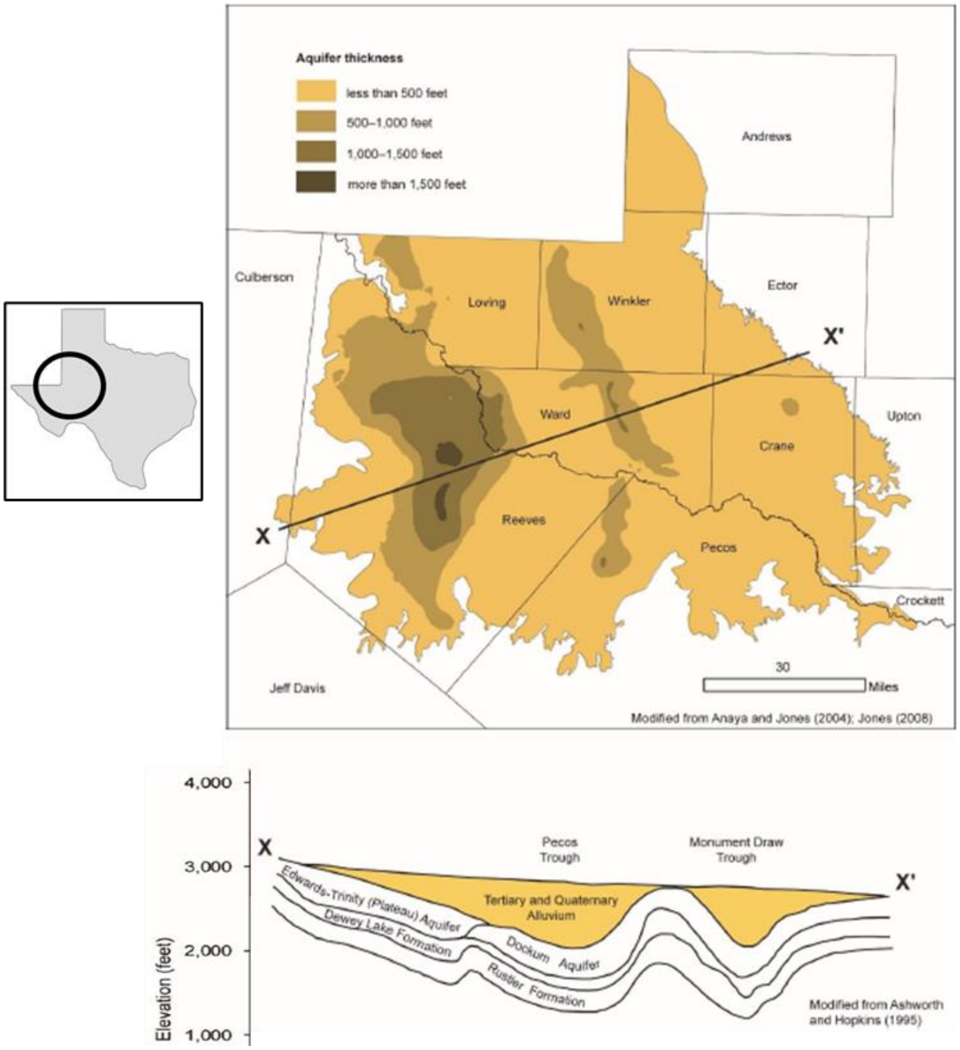


Figure 3: *Pecos Valley aquifer thickness, and generalized cross-section (Modified from Ashworth and Hopkins, 1995; Anaya and Jones, 2004 & 2009; Jones, 2008).*

2.2.2.2 Edwards–Trinity (Plateau) Aquifer

Underlying the southern region of the Pecos Valley aquifer is the Edwards-Trinity (Plateau). In most areas, the Edwards-Trinity (Plateau) aquifer is unconfined. The unconfined part of the aquifer outcrops across 8.38x10^{4} km^{2} (3.24x10^{4} mi^{2}) whereas the confined aquifer sub-crop covers only 7,902 km^{2} (3,051 mi^{2}) (Fig. 4). The aquifer is comprised of limestone and dolomite of the Edwards Group and sands from the Trinity Group, with both groups from the Cretaceous age. The TDS concentrations in this aquifer range from very fresh (<1,000 mg/L) to brackish (3,000 – 10,000 mg/L), but the groundwater is typically very fresh. This aquifer is hydraulically connected to the following major and minor aquifers: Pecos Valley, Ogallala, Trinity, Edwards (Balcones Fault Zone), Dockum, Capitan Reef, and Rustler (Bruun et. al., 2016). The Edwards-Trinity aquifer has an average saturated thickness of 132 m (433 ft), but ranges from less than 30 m (100 ft) in the north to about 244 m (800 ft) in the south. The saturated thickness is influenced by the dip of the underlying deposits and the surface topography (Barker and Ardis, 1996). In general, the water table in this aquifer has remained stable since pumping began around the 1950's, which indicates that recharge has kept pace with pumping. Hydraulic conductivity is approximately 2.4 – 3.7 m/day (8 – 12 ft/day) in the predominant non-karst areas (Barker and Ardis, 1996) and S_y is approximately 0.03. The total storage in the aquifer is approximately 5.30×10^{10} m^3 (4.50×10^7 ac-ft), with a recoverable storage of 1.39×10^{10} – 4.21×10^{10} m^3 (1.13×10^7 to 3.41×10^7 ac-ft). These volumes were estimated with a GAM (Bruun et. al., 2016). The water quality is hard (high calcium content) but has low TDS (0 – 1,000 mg/L). The TDS increases towards the west, with small, localized areas of brackish waters. Some radionuclides are present in the groundwater in the northwest and some wells contain nitrate concentrations that exceed primary drinking water standards of the US EPA (10 mg/L N-NO_3). Furthermore, some wells have TDS (500 mg/L), sulfate (250 mg/L), and less commonly chloride (250 mg/L), fluoride (2 mg/L), iron (0.3 mg/L), and manganese (0.05 mg/L) that exceed secondary drinking water standards indicated in parentheses (Reedy et. al. 2011).

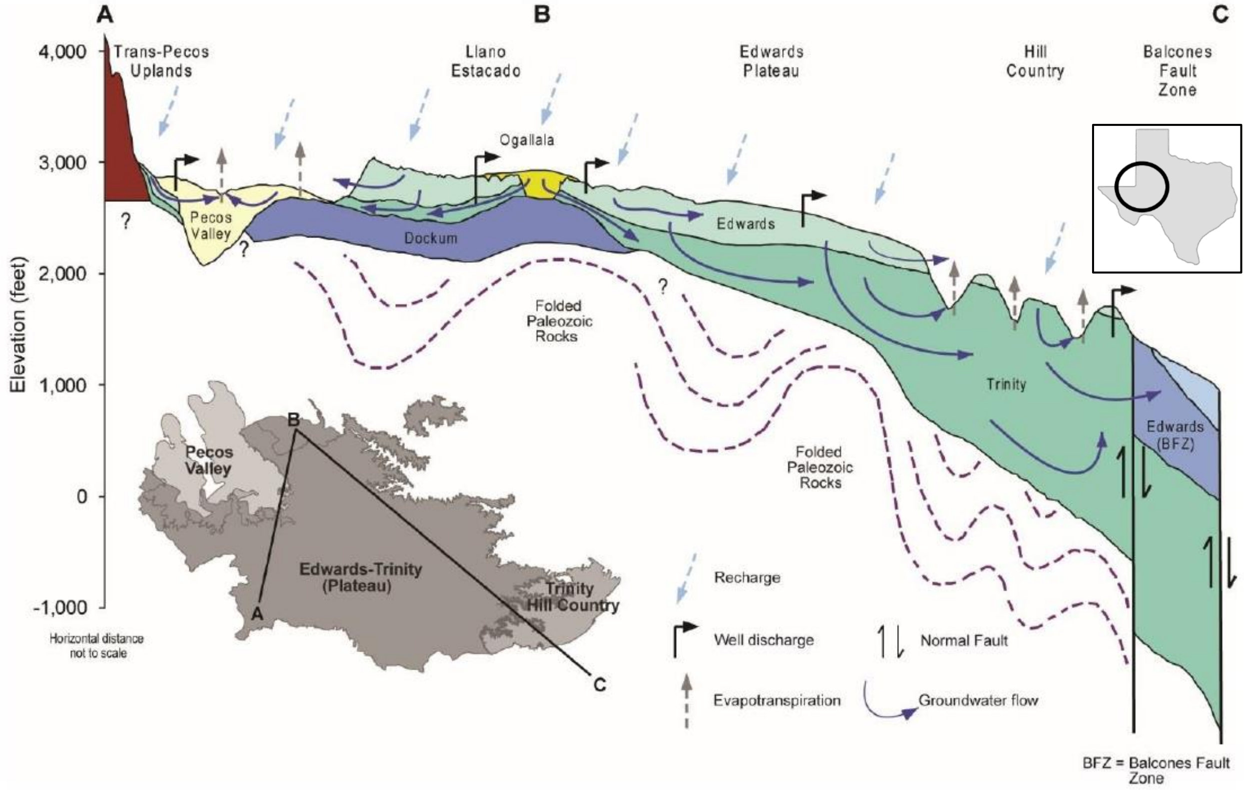


Figure 4: Conceptual model and generalized cross section of the Edwards-Trinity (Plateau) aquifer (Modified from Anaya and Jones, 2004 & 2009).

2.2.2.3 Dockum Aquifer

In contrast to the two previously described unconfined aquifers, the Dockum is a deeper aquifer that is confined across most of its area. The outcropping area of the Dockum aquifer has a footprint of 9,130 km^2 (3,525 mi^2), whereas the sub-cropping (confined) footprint is 5.71x10^4 km^2 (2.20x10^4 mi^2) (Fig. 5). The Dockum is approximately 300 m (1,000 ft) thick, and is comprised of sandstones, conglomerate, mudstones, and siltstones deposited during the late Triassic. The Dockum aquifer is hydraulically well-connected to the lower Ogallala aquifer but poorly connected to the Pecos Valley and Edwards-Trinity (Plateau) aquifers. The close hydraulic relationship between the Dockum and the lower Ogallala aquifers was used as justification for including both aquifers in the same High Plains System GAM (Deeds et. al., 2015). At the bottom of this High Plains System, Permian red-bed shales form an impermeable boundary, known as the Dewey Lake Formation (Bruun et. al., 2016). Recharge to the Dockum is very low but has increased over the last 100 years from approximately 3.8 to 14.7 mm/year (0.15 to 0.58 in/year), and the outcropping area of the aquifer is down hydraulic gradient from confined portions (Bruun et. al., 2016). In some confined areas, the hydraulic heads in the Dockum are higher than the hydraulic heads in the overlying Ogallala aquifer, suggesting the potential for upward fluxes into the Ogallala (Deeds et. al., 2015). Unfortunately, in the areas that the Dockum outcrops at land surface many of the flowing artesian springs such as the Pecos River, are now dry or have lower flows than they did it the past (Bradley and Kalaswad, 2003). Hydraulic conductivity in the Dockum typically ranges from 0.06 to 0.12 m/day (0.2 to 0.4 ft/day) (Ewing, et. al., 2008) but can reach 6.7 m/day (22 ft/day) (Deeds et. al., 2015). Specific storage is typically 1.33×10^{-5} m^{-1} giving a S of 0.004 (Ewing, et. al., 2008). Total stored water in the aquifer is about 1.85×10^{12} m^3 (1.50×10^{9} ac-ft). Recoverable storage is between 4.61×10^{11} and 1.36×10^{12} m^3 (3.74×10^{8} to 1.10×10^{9} ac-ft) (Bruun et. al., 2016). The water quality is hard (high calcium content) and poor, with very fresh water towards the east and brackish waters towards the west. Alpha radiation (15 pCi/L) from naturally occurring uranium, as well as Radium-226 and -228 (5 pCi/L), and nitrate (10 mg/L N-NO_3) exceed primary US EPA drinking water standards which are stated in parentheses (Bruun et. al., 2016). Furthermore, chloride (250 mg/L), fluoride (2 mg/L), iron (0.3 mg/L), and sulfate (250 mg/L) concentrations, and TDS (500 mg/L) in groundwater exceeds US EPA secondary drinking water standards in approximately 100 of the 300 wells tested (Reedy, et. al., 2011).

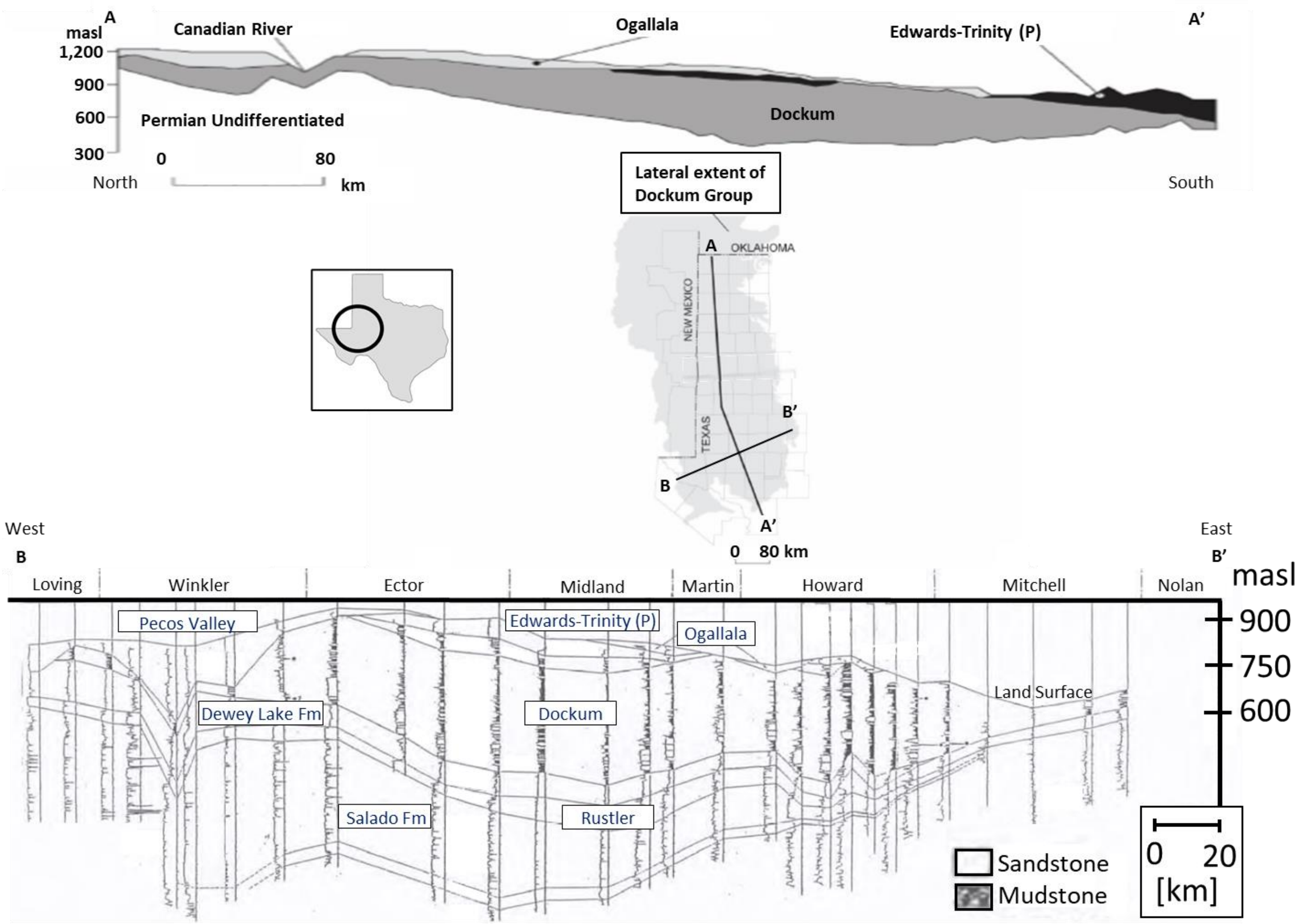


Figure 5: Dockum aquifer conceptual model and generalized cross-section (Modified from Bradley and Kalaswad, 2003; McGowen et. al., 1977).

In summary, the aquifers of west Texas contain massive volumes of water that varies in quality but is generally suitable for use irrigating and drinking. This abundance, however, is offset by the fact that there is very little recharge to these aquifers so their use should be considered the “mining” of a non-renewable resource.

2.3 Study Area

2.3.1 Geography

The Permian Basin is a region in west Texas and southeastern New Mexico. The Basin spans an area of approximately 1.94×10^5 km^2 (7.50×10^4 mi^2). It is approximately 400 km (250 mi) wide from east to west, and 483 km (300 mi) long from north to south. Today, this ancient basin is now an arid, flat land. It is covered by the Llano Estacado and the northwestern portion of the Edwards Plateau. In the State of Texas, the Basin encompasses 17 counties which lie within regions E, F, and O of the Texas Water Planning Groups of the Texas Water Development Board (TWDB). The southeastern part of the Permian Basin is home to both the Guadalupe Mountains and the Pecos River. The Pecos River has an average discharge of 7.5 m^3/s (265 ft^3/s), making it a critical source of water for farmers, ranchers, and residents in this arid region.

2.3.2 Climate

The region has a potential evapotranspiration (ET) of 234 cm/year (0.64 cm/day), and receives approximately 35.6 cm/year of precipitation according to the Texas ET Network (https://texaset.tamu.edu/). However, the Pecos River is a major tributary of the over-allocated Rio Grande, making it nearly impossible to allocate any water to newcomers since surface water in Texas is regulated according to the so-called “first in time, first in right” legal doctrine (TWDB, 2017). This means that the oil companies that want to perform HF in the Permian Basin need to use groundwater.

Selling water to oil companies is profitable. Prior to the introduction of tube-well drilling technology in the early 20th century, agriculture was unproductive in water-scarce regions like these (Jim Buice, personal communication, February 12, 2021). Some farmers, who struggle with growing enough food or raising enough cattle to be profitable, can sell their groundwater for HF supply. On the other hand, the region recently experienced a long drought in 2011-2013 (Nielsen-Gammon, 2012), which reminded farmers how precious and fragile good quality groundwater is (Jim Buice, personal communication, February 12, 2021).

2.3.3 Population and Regional Economy

There are two major cities in the Permian Basin: Midland and Odessa. Currently, the population of Midland is approximately $1.39\text{x}10^5$ people, and Odessa has approximately $1.12\text{x}10^5$ people. In 2018, Midland and Odessa were among the fastest-growing metropolitan areas in the US. Midland had the highest growth rate of all US metros of 4.3% and Odessa had the fifth highest growth rate of 3.2% (Hagan, 2019). This growth was mostly related to oil and gas production since these cities are at the heart of the oil boom in the Permian Basin. Conversely, since oil prices plummeted during the 2020 COVID-19 pandemic, the growth of these cities have slowed down. Nevertheless, if measured from January, 2019 to December, 2020, the region continued to steadily grow at 2.3%/year (World Population Review, 2021).

2.3.4 Regional Water Demand

Management of the three regional water planning areas (E, F, O) spanning the Permian Basin is funded by the Texas government. A new water plan is made for each region every five years. The water plan for the regional water planning areas contribute to the state water plan which is released every seven years. The regional water planning area most relevant to UL properties is Region F since it contains all the UL water supply wells that this study focuses on.

In 2020, in Region F, the permitted groundwater pumping volumes for irrigation, municipal, manufacturing, steam electric power, livestock, and mining (including for HF supply) were 7.32×10^8 m^3 (5.93×10^5 ac-ft), 1.74×10^8 m^3 (1.41×10^5 ac-ft), 1.38×10^7 m^3 (1.11×10^4 ac-ft), 2.35×10^7 m^3 (1.91×10^4 ac-ft), 2.09×10^7 m^3 (1.69×10^4 ac-ft), and 6.87×10^7 m^3 (5.57×10^4 ac-ft), respectively (TWDB, 2016). In 2020, only 0.8% of the total permitted water demand by all sectors within Region F was supplied from the Dockum aquifer. The Edwards-Trinity (Plateau) and the Pecos Valley aquifers supplied 52.4% of the total water demand. Overall, groundwater supplies more than 80% of permitted water demand in Region F. By 2070 the total water supply is projected to decline by 6%, primarily owing to reservoir sedimentation and groundwater "mining" of the Ogallala aquifer. In 2020, the Ogallala supplied 10% of water for Region F (TWDB, 2016). Here, "mining an aquifer" is defined as an aquifer that is pumped at a rate that exceeds the rate of recharge (Konikow and Kendy, 2005).

The sectors in Region F that contribute the most to the economy are the oil & gas industry, healthcare, manufacturing, and agriculture. The region's population is expected to increase 43% by 2070, increasing the water demand by 2%. The largest annual deficits in total stored water resources (surface and ground water) for 2020 are driven by water use for agriculture (TWDB, 2016). Therefore, irrigation water conservation strategies play a major role in water management. Indeed, two thirds of all water conservation strategies involves reduction in irrigation. The 291 strategies and 145 projects described in the 2016 region F water plan would provide an additional 2.61×10^8 m^3 (2.12×10^5 ac-ft) of water by 2070, at a cost of $1.20 billion (TWDB, 2016).

2.3.5 Permian Basin Oil and Gas Production

During the beginning of the study period (2012), the Permian Basin oil production was steadily increasing at a rate of over $1x10^6$ bbl/d per year, according to the US EIA (https://www.eia.gov/petroleum/drilling/pdf/permian.pdf). The volume of oil produced by the 500 newly added wells, per rig, was approximately 150 bbl/d in 2012. Near the end of the study period (2020), oil production in the region reached a peak at nearly $5x10^6$ bbl/d, but then plummeted to $4x10^6$ bbl/d as all the non-essential workers in the country were told to quarantine due to the global COVID pandemic, thereby slashing oil and gas demand. As of July, 2021, oil production in the Permian Basin was recovering, producing approximately $4.5x10^6$ bbl/d. Also at this time, the volume of oil produced by the 400 newly added wells, per rig, is approximately 1,200 bbl/d, revealing an 8-fold increase in productivity per well since 2012.

3. METHODS

3.1 Data Acquisition

The shapefiles and databases used to generate the results in this research are available online from governmental and private company websites. Much of the work to generate the results, however, involved merging information from two or more databases and the merged databases are available here. These databases are described in this section.

The Dockum Groundwater Availability Model (GAM) was downloaded from the TWDB website. This includes detailed calibrated models of aquifers to simulate past and future water levels. Each GAM is based in the United States Geological Survey's (USGS) software MODFLOW-2000 (Harbaugh, et. al., 2000), but the models were run in Groundwater Modeling System (GMS version 10.4, Aquaveo, LLC., Provo, Utah). The TWDB GAM database contains multiple shapefiles which can be found under the "GIS Data" tab. These shapefiles include administrative boundaries and natural features. Administrative boundaries include groundwater conservation districts (GCDs) and groundwater management areas (GMAs). Natural features include shapefiles of major and minor aquifers, existing surface water reservoirs, precipitation, and major rivers (https://www.twdb.texas.gov/mapping/gisdata.asp).

On the TWDB website there is information on groundwater chemistry and hydraulic heads. The chemistry information can be found under the "Groundwater" tab, by selecting "Data", and clicking on "Groundwater Database (GWDB) Reports". There are also submitted driller reports (SDR) (https://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp?) which detail the well report number, well type, proposed use, county, well owner, GPS location, and borehole depth. The SDR database does not report the screened intervals in the water supply wells, nor does it report the aquifer providing the water. The SDR database can be found under the “Groundwater” tab, by selecting “Data”, and clicking on “Submitted Drillers Reports (SDR) Database”.

University Lands has a database that contains information about the multiple types of wells on their property. The shapefile of University Land’s acreage was downloaded from their website under the “Resources” tab and clicking on “GIS Data” (http://universitylands.utsystem.edu/Resources/GIS). Water supply well locations with reported TDS, aquifer, well depth, and screened intervals were downloaded under the “Surface” tab and clicking on “Water Well Inventory” (https://www.utlands.org/gmp/waterwellsearch.aspx). The HF well locations with American Petroleum Institute (API) numbers were found under the “Well Library” tab and clicking on “Maps & Resources”, by filtering the search to show horizontal wells only (http://universitylands.utsystem.edu/WellLibrary). The vertical wells are conventional oil wells. The total water volume used for each HF event is not reported in the University Lands database.

The total water volume used per HF event was required to assign pumping rates of Rig/Frack supply wells in the models simulating the effects of groundwater pumping on hydraulic heads. This information was obtained from the publicly available FracFocus database. FracFocus reports “total base water volume” (gallons) of HF events as well as API numbers. The main purpose of this database is for keeping track of chemicals used in HF, volumes of oil extracted, and water volumes injected.

3.2 Aquifer Mapping

3.2.1 Hydraulic Head and Water Quality Mapping

Hydraulic head and water chemistry mapping was performed to assess the spatial distribution of groundwater quality in the region underlying and surrounding UL lands. This mapping enabled the formation of targeted research questions. For example: what is the impact of pumping from a brackish water part of an aquifer on the volumetric fluxes of fresh water into the brackish aquifer from overlying or adjacent fresh water aquifers? The hydraulic head data was obtained from the TWDB water level database which is updated on a regular basis. Hydraulic head observation wells commonly contained multiple observations over time. For the initial analysis of the spatial distribution of hydraulic heads and depth to the water level, only the most recent hydraulic head observation for each well during the period from 1980 to 2020 (40 years) were contoured on one map. An analysis of the reported changes in water levels from each aquifer, suggested that the water levels have been historically stable in most of the region. This data was projected in ArcMap (version 10.7, Environmental Systems Research Institute, West Redlands, California). Then, the “Natural Neighbor” tool was used, which can be found under “Spatial Analyst” and then selecting “Interpolation”. The natural neighbor tool was implemented to produce a surface raster of the water levels. Lastly, the Intersect tool was implemented on both the newly produced contour and the shapefile of the targeted aquifer to ensure that the contours did not exceed the extent of the aquifer.

To make groundwater quality maps the same steps were followed as described above for the hydraulic heads. The assigned values for the colors in the TDS maps were separated in the following manner: 1) <1,000 mg/L TDS was very fresh; 2) 1,000 – 3,000 mg/L TDS was fresh; 3) 3,000 – 10,000 mg/L TDS was brackish; and 4) 10,000 – 35,000 mg/L TDS, was saline. The contour intervals chosen for mapping the specific ions were guided by World Health Organization (2017) values for detectable taste in the water. These values were 200, 250, and 250 mg/L for sodium, sulfate and chloride, respectively. The next size intervals were in steps of 2,000 mg/L. Lastly, water hardness (calcium) was classified as: 1) 60 mg/L, soft; 2) 60 – 120 mg/L, moderate; 3) 120 – 180 mg/L, hard; and 4) >180 mg/L, very hard. The specific ion concentration contour maps are reported in the Appendix (section A1).

3.2.2 Water Chemistry Analysis

Piper plots and Gibbs Diagrams were created to visualize and explain groupings of groundwater chemistry observations in terms of the hydro-geochemical processes operating in the aquifers. The rationale behind a Piper Plot is that a small number of related cations and anions typically dominate the water charge in the aquifer, and from this a major ion “type” can be stated (i.e., Ca-CO_3 type). The water type often corresponds to the type of rocks and minerals found in the aquifer (Piper, 1944). The data was run using PIED Piper which is a MATLAB code that will produce Piper plots (Russoniello and Lautz, 2020). Gibbs Diagrams establish whether the overall TDS of water is being driven by water-rock interactions, evaporation, or precipitation (Gibbs, 1970). Gibbs Diagrams were created in excel using an image of a blank Gibbs Diagram and plotting the values for each axes so that the edges of the scatterplot were matched up with those of the blank diagram. The Piper plots and Gibbs diagrams are reported in the Appendix (section A2).

3.3 Merging Databases

3.3.1 Merging Hydraulic Fracturing Databases: FracFocus and University Lands

Extracted groundwater volumes used in HF operations on UL property were needed to assess the impact of this pumping on the aquifers. The volumes of water consumed by HF was not reported in the UL HF database, however, this information was available in the FracFocus database. Combining the databases has the advantage of forming a new database which includes the GPS locations of only the HF wells listed in the UL database, along with the reported water used for oil extraction. To combine them, the databases were joined in ArcMap using the API numbers, which are listed for horizontal HF wells in both databases, using the “joining attributes” function. This resulted in a new table with all the necessary attributes from both databases (API numbers, GPS locations of only HF wells in UL, and reported water volumes).

3.3.2 Assigning Groundwater Pumping for HF Supply to Nearest Rig/Frack Supply Well

Theissen polygons were utilized for the third modeling approach, which assumes that the nearest Rig/Frack supply well provides water to each individual HF event. To do this, the Rig/Frack supply wells listed in the SDR database had to be cross-referenced to each HF well listed in the newly created combined HF database (Obkirchner, 2019). The first step was to remove all monitoring wells from the SDR database. All the remaining wells were considered to be Rig/Frack supply wells whether they were officially designated as such or not (Richard Brantley, personal communication, August 11, 2020). After uploading the remaining pumping wells in ArcMap, Thiessen polygons were created using the “Create Thiessen Polygons” tool function, found under the “Analysis” tab and clicking on “Proximity”. Each polygon, and SDR well at the center of each polygon, in the new layer had a unique Feature Identification (FID). Next the “Intersect” tool, found under the “Analysis” tab and clicking “Overlay”, was run jointly on the Thiessen polygons and the newly created HF well database. This action produced a list of all the HF wells with both their FID and FID of the Rig/Frack supply well in whose polygon that HF well was located. In other words, the closest Rig/Frack supply well, and therefore a likely water source. The result is a table that contains key attributes (well report number, well type, proposed use, county, well owner, GPS location of water supply well, borehole depth, API numbers, GPS locations of only HF wells in UL, and reported water volumes) from merging the UL HF, FracFocus, and the SDR databases.

3.3.3 Assigning SDR Wells to Aquifers

The SDR database lacked information about which aquifer the well was screened in. Only the borehole depth was available. Therefore, the aquifer was assigned by using the raster files of the top and bottom of each aquifer from the aquifer GAMs and the reported borehole depth. The criteria for aquifer assignment was that the well had to terminate between the top and bottom elevations of an aquifer. By using the Arc tool “Extract Values to Points”, found under the “Spatial Analyst” tab and clicking on “Extraction”, the SDR wells are selected as the input point feature, and the desired raster file is selected for the input raster. This action produces a table with the elevation of the selected raster file (top or bottom elevation of aquifer) at the selected points. The digital elevation model (DEM) and all the top and bottom aquifer raster elevation values were obtained and then uploaded into excel. The borehole depth was subtracted from the earth surface elevation (DEM raster value), to calculate the elevation of the well bottom. After this step, the IF() and AND() functions in excel were combined to assign the names of the aquifers to each well depending on the elevation of the well bottom. A “check” option was included for any values that did not lie explicitly within the top and bottom elevations of an aquifer. These wells just mentioned were manually assigned based on proximity to the nearest aquifer. If the elevation of the well bottom was within a 50 m distance from the top of an aquifer and was also at a further distance than 50 m from the overlying aquifer’s bottom, it was assigned to the deeper aquifer. If the elevation of the well bottom was within a 50 m distance from the bottom of an aquifer and was at a further distance than 50 m above the top of the next aquifer, then it was assigned the shallower aquifer. The code can be found in the Appendix (section A3). Once all this required information was joined into a single table, it was ready to be assigned transient pumping rates for input into the groundwater model. Over the study period (2012-2020) the median distance between the nearest water supply well to each HF well was 979 m (3,212 ft) (average was 1,205 m). Out of the 558 selected water supply wells that had at least one HF event within their Theissen Polygon (also known informally as a catchment), 313 were assigned to the Dockum aquifer, 206 were assigned to Edwards-Trinity (Plateau), and 34 were assigned to Pecos Valley, based on their depths.

3.4 Groundwater Modeling

3.4.1 Model Design

The TWDB's Dockum GAM MODFLOW datasets were developed to be compatible with Groundwater Vistas for Windows (Version 4, Environmental Simulations Inc., Leesport, Pennsylvania). When these files are opened in GMS, a "possible data loss" message needs to be accepted to add the UL HF pumping schedules and run the model. The cells are 1×1 mile grid squares and the GAM consists of 3 layers. The bottom two layers represent the lower and upper Dockum, and the uppermost layer represents the lower Ogallala and other younger formations which are bounded at the top by surface topography. All the recharge, pumping, and surface water interaction that occur within these younger formations are aggregated into the general-head boundary condition applied to all layer 1 cells.

3.4.1.1 Boundary Conditions

Boundaries requiring specification include lateral and vertical boundaries, surface-water boundaries, recharge boundaries, and discharge boundaries, including evapotranspiration and pumping. Lateral boundaries are no-flow boundaries defined by the extent of the Dockum aquifer. Vertical boundaries at the bottom of layer 3 are no-flow boundaries, and the top of layer 1 of the model has a head-dependent flow boundary which was adjusted to account for water level changes within the Ogallala over time (Ewing, et. al., 2008). Surface-water reservoirs were not included in the model because they likely do not interact with the Dockum, but the mean stream flow was used over the transient period as a head-depended flow for the top of layer 3 and a small portion of layer 2 (Ewing, et. al., 2008). Recharge and ET were calculated as non-homogenous values as described in the GAM report; and the details, of how the transient pumping schedule of the wells included in layer 3 of the model was made, are also further summarized in the GAM report (Ewing, et. al., 2008).

3.4.1.2 Calibration of Transient Model

Simulated water-level elevations were compared to measured values for the calibration period from 1980 to 1997. Transient targets included 25 water-level measurements from 5 well locations in the upper portion of the Dockum aquifer and 1,293 water-level measurements from 352 locations in the lower portion of the Dockum aquifer (Ewing, et. al., 2008). Positive residuals indicate overpredicted values, and negative residuals indicate underpredicted values. Residuals in the upper portion of the Dockum aquifer fall between -18.5 and 50 m (-60.7 and 164 ft) with 84 percent falling between -30 to 30 m (-100 and 100 ft), overpredicting in 76% of values. Residuals in the lower portion of the Dockum aquifer fall between -75 to 95 m (-244 and 316 ft) with 81 percent falling between -30 and 30 m, overpredicting in 61% of values (Ewing, et. al., 2008). Mean absolute error for the transient calibration of the upper and lower Dockum are 20 to 21 m (65 and 69.6 ft), respectively; and root mean square error values for the upper and lower Dockum are 25 and 30 m (82.2 and 98.2 ft), respectively. The overall mass balance error for the transient simulation was 0.01% and the mass balance errors for individual stress periods never exceeded 0.03%, well under the GAM requirement of 1% (Ewing, et. al., 2008).

3.4.2 Setting-Up the Groundwater Availability Model

The goal of the groundwater modeling is to assess the impacts on the aquifer in terms of hydraulic heads and volumetric fluxes, from pumping the Dockum aquifer to supply water for HF activities in the Northern Midland Basin, Delaware & Central Basins, and Southern Midland Basin regions of UL acreage. A GMS GAM baseline was run (simulating from 1950 to 2050, including both the past and future study time periods) without the estimated pumping for HF supply on UL properties to assess the impact of pumping from the water supply wells that were included in the GAM (Ewing, et. al., 2008), unrelated to the other sector wells within UL. The pumping from the other sector wells were not included in these models since only 1 out of the 122 other sector water supply wells within UL reported a pumping rate (a map of the UL wells differentiated by sector is reported in the Appendix, section A4). Importantly, pumping for HF supply does occur outside of UL properties, which means that any estimates of impacts by groundwater pumping for HF supply by UL operators is a conservative estimate compared to the overall impacts of the entire HF industry across the Basin. The baseline model drawdowns from historical pumping by 2012, relative to when pumping begun in 1950, can be found in the Appendix (section A5). After running the baseline model, the three models described in section 3.4.3, which assess the impacts on the aquifers from pumping groundwater to supply HF activities at UL were developed as described next.

To import the GAM into the software GMS, the “.nam” file was opened to view the MODFLOW model. To ensure the layers in the model were displayed properly, the reports of the GAM contain details on the origin of the GAM projection which were entered by clicking on properties of the “grid” tab, and typing the given origin coordinates found in the GAM report: 19,477,268 ft north, and 3,663,110 ft east (Ewing, et. al., 2008). Once the projections were designated, the Rig/Frack supply well pumping volumes were uploaded using the function “create a new conceptual model” and choosing the “new coverage” option. Next, the pumping schedule was imported from a folder and the type of data was selected as “pumping”. Then, the right button of the mouse was clicked over the coverage and the option “Map To – MODFLOW/MODPATH” was selected. Before saving and running the model, it was important to check the “output control” to ensure that drawdown “.drw” files were saved as well as cell-to-cell flow “.ccf” files. This allows the drawdown (.drw) from pumping to be displayed, and for the volumetric fluxes between cells and layers to be stored in the zone budget (.ccf).

3.4.3 Rig/Frack Supply Well Locations and Pumping Schedules

The columns of the Rig/Frack supply well location data were arranged from left to right in this order: name of well, longitude (X), latitude (Y), elevation (Z), and well depth (ft). Other columns which were included but are not essential for this study include: screen length (ft), flow rate (ft^3/d), radius (ft), screen top (ft), screen bottom (ft). Units were converted into metric when reporting results.

To obtain pumping schedules, the columns were organized in the following order: name of well (to reference the well location), date (mm/dd/yyyy), time (hr:m:s), and flow rate (ft^3/d). The exact source of the water for each HF event recorded in FracFocus was not known (and is, in fact, not even know by the companies doing the hydraulic fracturing). The region, however, is vast, so the water is unlikely to have come from a long distance since transporting water is costly (Personal Communication, Jim Buice, February 12, 2021). Therefore, three different approaches for allocating water volumes used for HF events were considered. Each approach generated a unique pumping schedule. The three approaches are: 1) The UL properties were divided into three regions (N. Midland, D&C, and S. Midland) and aggregated water volumes used for HF supply were assumed to be derived equally from all Rig/Frack supply wells in that region; 2) The annual volume of water demand for HF was aggregated as described above, but was evenly allocated only to UL Rig/Frack supply wells that are screened in the Dockum aquifer; and 3) The water for HF events was assumed to be sourced from the nearest submitted driller report (SDR) well. In the third approach, pumping rates were calculated by dividing the total volume of water used for HF by the duration of each HF event. In the first two approaches, pumping is assigned at an annualized rate that only considers the days of HF activity per year, which was different for each region.

3.4.4 Stress Periods

The stress periods dictate the time periods when the inputs from the model remain constant. At the end of each stress period, MODFLOW outputs hydraulic heads, drawdowns relative to when pumping begins, and water budgets within assigned zones. To adjust the stress period, the “Global Options” tab was chosen after right-clicking on the MODFLOW tab in GMS.

Annualized stress periods for the study period from 01/01/2012 – 01/01/2021, were chosen to show how pumping impacted the lower Ogallala and Dockum aquifers each year, for both regional annualized models (first two approaches). The 30 year forecast models, which are scenarios of the first two approaches, used annualized stress periods from 01/01/2012 – 01/01/2021, but 5 year stress periods until ending at 01/01/2051. All the scenarios from the first two approaches also included the built in GAM stress periods which begin in the year 1950. These stress periods allowed the assessment of the impacts of pumping the Dockum aquifer (both historically and for HF) at specific points in the past, present, and future.

The third approach was chosen to have weekly stress periods, which were dependent on the pumping schedule calculated since the pumping rates were not annualized. The 313 water supply wells in the Dockum were assigned water pumping schedules that were created from the timing and amounts of cumulative water demanded for HF supply by fracked wells within that water supply well’s Theissen Polygon. This follows the method developed by Obkirchner (2019). In many cases, when more than one fracked well was located within the polygon of one water supply well, the cumulative pumping rates greatly exceeded reasonable rates for pumping an aquifer from a single well. This suggests that more than one water supply well was used during these multiple HF events operating at the same time within one polygon or that the water was pumped for weeks prior to the HF event and stored in pits as is commonly done (Jim Buice, personal communication, February 12, 2021). Aside from being physically unrealistic, these pumping rates drove drawdowns in the modeled aquifer that were greater than the thickness of the aquifer (Appendix, section A6), so this model will not be discussed any further.

3.4.5 Procedure for Summarizing the Impacts of Pumping for HF Supply on the Hydraulic Heads

Statistical analysis of the drawdowns in hydraulic heads over time owing to pumping for HF supply were analyzed in Excel after exporting the data from GMS as a text file. These drawdowns will have impacts on the water levels of the other sector wells screened in the Dockum within UL.

A list (made in Excel) of selected (1×1 mile grid) cells covering the UL regions – Northern Midland, D&C, and Southern Midland – was used to define the area where drawdown results will be extracted from the exported GMS text file. The text file exported from GMS displays the cell ID, row (i), column (j), layer (k), and drawdown results. The drawdown results under three UL regions in the exported text file from GMS are extracted using the selected list of cells (made in Excel). GMS drawdown results are extracted by uploading the text file in the same window as the list of selected cells, and using the “VLOOKUP()” function to look up the values of the selected list of cells. This was done after combining the “i, j, k” columns with the “CONCAT()” function to combine the three numbers into a single identifying “ijk” value for both the GMS text file with exported drawdown results and the selected cells list. The finished product is a new list with the drawdown results from the three UL regions. The drawdown results for the UL regions was then statistically analyzed using the “Histogram” tool under the “JMP” tab in Excel to measure the mean, median, 95th and 99th percentile drawdowns, as well as drawdown frequency histograms in the selected regions.

3.4.6 Calculating Changes in Volumetric Fluxes between Aquifers Owing to Pumping for HF Supply

By default, all the cells in the GAM model start out assigned to zone 1. Cells covering the three UL regions of interest in layer 1 (lower Ogallala) were assigned as zone 2. Cells in layer 2 and layer 3 (upper and lower Dockum) were assigned as zone 3. All other cells outside of the UL regions remained assigned to zone 1. These zones were important to calculate the volumetric fluxes entering and leaving each, as well as water fluxes between the two aquifers (zone 2 and zone 3) underneath the UL regions. The volumetric fluxes and changes in storage in each zone were exported as “.csv” files from GMS and opened in Excel for graphical analysis.

4. RESULTS

4.1 Recent Trends in Volumes of Groundwater Pumped for Hydraulic Fracturing in the Permian Basin

The water demand per HF event increased steadily between 2012 and 2020. In 2012, the median water demand per HF event was $3.01x10^4$ m^3. By 2020, this amount increased to $6.31x10^4$ m^3. The year with the most HF events was 2014, with 402 out of the 2,000 events reported during the past study period. Across the 9 year past study period, an approximate relationship between annual water demand for HF supply and the average annual price of oil was observed on UL's properties in the D&C and Southern Midland regions (Fig. 6). Groundwater pumping for HF supply in the Northern Midland region, however, increased steadily regardless of oil prices. Groundwater pumping in the D&C region dramatically increased following the second peak in oil prices in 2018 (the first peak was in 2013). Finally, groundwater pumping volumes in the Southern Midland region were the lowest overall in the UL regions.

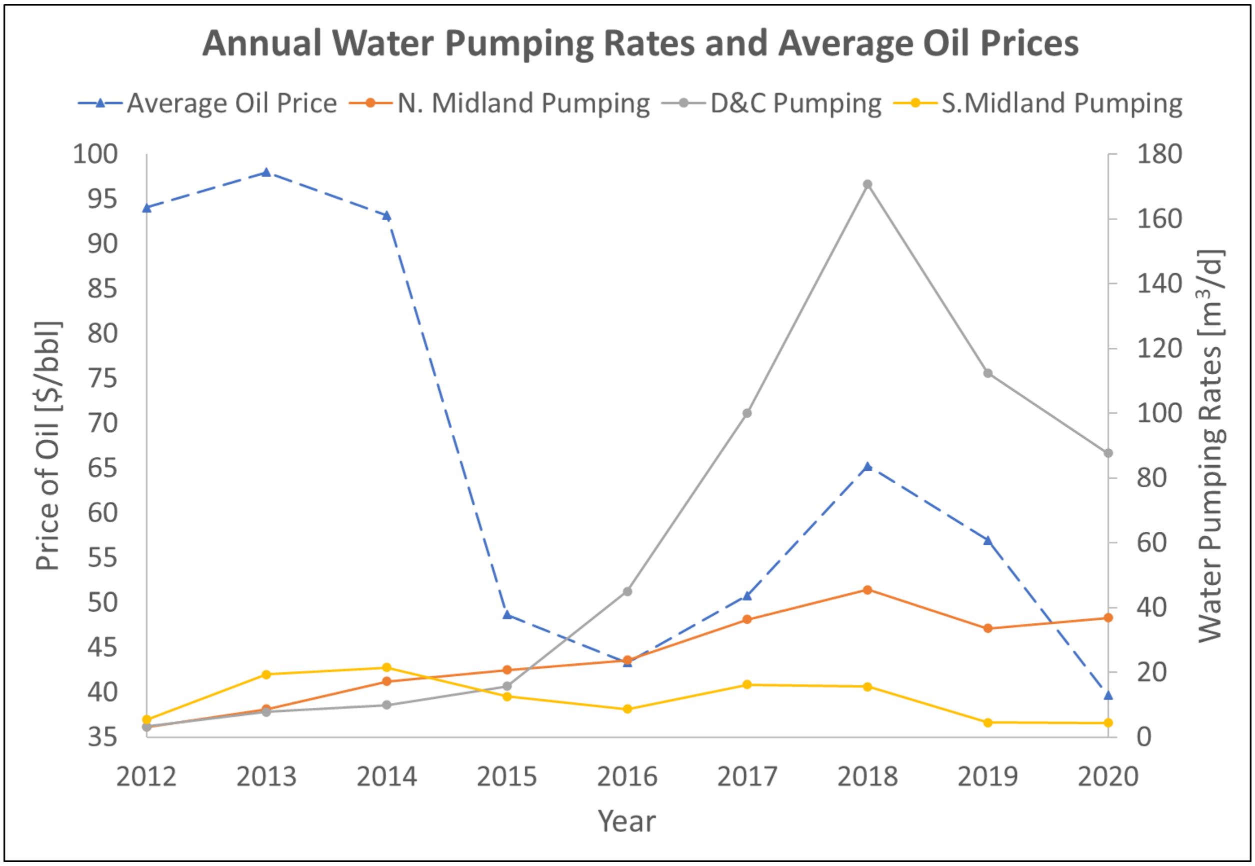


Figure 6: Annual pumped groundwater volumes for HF supply by region within University Lands compared to average annual oil prices.

The apparent relationship between the price of oil and the rate of groundwater pumping for HF supply (Fig. 6) was utilized to forecast plausible pumping rates for the 30 year forecast (future) study period. The low groundwater pumping rates observed in 2014 were chosen to represent a low rate of HF water supply in each region. The reason why the year 2012 was not selected, even though the pumping rates were lowest then in all regions, was because we assumed that HF was still a relatively new activity that needed some time for the technology and infrastructure (roads, pipelines, fracking pits, etc.) to be developed. High pumping rates for the future 30 year simulation were selected from the year 2018. This year had the highest pumping rates for two of the three regions which was coincident with high oil prices. These pumping rates were designed to consider all the reported water used by HF rigs, including the wells that became longer over time.

4.2 Groundwater Quality and Hydraulic Heads of Aquifers that Supply Water for Hydraulic Fracturing in University Lands

4.2.1 Pecos Valley

The unconfined Pecos Valley aquifer water quality within the three regions varies from very fresh, to brackish. The aquifer’s water at the Northern Midland region is fresh. The D&C region aquifer water quality is fresh and very fresh water with three localized brackish zones. Only a small portion of the Southern Midland region overlies the Pecos Valley aquifer. Not enough well water chemistry observations were available to contour TDS across the full extent of the aquifer. Outside of the UL regions, there is a zone in the southeast part of the aquifer where saline water has been reported (Fig. 7).

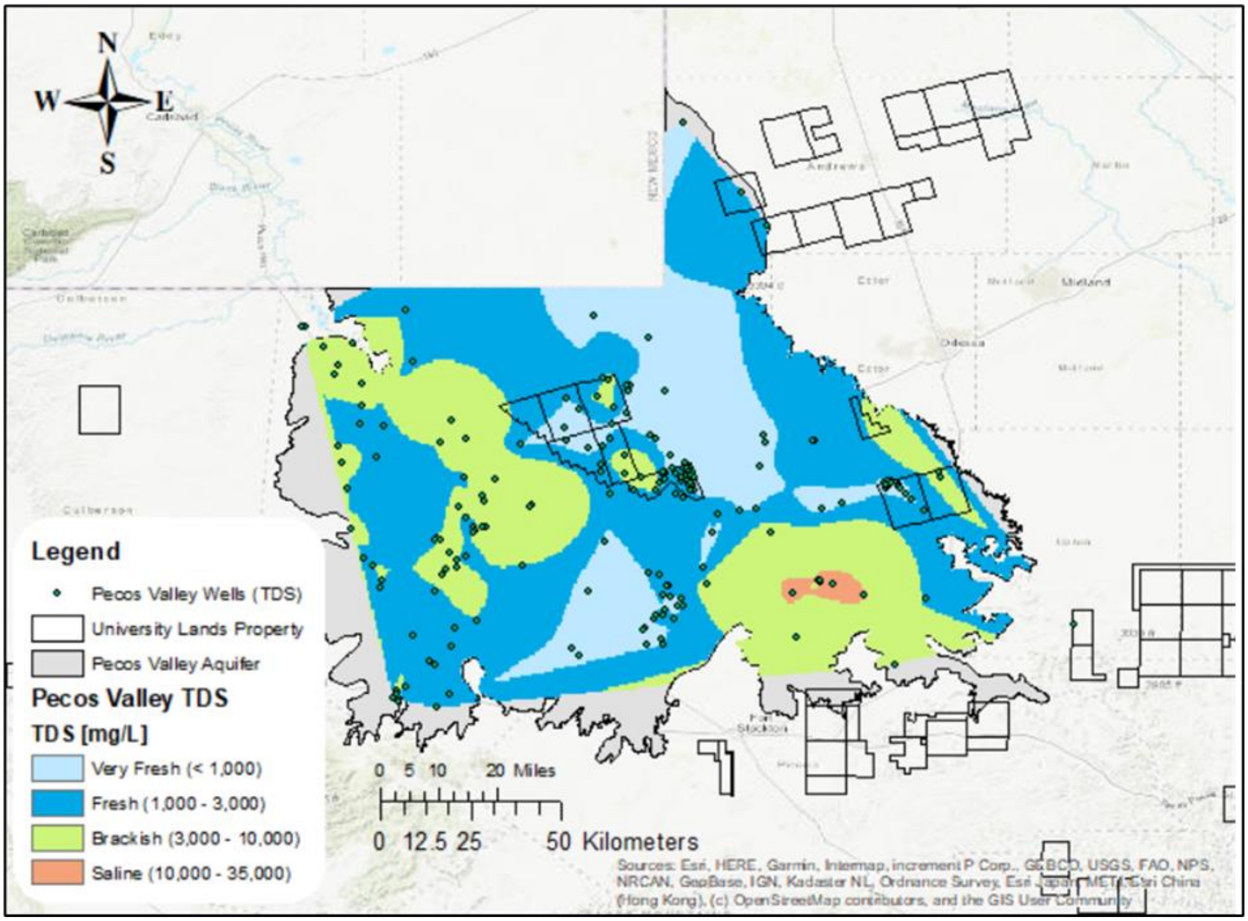
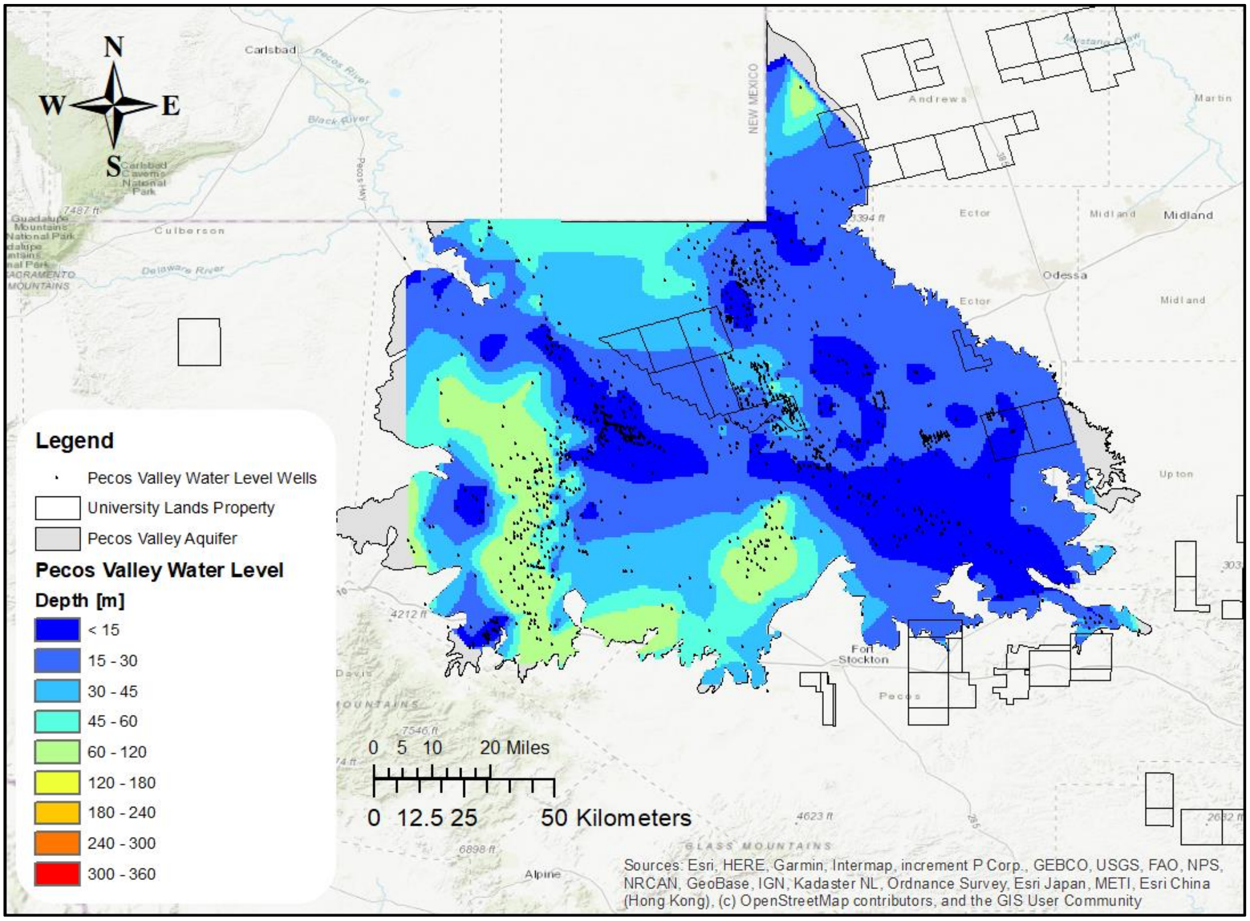


Figure 7: Pecos Valley aquifer TDS concentrations [mg/L].

The hydraulic head within the three regions varies from less than 15 to 45 m (<50 to 150 ft). The depth to the water table in the Northern Midland, D&C, and Southern Midland regions ranged from approximately 15 to 45 m (50 to 150 ft). Outside of the UL regions, in the southeast the water table is less than 15 m (<50 ft) below the surface. The deepest water table occurs in the southwest reaching 120 m (400 ft) below surface (Fig. 8).

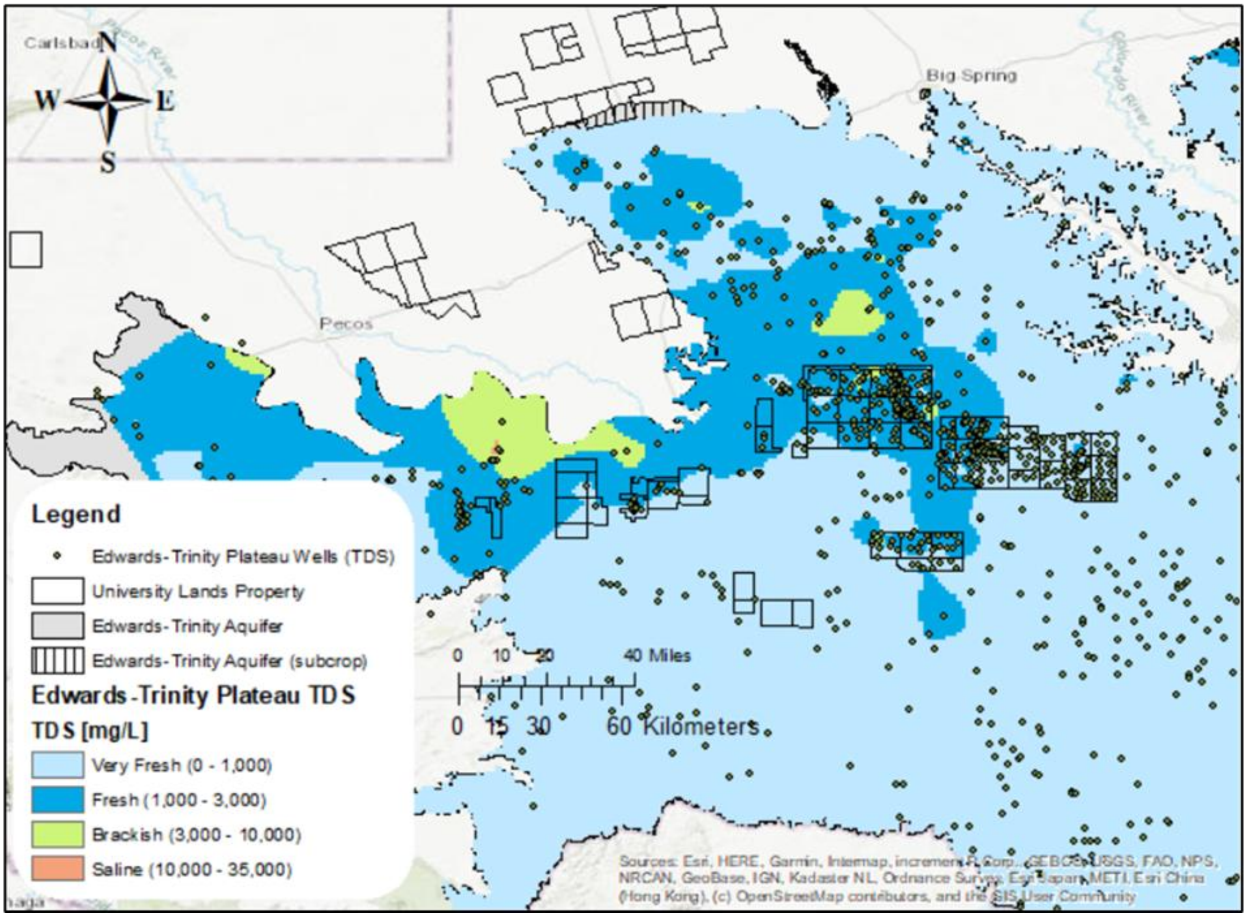


Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 8: Pecos Valley aquifer depth to water table [m].

4.2.2 Edwards-Trinity (Plateau)

The groundwater quality within the unconfined Edwards-Trinity (Plateau) aquifer underneath the three regions varies from very fresh to brackish. The Northern Midland region and the D&C region do not overlie the Edwards-Trinity (Plateau). However, in the Southern Midland Basin the groundwater quality ranges from very fresh to fresh water with the exception of two localized brackish zones (Fig. 9). Outside of the UL properties the groundwater quality in this aquifer is very fresh and abundant with the exception of a single localized zone towards the northwestern part of the aquifer where saline water has been reported.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 9: Edwards-Trinity (Plateau) aquifer TDS concentrations [mg/L].

The depth to the water table in the Southern Midland Basin ranges from less than 15 m to 180 m (<50 to 600 ft). Outside of the UL regions, in the southeast part of the aquifer, the depth to water table is less than 15 m (<50 ft), and the deepest depth to the water table reaches 360 m (1,200 ft), found towards the southwest (Fig. 10).

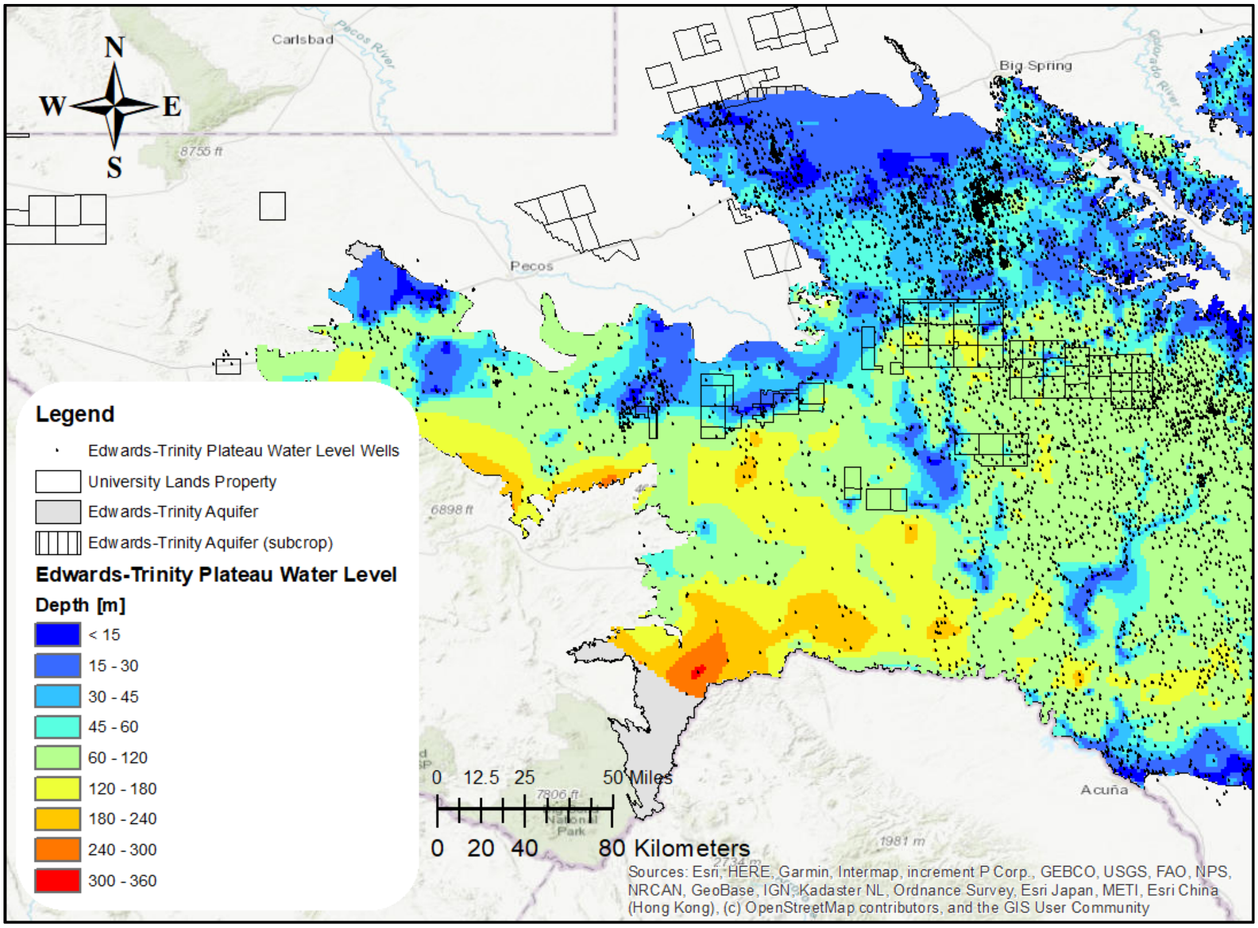
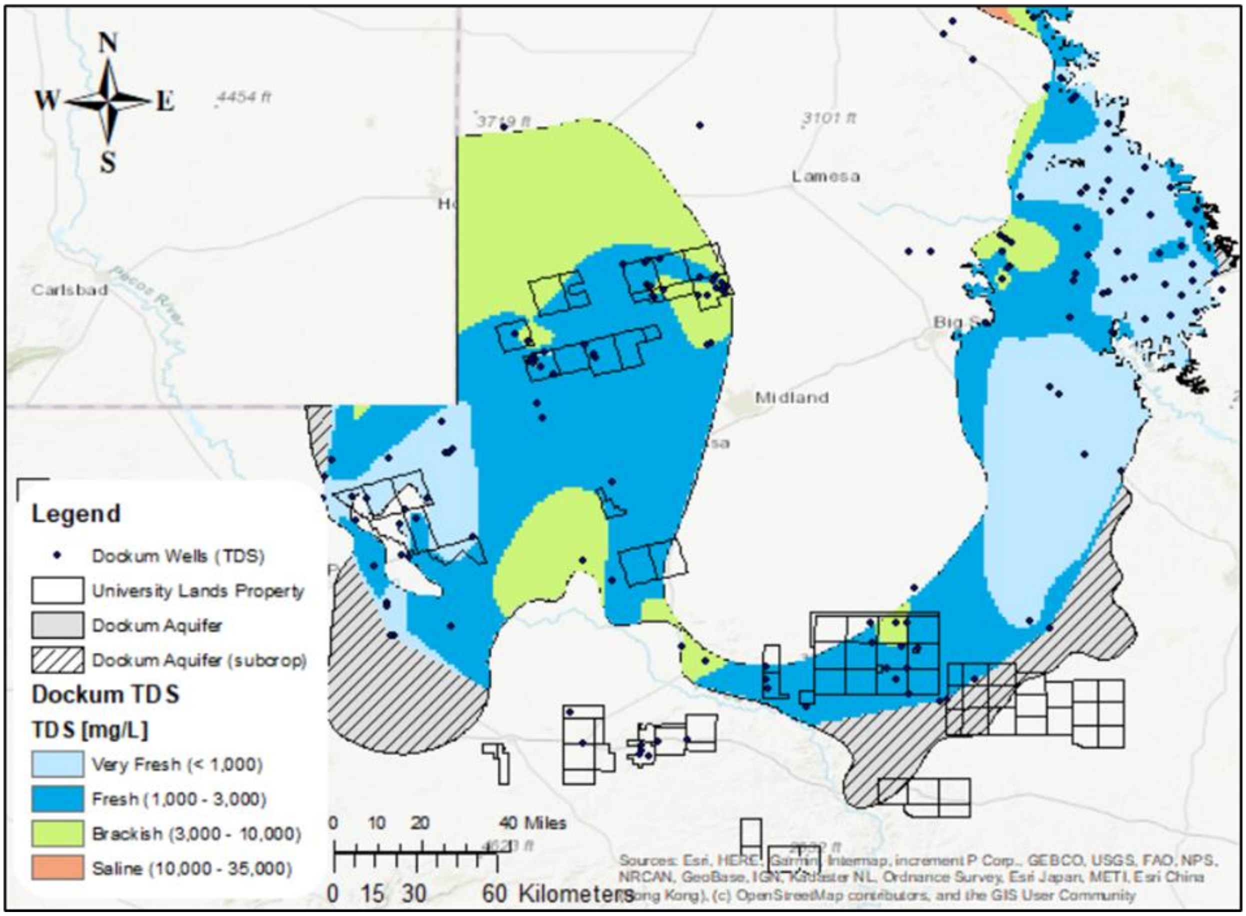


Figure 10: Edwards-Trinity (Plateau) aquifer depth to water table [m].

4.2.3 Dockum

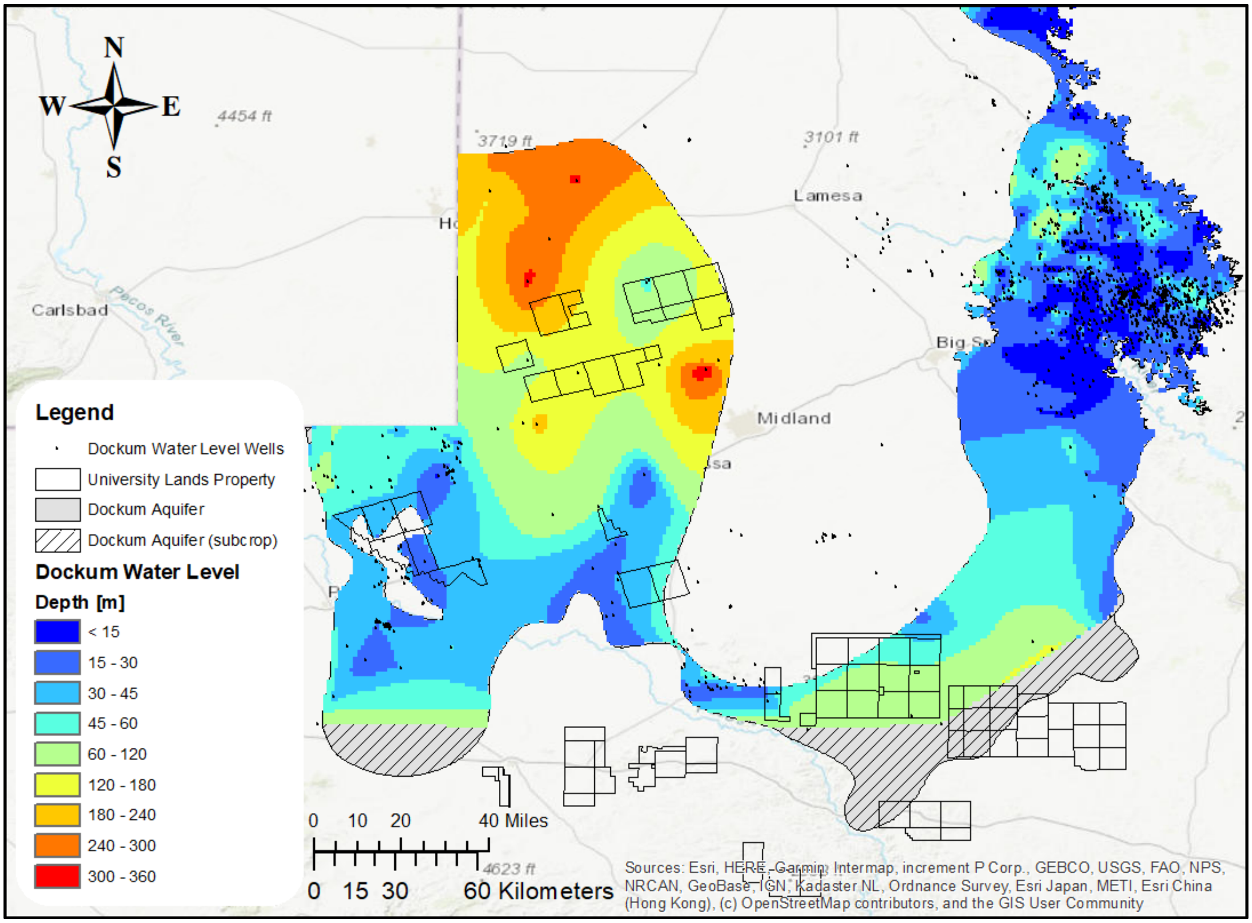
The water quality in the confined Dockum aquifer within the three regions varies from very fresh to brackish (Fig. 11). The groundwater in the Northern Midland region ranges from fresh to brackish. The groundwater in the D&C region has the best water quality ranging from very fresh to fresh. The Southern Midland region aquifer water quality is mostly fresh, with a single brackish zone. Outside of the UL regions, the groundwater quality in this aquifer ranges from very fresh to even saline. The single saline zone is found towards the eastern portion of the aquifer, but it is far from the UL regions.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 11: Dockum aquifer TDS concentrations [mg/L].

The hydraulic head within the three regions varies from less than 15 to 300 m (<50 to 1,000 ft) (Fig. 12). The depth to water level (hydraulic head) in this confined aquifer in the Northern Midland region ranges from approximately 30 to 240 m (100 to 800 ft). The depth to water level in the D&C region ranges from less than 15 to 30 m (<50 to 100 ft). In the Southern Midland Basin the depth to water level ranges from 45 to 120 m (150 to 400 ft). The deepest depth to water level is found south of the Northern Midland region (Fig. 12).



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 12: Dockum aquifer depth to water level [m].

4.3 Groundwater Modeling

To establish baseline conditions in the Dockum aquifer without the impacts from pumping for HF supply, the numerical groundwater model (GAM) was run simulating from 1950 to 2050, only with pumping from the native wells (i.e., other sector wells) in the model. The baseline model revealed that historical pumping had not impacted water levels or fluxes in the Southern Midland and Delaware & Central regions as of 2012, relative to 1950. However, by 2012, the Northern Midland region experienced drawdowns of up to 2 m (7 ft), only within the north-eastern portion of the property (block numbers 5, 6, 7, and 8). The actual existing wells in that region that experienced drawdown were: 1 domestic well, 3 commercial wells, 1 testing well, and 1 public water supply well. These drawdowns remained the same by the end of 2020 and 2050 (maps with the labeled block numbers of UL property is reported in the Appendix, section A7). The greatest impact from historical pumping outside of UL properties was underneath the cities of Midland and Odessa, which experienced drawdowns of 10 to 20 m over the entire study period (2012 – 2050).

4.3.1 Annualizing Water Pumping for HF Across All Rig/Frack Supply Wells Screened in All Aquifers

In this first approach to allocate the rates and timing of groundwater pumped for HF supply, the water demand reported in FracFocus for each region was annualized and allocated to the Rig/Frack supply wells reported in the UL water well database. No assumption was made about which aquifer was preferred so the water demand was evenly allocated on a per well basis in all the aquifers. In the Northern Midland (Table 1), D&C (Table 2) and Southern Midland (Table 3) regions, annual pumped volumes were evenly allocated across 234, 82 and 1,204 wells, respectively. This modeling approach was also designed to perform a 30 year forecast with the selected low (2014) and high (2018) pumping rates, and assuming 0% and 30% of the flowback water is recycled/treated. The same wells were assumed to supply that future pumping.

In all the scenarios from 30% recycling, the drawdown results were similar to the results of the scenarios from 0% recycling. There are multiple Rig/Frack supply wells that are in the most densely populated 1×1 mi grid cells of the GAM, and 30% recycling of water is not enough to show a significant difference in the changes in hydraulic head within these cells. All scenarios from 30% recycling only showed different maximum changes in hydraulic head compared to when there is no recycling and are thus presented in section A8 of the Appendix. The results, for gross water volumes and fluxes that entered and left the aquifers in all the scenarios assuming 30% recycling, are reported and further discussed in later sections.

Table 1: Annualized water demand for HF events within the Northern Midland region, assuming all existing Rig/Frack supply wells screened in all underlying aquifers supplied the water.

Northern Midland (234 Wells)				
Year (days of HF activity)	**Annual H_2O supplied (bbl)**	**Pumping rate used (bbl/d)**	**Annual H_2O supplied (m^3)**	**Pumping rate used (m^3/d)**
2012 (129)	7.74×10^5	19	9.24×10^4	3
2013 (337)	5.72×10^6	54	6.82×10^5	9
2014 (341)	1.15×10^7	108	1.37×10^6	17
2015 (360)	1.46×10^7	130	1.74×10^6	21
2016 (366)	1.71×10^7	150	2.04×10^6	24
2017 (353)	2.52×10^7	229	3.00×10^6	36
2018 (324)	2.90×10^7	286	3.46×10^6	46
2019 (360)	2.40×10^7	211	2.87×10^6	34
2020 (121)	2.64×10^7	700	3.15×10^6	111

Table 2: Annualized water demand for HF events within the Delaware & Central region, assuming all existing Rig/Frack supply wells screened in all underlying aquifers supplied the water.

Delaware & Central (82 Wells)				
Year (days of HF activity)	**Annual H_2O supplied (bbl)**	**Pumping rate used (bbl/d)**	**Annual H_2O supplied (m^3)**	**Pumping rate used (m^3/d)**
2012 (218)	4.83×10^5	20	5.76×10^4	3
2013 (346)	1.84×10^6	48	2.19×10^5	8
2014 (347)	2.35×10^6	62	2.80×10^5	10
2015 (351)	3.79×10^6	99	4.53×10^5	16
2016 (359)	1.11×10^7	283	1.32×10^6	45
2017 (351)	2.42×10^7	630	2.88×10^6	100
2018 (365)	4.28×10^7	1,073	5.11×10^6	171
2019 (358)	2.77×10^7	707	3.30×10^6	112
2020 (290)	2.20×10^7	695	2.63×10^6	111

Table 3: Annualized water demand for HF events within the Southern Midland region, assuming all existing Rig/Frack supply wells screened in all underlying aquifers supplied the water.

Southern Midland (1204 Wells)				
Year (days of HF activity)	**Annual H_2O supplied (bbl)**	**Pumping rate used (bbl/d)**	**Annual H_2O supplied (m^3)**	**Pumping rate used (m^3/d)**
2012 (324)	1.75×10^7	34	2.08×10^6	5
2013 (361)	7.06×10^7	122	8.43×10^6	19
2014 (365)	7.91×10^7	135	9.44×10^6	21
2015 (341)	4.31×10^7	79	5.15×10^6	13
2016 (364)	3.15×10^7	54	3.76×10^6	9
2017 (365)	5.98×10^7	102	7.13×10^6	16
2018 (344)	5.40×10^7	98	6.44×10^6	16
2019 (361)	1.62×10^7	28	1.93×10^6	4
2020 (102)	1.62×10^7	99	1.93×10^6	16

4.3.1.1 Upper Dockum

As of 2020, the change in hydraulic head of the upper Dockum aquifer that underlies the UL regions, owing to pumping for HF (1Hpast), ranged from -4.26 to 3.04 m, compared to 2012 heads (Fig. 13). Negative changes in head represented drawdowns. The median and mean changes were 0 m and -0.12 m, respectively. The 95th percentile was -0.91 m, and the 99th percentile was -2.13 m.

The forecasted change in hydraulic heads within the upper Dockum aquifer underneath the UL regions across the future time period from 2021 to 2050, assuming the low water demand for HF supply (1HL), will range from -3.96 to 3.35 m, with a median and mean value of 0 and -0.15 m (Fig. 14). The expected 95th percentile is -0.91 m, and the 99th percentile is -2.44 m.

In contrast, assuming the high water demand for HF supply (1HH), the change in hydraulic head will range from -6.40 to 3.35 m, with median and mean values of 0 m and -0.19 m, respectively (Fig. 15). The expected 95th percentile is -1.22 m, and the 99th percentile is -3.35

m. These median and mean values show that there was minimal impact on water levels, and these results are further discussed in section 5.3.

4.3.1.2 Lower Dockum

The change in hydraulic head by the end of 2020, owing to pumping for HF (1Hpast), ranged from -3.35 to 1.21 m, compared to 2012 heads (Fig. 16). The median and mean changes were 0 m and -0.05 m, respectively. The 95th percentile was -0.30 m, and the 99th percentile was -0.91 m.

The forecasted change in hydraulic heads within the lower Dockum aquifer underneath the UL regions across the future time period from 2021 to 2050, assuming the low water demand for HF supply (1HL), will range from -3.65 to 2.13 m, with a median and mean value of 0 and -0.15 m (Fig. 17). The expected 95th percentile is -0.91 m, and the 99th percentile is -1.83 m.

In contrast, assuming the high water demand for HF supply (1HH), the change in hydraulic head will range from -7.01 to 1.82 m, with median and mean values of 0 m and -0.20 m, respectively (Fig. 18). The expected 95th percentile is -0.91 m, and the 99th percentile is -3.05 m. All the results stated in this section are summarized in Fig. 19, and both drawdown frequency histograms and a summarized table of these results are reported in section A9 of the Appendix.

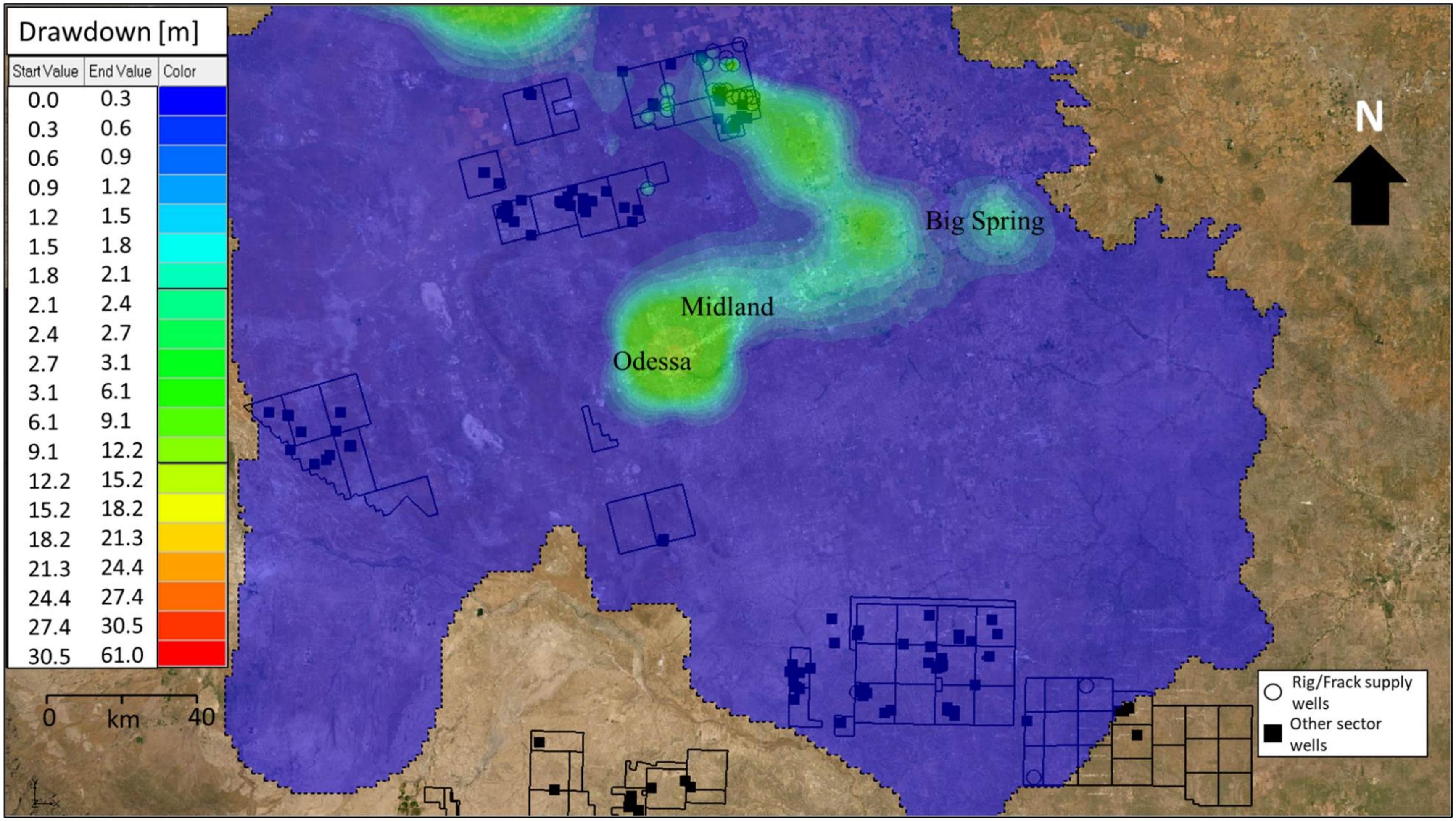


Figure 13: Drawdown in hydraulic heads within the upper Dockum aquifer assuming that pumped volumes for HF supply was supplied from wells in all underlying aquifers (2012-2020, 1Hpast). Results for scenario 1Lpast are similar.

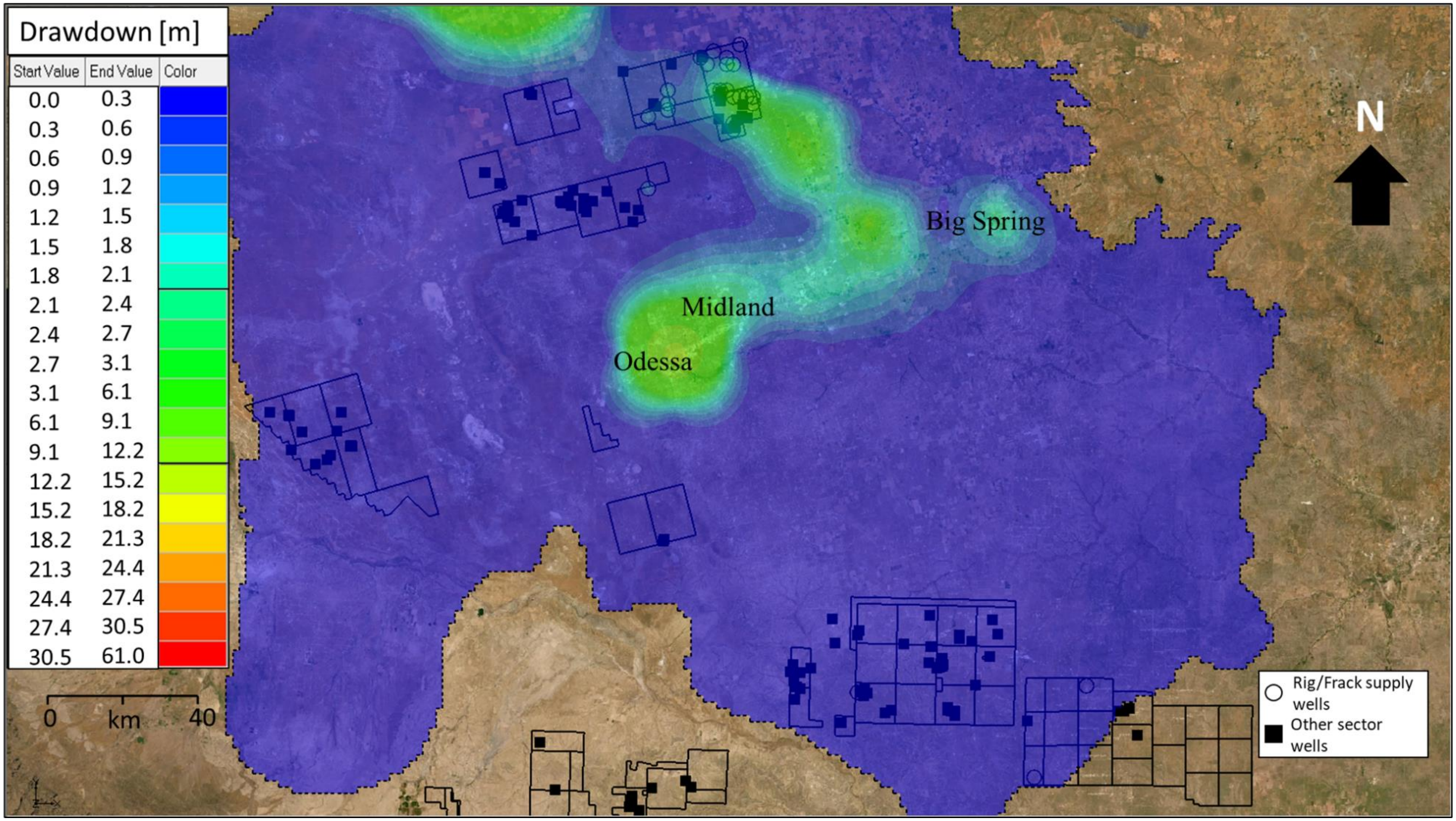


Figure 14: Expected additional future drawdown in hydraulic heads in the upper Dockum assuming the low pumping rate of water supply for HF is sourced from wells in all underlying aquifers (2021-2050, 1HL). Results for scenario 1LL are similar.

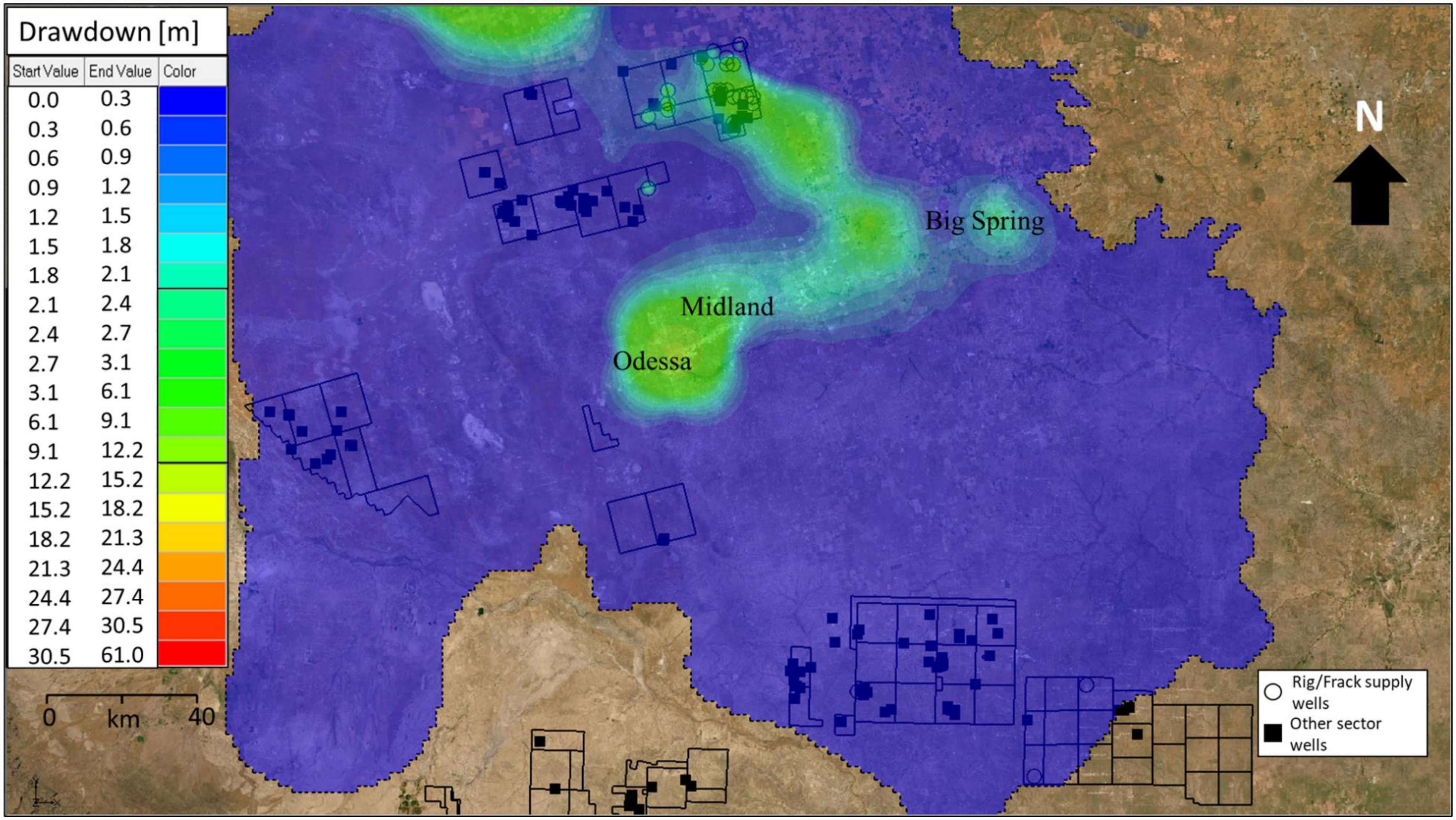


Figure 15: Expected additional future drawdown in hydraulic heads in the upper Dockum assuming the high pumping rate of water supply for HF is sourced from wells in all underlying aquifers (2021-2050, 1HH). Results for scenario 1LH are similar.

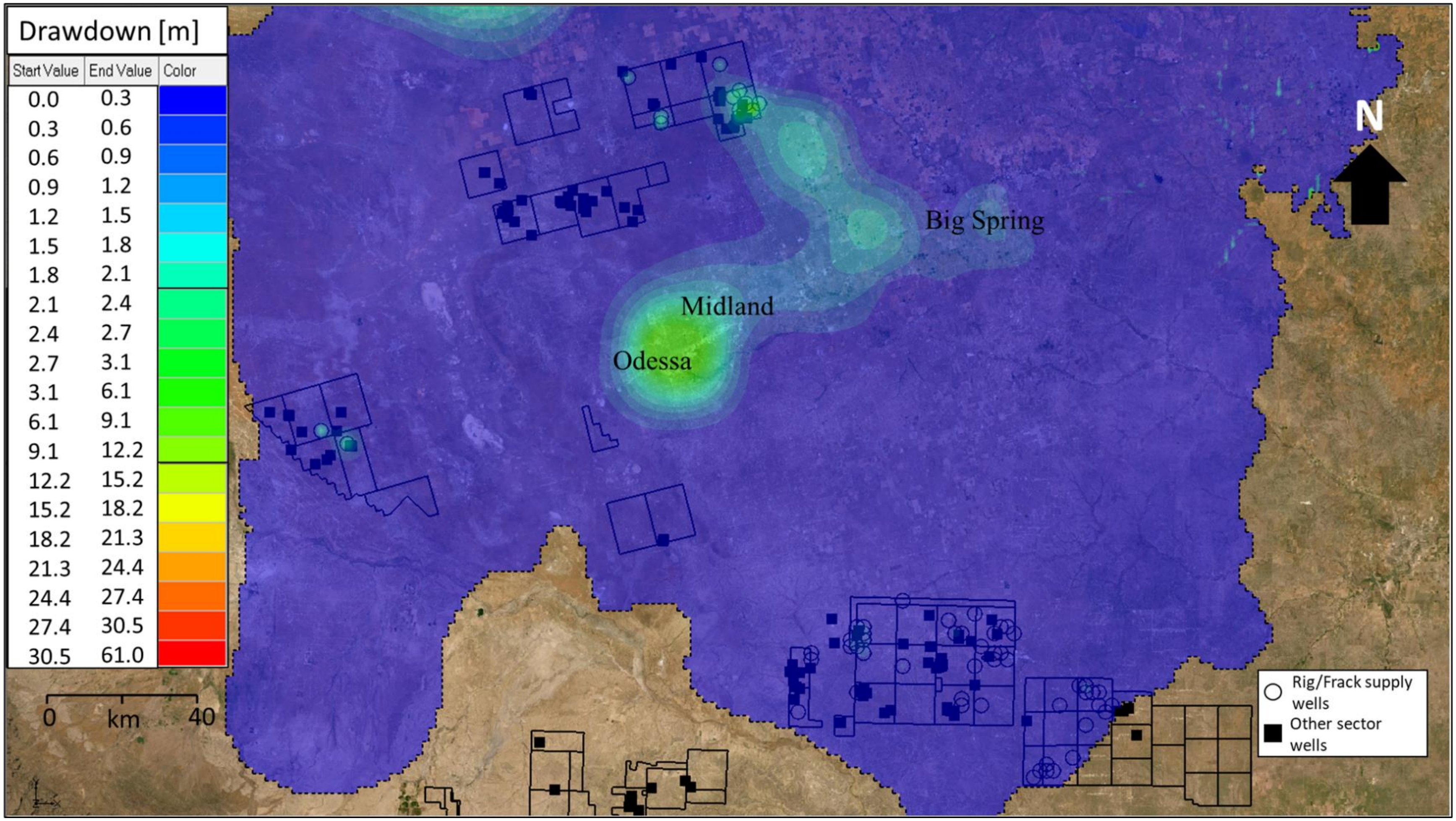


Figure 16: Drawdown in hydraulic heads within the lower Dockum aquifer assuming that pumped volumes for HF supply was supplied from wells in all underlying aquifers (2012-2020, 1Hpast). Results for scenario 1Lpast are similar.

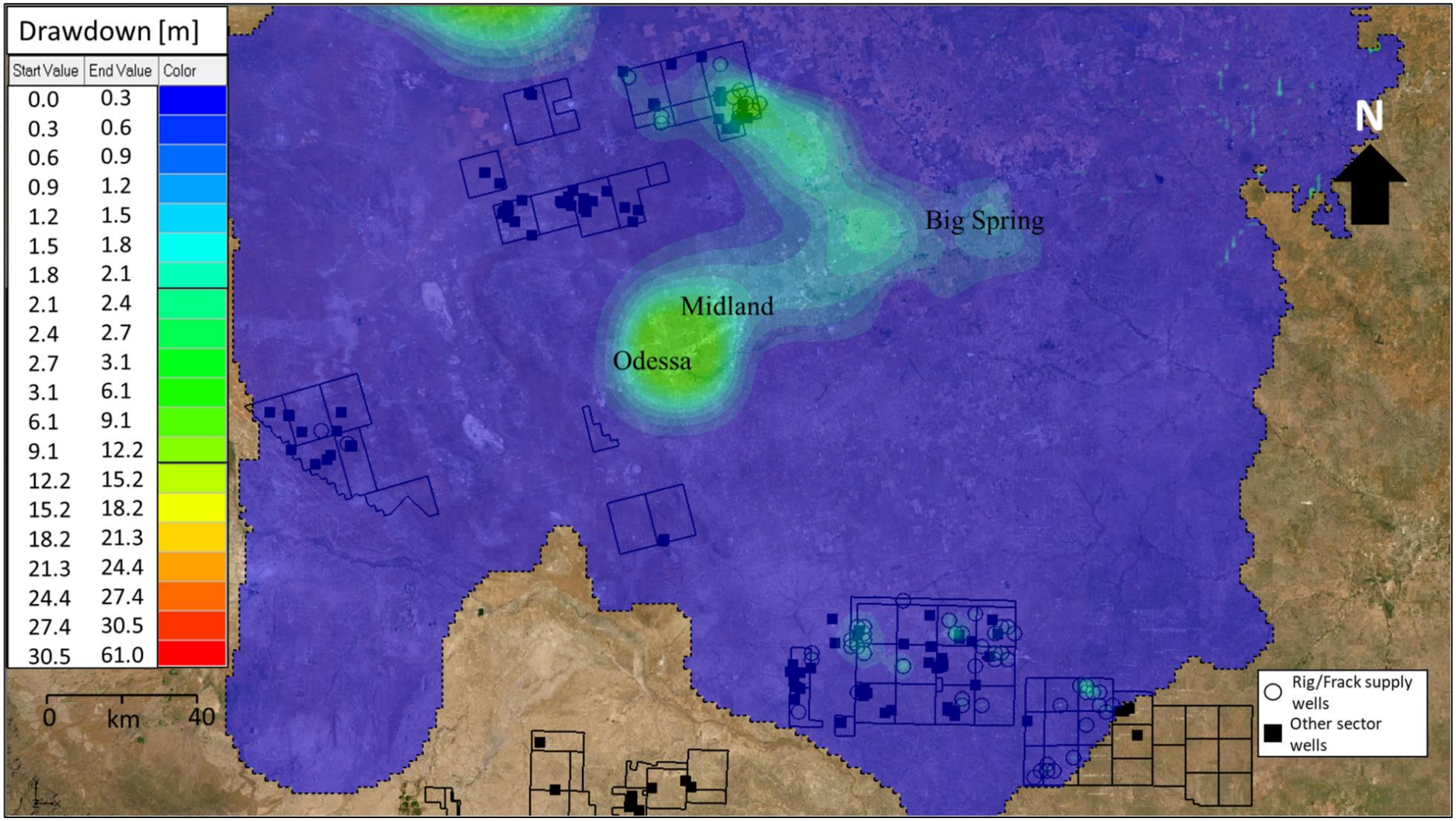


Figure 17: Expected additional future drawdown in hydraulic heads in the lower Dockum assuming the low pumping rate of water supply for HF is sourced from wells in all underlying aquifers (2021-2050, 1HL). Results for scenario 1LL are similar.

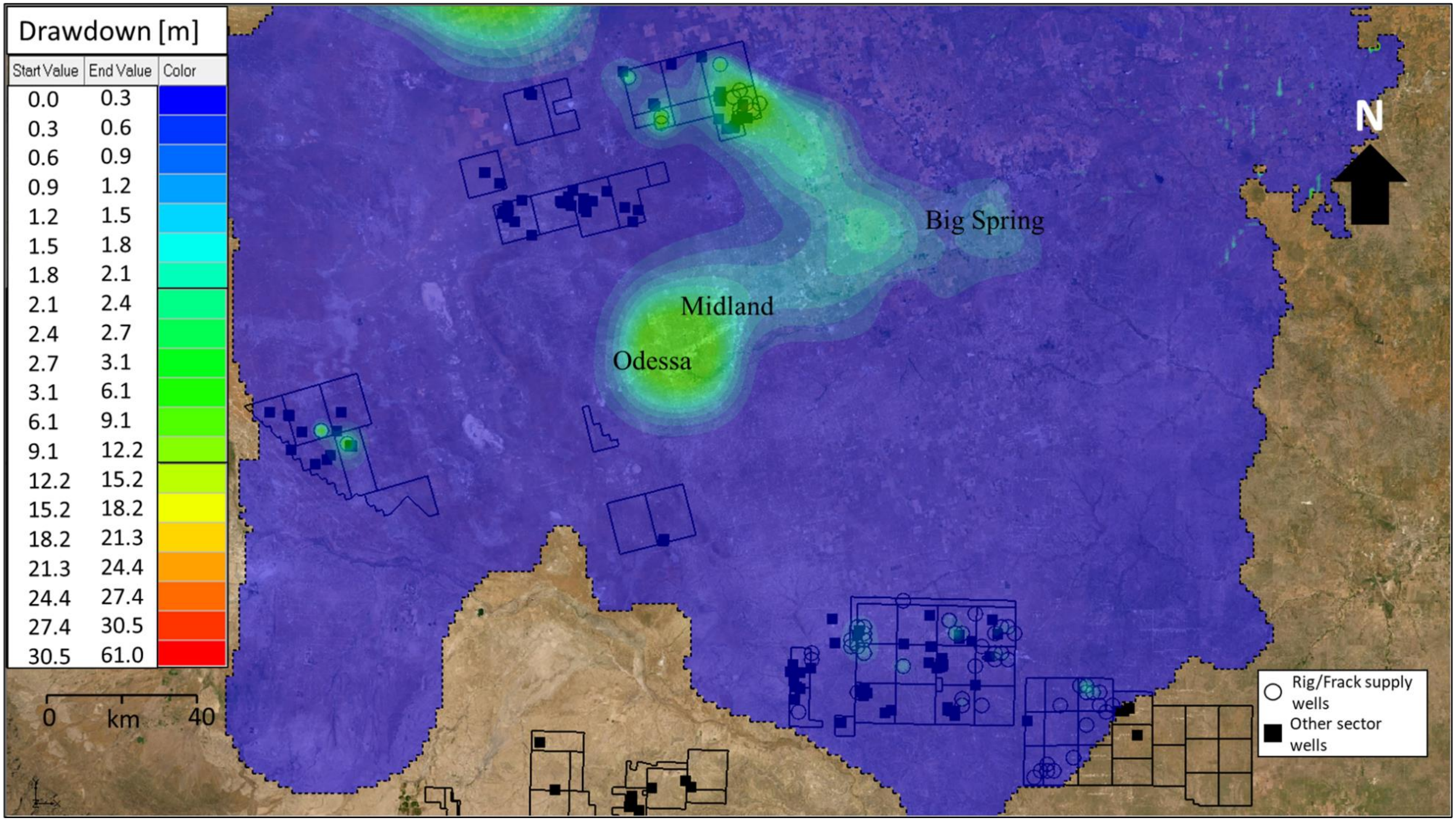


Figure 18: Expected additional future drawdown in hydraulic heads in the upper Dockum assuming the high pumping rate of water supply for HF is sourced from wells in all underlying aquifers (2021-2050, 1HH). Results for scenario 1LH are similar.

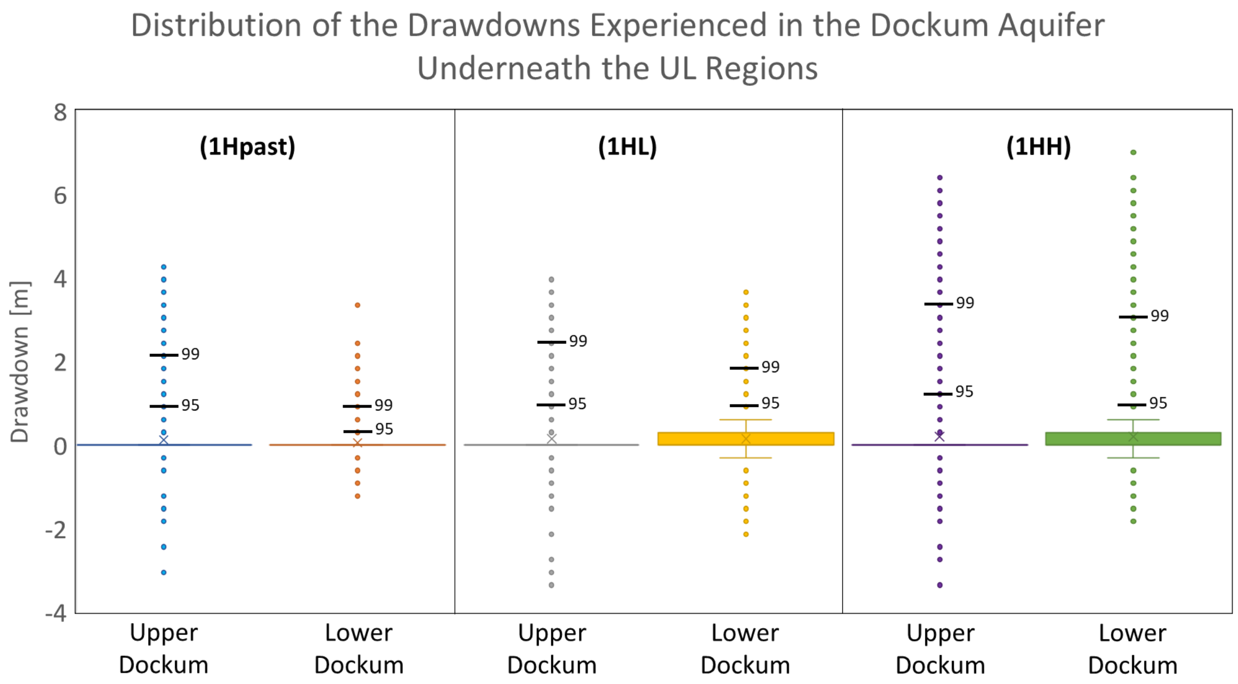


Figure 19: Summary of changes in hydraulic head from annualizing water pumping for HF across all Rig/Frack supply wells in each region screened in all aquifers.

4.3.2 Annualizing Water Pumping for HF Across Only Rig/Frack Supply Wells Screened in the Dockum Aquifer

The second approach allocated the rates and timing of groundwater pumped for HF to the Dockum aquifer. This agrees with the official UL water management plan in place since 2012. The water demand reported in FracFocus for each region was annualized and allocated to the Rig/Frack supply wells reported in the UL water well database that were screened in the Dockum aquifer. In the Northern Midland (Table 4), D&C (Table 5) and Southern Midland (Table 6) regions, annual water demand was evenly allocated across 47, 4 and 107 wells, respectively. This model was also designed to perform a 30 year forecast assuming historical low (2014) and high (2018) pumping rates for HF supply, and assuming 0% and 30% of the flowback water is recycled/treated. Scenario results assuming 30% recycling are reported in section A10 of the Appendix because they are similar to the results assuming 0% recycling.

Table 4: Annualized water demand for HF events within the Northern Midland region, assuming all existing Rig/Frack supply wells screened in the Dockum aquifer supplied the water.

Northern Midland (47 Wells)				
Year (days of HF activity)	**Annual H_2O supplied (bbl)**	**Pumping rate used (bbl/d)**	**Annual H_2O supplied (m^3)**	**Pumping rate used (m^3/d)**
2012 (129)	$7.74x10^5$	96	$9.24x10^4$	15
2013 (337)	$5.72x10^6$	271	$6.82x10^5$	43
2014 (341)	$1.15x10^7$	537	$1.37x10^6$	85
2015 (360)	$1.46x10^7$	646	$1.74x10^6$	103
2016 (366)	$1.71x10^7$	745	$2.04x10^6$	118
2017 (353)	$2.52x10^7$	1,138	$3.00x10^6$	181
2018 (324)	$2.90x10^7$	1,426	$3.46x10^6$	227
2019 (360)	$2.40x10^7$	1,051	$2.87x10^6$	167
2020 (121)	$2.64x10^7$	3,485	$3.15x10^6$	554

Table 5: Annualized water demand for HF events within the Delaware & Central region, assuming all existing Rig/Frack supply wells screened in the Dockum aquifer supplied the water.

Delaware & Central (4 Wells)				
Year (days of HF activity)	**Annual H_2O supplied (bbl)**	**Pumping rate used (bbl/d)**	**Annual H_2O supplied (m^3)**	**Pumping rate used (m^3/d)**
2012 (218)	$4.83x10^5$	416	$5.76x10^4$	66
2013 (346)	$1.84x10^6$	993	$2.19x10^5$	158
2014 (347)	$2.35x10^6$	1,267	$2.80x10^5$	201
2015 (351)	$3.79x10^6$	2,027	$4.53x10^5$	322
2016 (359)	$1.11x10^7$	5,795	$1.32x10^6$	921
2017 (351)	$2.42x10^7$	12,911	$2.88x10^6$	2,053
2018 (365)	$4.28x10^7$	21,999	$5.11x10^6$	3,497
2019 (358)	$2.77x10^7$	14,492	$3.30x10^6$	2,304
2020 (290)	$2.20x10^7$	14,254	$2.63x10^6$	2,266

Table 6: Annualized water demand for HF events within the Southern Midland region, assuming all existing Rig/Frack supply wells screened in the Dockum aquifer supplied the water.

Southern Midland (107 Wells)				
Year (days of HF activity)	**Annual H_2O supplied (bbl)**	**Pumping rate used (bbl/d)**	**Annual H_2O supplied (m^3)**	**Pumping rate used (m^3/d)**
2012 (324)	$1.75x10^7$	377	$2.08x10^6$	60
2013 (361)	$7.06x10^7$	1,371	$8.43x10^6$	218
2014 (365)	$7.91x10^7$	1,519	$9.44x10^6$	242
2015 (341)	$4.31x10^7$	886	$5.15x10^6$	141
2016 (364)	$3.15x10^7$	607	$3.76x10^6$	97
2017 (365)	$5.98x10^7$	1,148	$7.13x10^6$	183
2018 (344)	$5.40x10^7$	1,100	$6.44x10^6$	175
2019 (361)	$1.62x10^7$	315	$1.93x10^6$	50
2020 (102)	$1.62x10^7$	1,112	$1.93x10^6$	177

4.3.2.1 Upper Dockum

As of 2020, the change in hydraulic head of the upper Dockum aquifer that underlies the UL regions, owing to pumping for HF from only the Dockum aquifer (2Hpast), ranged from -13.4 to 3.04 m, compared to 2012 heads (Fig. 20). The median and mean changes were 0 m and -0.23 m, respectively. The 95th percentile was -1.22 m, and the 99th percentile was -4.57 m.

The forecasted change in hydraulic heads within the upper Dockum aquifer underneath the UL regions across the time period from 2021 to 2050, assuming low water demand for HF supply (2HL), will range from -11.5 to 3.04 m, with a median and mean value of 0 and -0.31 m (Fig. 21). The expected 95th percentile is -1.52 m, and the 99th percentile is -4.88 m.

In contrast, at the high water demand for HF supply (2HH), the change in hydraulic head will range from -20.1 to 2.74 m, with median and mean values of 0 m and -0.46 m, respectively (Fig. 22). The expected 95th percentile is -2.13 m, and the 99th percentile is -8.23 m. These median and mean values show that there was minimal impact on water levels, but there was significant drawdown experienced locally, and these results are further discussed in section 5.3.

4.3.2.2 Lower Dockum

In the lower Dockum aquifer, the change in hydraulic head by the end of 2020, owing to pumping for HF supply from only the Dockum aquifer (2Hpast), ranged from -38.4 to 1.21 m, compared to 2012 heads (Fig. 23). The median and mean changes were 0 m and -0.40 m, respectively. The 95th percentile was -1.83 m, and the 99th percentile was -5.79 m.

The forecasted change in hydraulic heads within the lower Dockum aquifer underneath the UL regions across the time period from 2021 to 2050 (2HL), assuming low water demand for HF supply, ranges from -23.1 to 1.52 m, with a median and mean value of -0.30 and -0.74 m (Fig. 24). The expected 95th percentile is -3.66 m, and the 99th percentile is -8.23 m.

In contrast, at the high water demand for HF supply (2HH), the change in hydraulic head will range from -75.8 to 1.52 m, with median and mean values of -0.30 m and -1.13 m, respectively (Fig. 25). The expected 95th percentile is -4.88 m, and the 99th percentile is -15.9 m. The local area that will experience approximately 75.8 m of drawdown in the D&C region was the area impacted the most in all the scenarios. All the results stated in this section are summarized in Fig. 26, and both drawdown frequency histograms and a summarized table of the results are reported in section A11 of the Appendix.

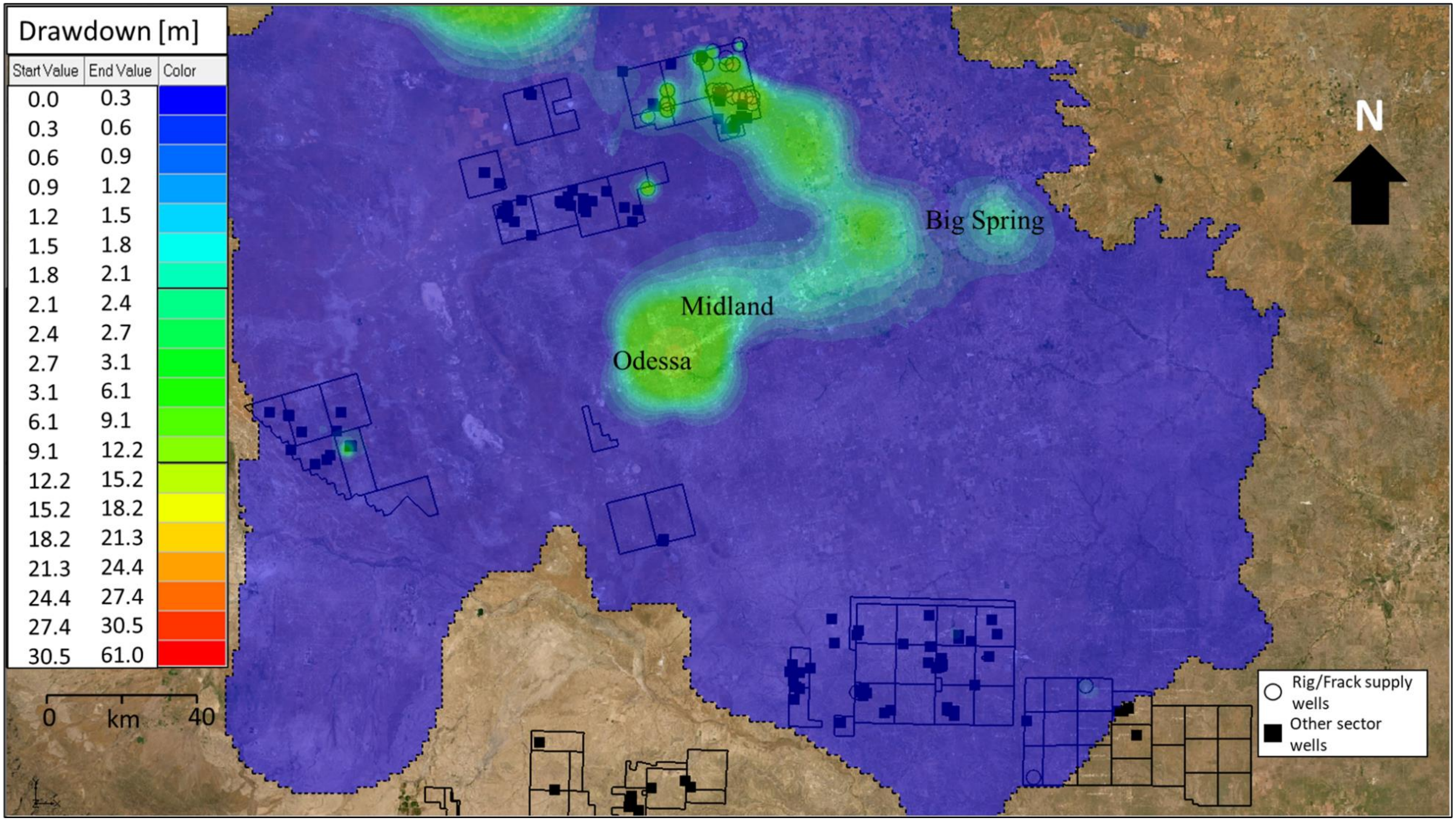


Figure 20: Drawdown in hydraulic heads within the upper Dockum aquifer assuming that pumped volumes for HF supply was supplied from wells in the Dockum aquifer (2012-2020, 2Hpast). Results for scenario 2Lpast are similar.

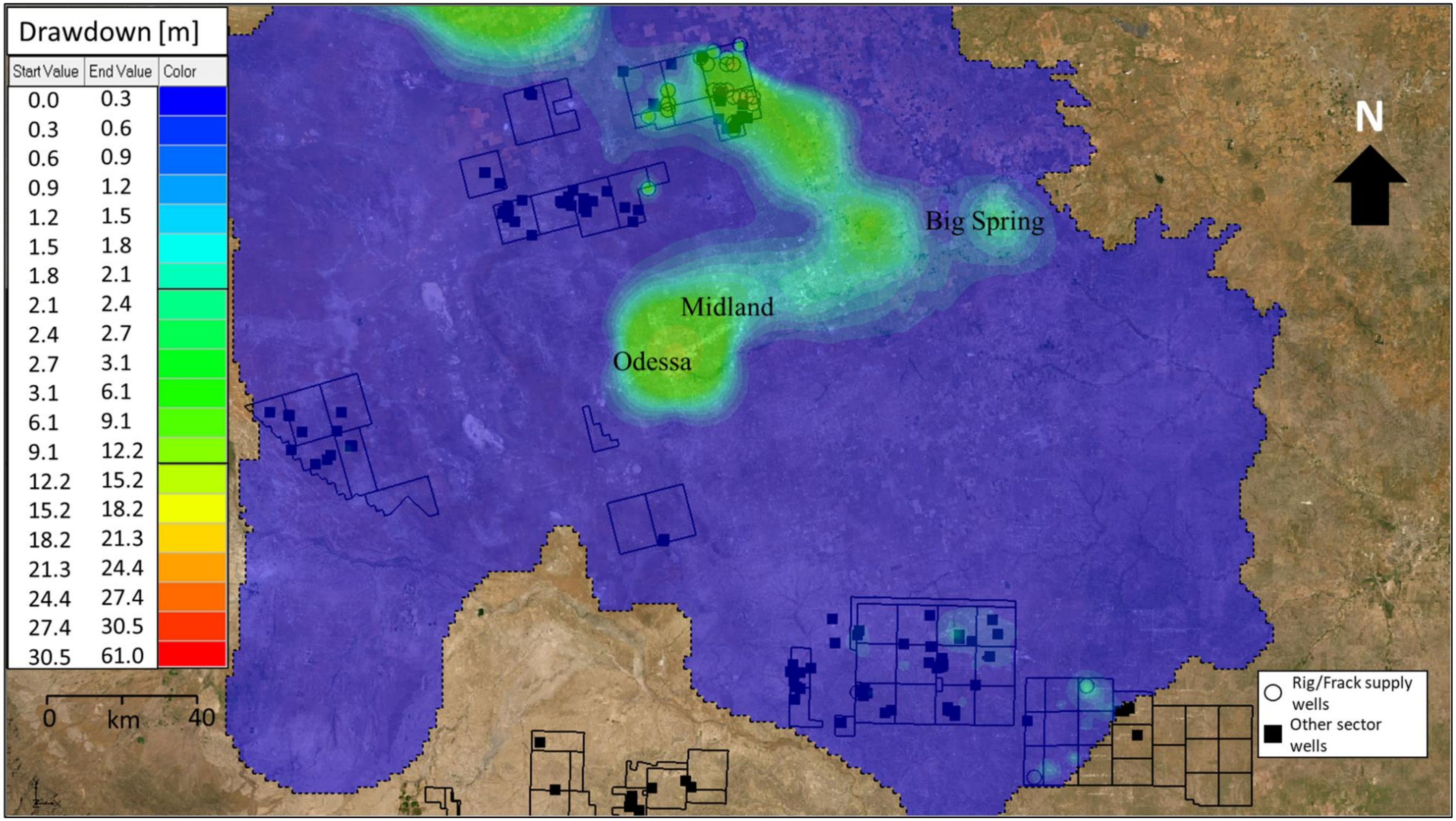


Figure 21: Expected additional future drawdown in hydraulic heads in the upper Dockum assuming the low pumping rate of water supply for HF is sourced from wells in the Dockum aquifer (2021-2050, 2HL). Results for scenario 2LL are similar.

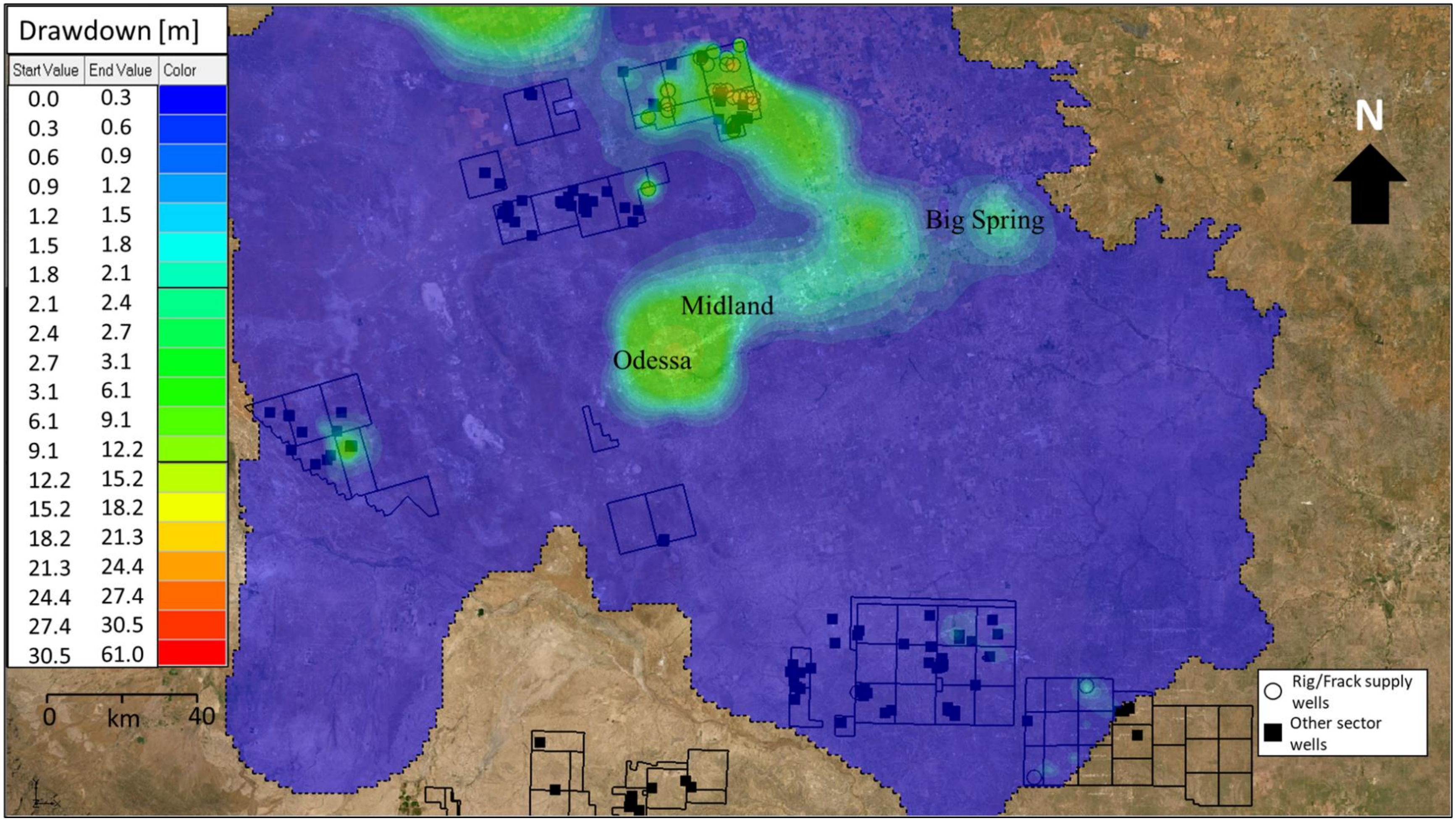


Figure 22: Expected additional future drawdown in hydraulic heads in the upper Dockum assuming the high pumping rate of water supply for HF is sourced from wells in the Dockum aquifer (2021-2050, 2HH). Results for scenario 2LH are similar.

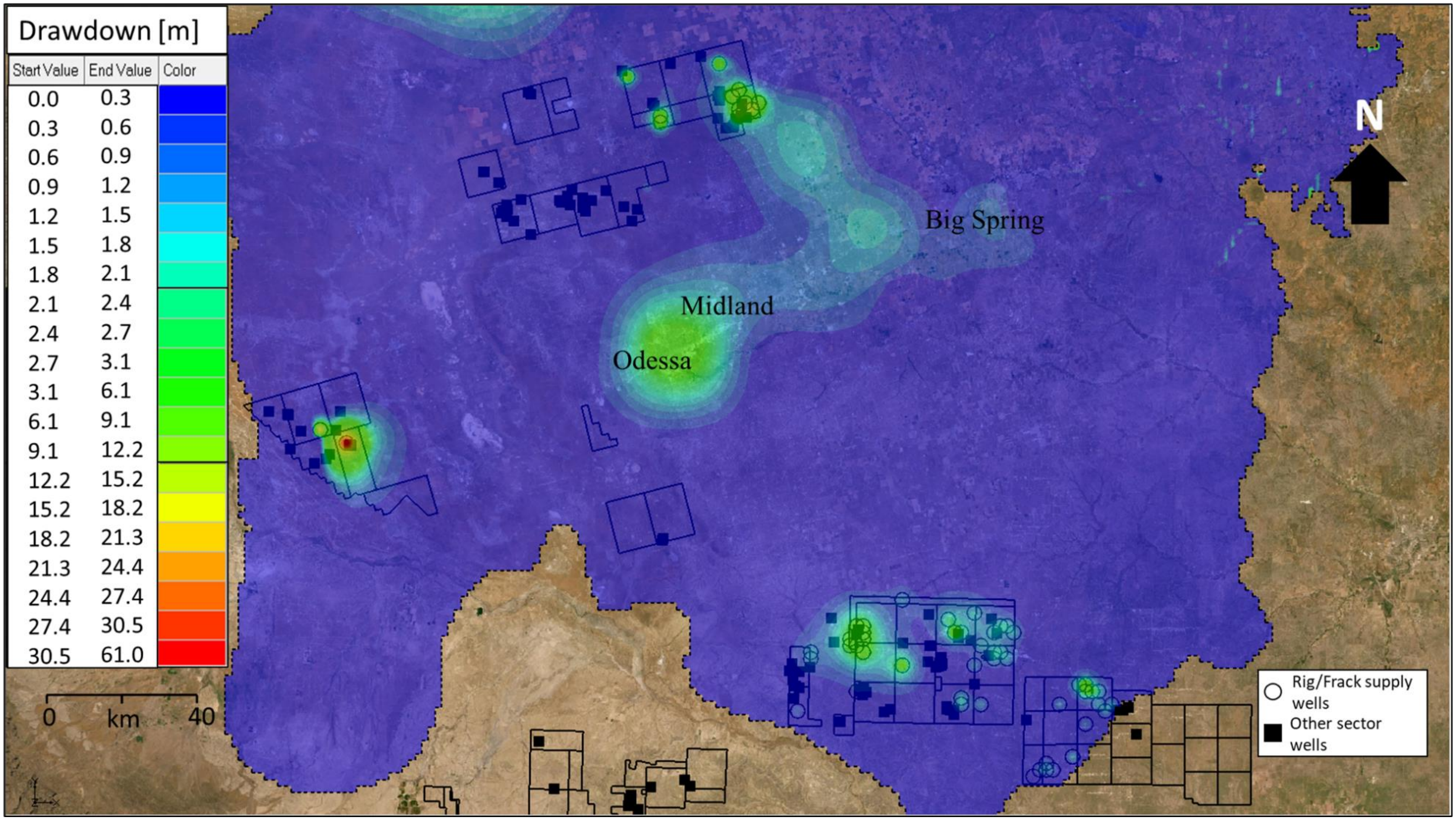


Figure 23: Drawdown in hydraulic heads within the lower Dockum aquifer assuming that pumped volumes for HF supply was supplied from wells in the Dockum aquifer (2012-2020, 2Hpast). Results for scenario 2Lpast are similar.

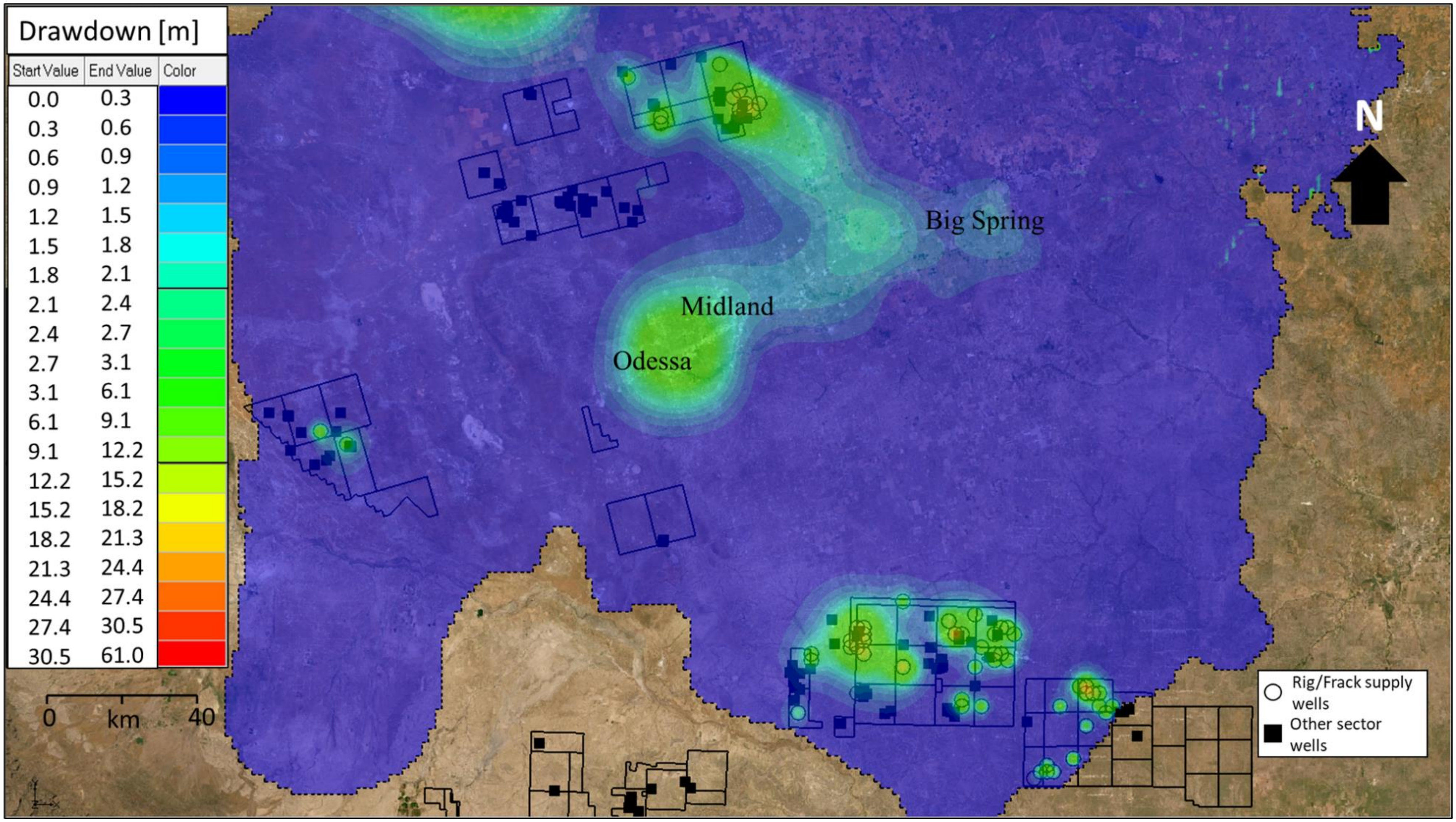


Figure 24: Expected additional future drawdown in hydraulic heads in the lower Dockum assuming the low pumping rate of water supply for HF is sourced from wells in the Dockum aquifer (2021-2050, 2HL). Results for scenario 2LL are similar.

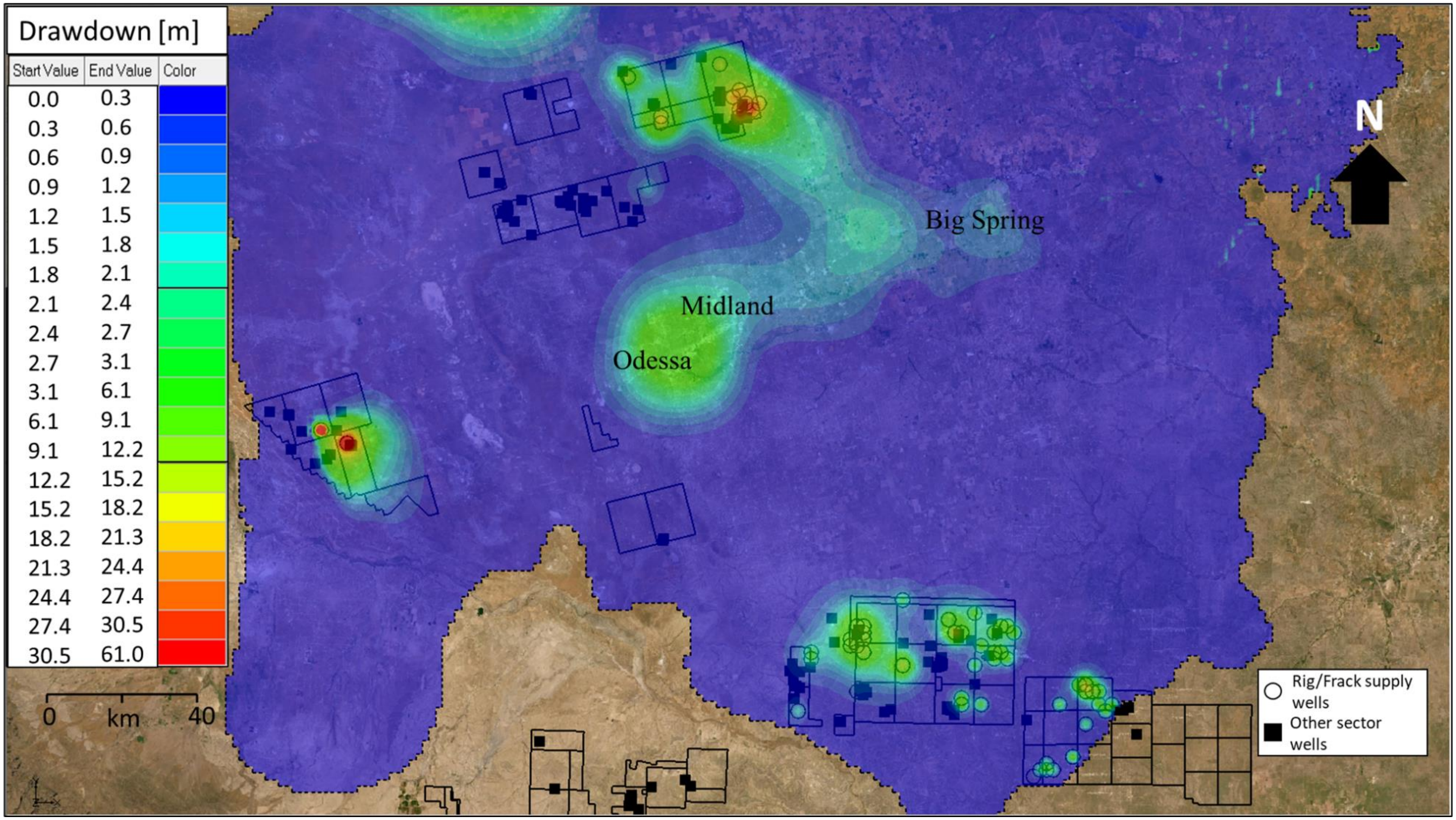


Figure 25: Expected additional future drawdown in hydraulic heads in the lower Dockum assuming the high pumping rate of water supply for HF is sourced from wells in the Dockum aquifer (2021-2050, 2HH). Results for scenario 2LH are similar.

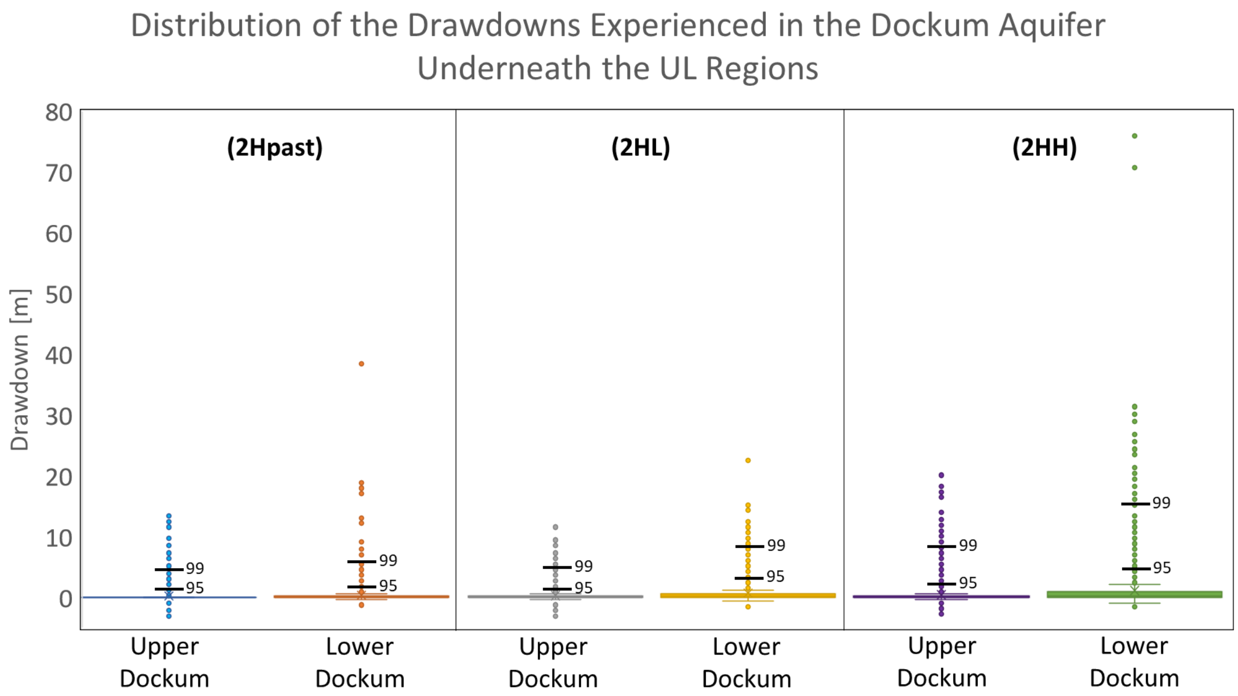


Figure 26: Summary of changes in hydraulic head from annualizing water pumping for HF across all Rig/Frack supply wells in each region screened in the Dockum aquifer.

4.3.3 Gross Water Fluxes To and From Aquifers in Response to Pumping for HF Supply

This section shows the results after quantifying the gross water volumes and fluxes that entered and left (or passed through) the aquifers. Gross water volume results are further analyzed in the discussion of this thesis. To obtain these gross water volumes, the results of the total water “in” and “out”, were aggregated over the course of the past and future study periods. These aggregated water volumes are found in the water budget for each stress period, starting since 2012. Fluxes were derived by assuming that gross water volumes were spread evenly amongst the years of study. To quantify these values within the lower Ogallala and Dockum aquifers in a water budget, the extents of these two aquifers underneath UL property were designated as distinct zones in the following manner. The UL regions’ extent within layer 1 of the model, which represented the lower Ogallala aquifer, was designated as zone 2; and within layers 2 and

3 of the model, which represented the upper and lower Dockum aquifer, were both designated as zone 3. The rest of the model was designated zone 1.

4.3.3.1 Gross Water Volumes and Fluxes To and From Aquifers by 2020

As of 2020, the gross water volume that entered the lower Ogallala and Dockum aquifers underneath the three UL regions during the time period from 2012 to 2020, assuming 0% recycling of the flowback water and pumping from all aquifers (1Hpast), was approximately equal to the volume of water that exited these aquifers. Approximately $5.22\text{x}10^6$ m^3 of water entered and exited these aquifers. The average annual volumetric flux into and out of this group of aquifers was approximately $5.80\text{x}10^5$ m^3/yr. Even when we assume that HF companies recycled 30% of the water used (1Lpast), approximately $5.22\text{x}10^6$ m^3 of water enters and exits the aquifers over the 2012 to 2020 time period, with the same average annual flux of $5.80\text{x}10^5$ m^3/yr (Fig. 27). When the assumption changes to 0% recycling and pumping from only the Dockum aquifer (2Hpast), $5.43\text{x}10^6$ m^3 of water appears to both enter and exit the aquifers. The flux was approximately $6.03\text{x}10^5$ m^3/yr. However, if we assume 30% recycling while only pumping the Dockum (2Lpast), these gross water volumes entering and exiting the aquifers are reduced to $5.36\text{x}10^6$ m^3 (Fig. 27), and the average annual volumetric flux is reduced to $5.96\text{x}10^5$ m^3/yr.

In summary, compared to when pumping is assumed to be from all aquifers underlying UL properties (1Hpast), annual fluxes increased by 4% when pumping is from only the Dockum (2Hpast). When there is 30% recycling (2Lpast), the annual fluxes increased by only 3% compared to case 1Hpast.

4.3.3.2 Gross Water Volumes and Fluxes To and From Aquifers by 2050, Assuming Low Pumping from All Aquifers

By the end of 2050, forecasted gross water volumes entering and exiting the lower Ogallala and the Dockum aquifers underneath UL (2012 – 2050), assuming 0% recycling of the flowback water (1HL), will be 9.25×10^6 and 8.68×10^6 m^3, respectively. The influx will be 2.37×10^5 m^3/yr, and the efflux will be 2.23×10^5 m^3/yr. This implies a net gain of $+1.40 \times 10^4$ m^3/yr. When we assume that HF companies will recycle 30% of the water used (1LL), the gross water volumes entering and exiting the aquifers will be 9.23×10^6 and 8.66×10^6 m^3, respectively (Fig. 28). The influx will be the same as above, and the efflux will be 2.22×10^5 m^3/yr. This is a net flux of $+1.50 \times 10^4$ m^3/yr.

When we compare the results when there is 0% (1HL) and 30% (1LL) recycling, the annual influx will remain the same, but the efflux decreases by 0.5%. However, these annual influx and efflux values mentioned above decreased by 59% and 62%, respectively, when there is both 0% (1HL) and 30% (1LL) recycling of water assuming low pumping rates, compared to the average annual fluxes between 2012 and 2020 (1Hpast, 1Lpast). This large decrease shows that relatively low long-term pumping rates greatly slows down the rate of fluxes within aquifers underneath UL.

4.3.3.3 Gross Water Volumes and Fluxes To and From Aquifers by 2050, Assuming High Pumping from All Aquifers

By 2050, when 0% recycling is assumed (1HH), 9.26×10^6 m^3 of water will enter and 8.69×10^6 m^3 will exit the aquifers (Fig. 28). The influx will be the same as if we assumed low pumping (1HL), and the efflux will be slightly reduced, resulting in a net flux of $+1.40 \times 10^4$ m^3/yr. However, if we assume 30% of recycling (1LH), the expected amount of water entering and exiting these aquifers will be slightly reduced to 9.24x10^6 and 8.68x10^6 m^3, respectively, but the fluxes were the same as stated above.

4.3.3.4 Gross Water Volumes and Fluxes To and From Aquifers by 2050, Assuming Low Pumping from Only the Dockum Aquifer

In this scenario, forecasted gross water volumes entering and exiting the lower Ogallala and the Dockum aquifers underneath UL (2012 – 2050), assuming 0% recycling of the flowback water (2HL), will be 9.63x10^6 and 9.03x10^6 m^3, respectively. The influx will be 2.50x10^5 m^3/yr, and the efflux will be 2.32x10^5 m^3/yr. This implies a net gain of +1.80x10^4 m^3/yr. When we assume that HF companies will recycle 30% of the water used (2LL), the net cumulative water volumes entering and exiting the aquifers will be 9.50x10^6 and 8.91x10^6 m^3, respectively (Fig. 28). The influx will be 2.45x10^5 m^3/yr, and the efflux will be 2.28x10^5 m^3/yr. This is a net flux of +1.70x10^4 m^3/yr.

If we compare these results when there is 0% (2HL) and 30% (2LL) recycling, the net flux decreases by 6%. However, these annual influx and efflux values mentioned above decreased again by 59% and 62%, respectively, when there is both 0% (2HL) and 30% (2LL) recycling of water assuming low pumping rates, compared to the fluxes between 2012 and 2020 (2Hpast, 2Lpast). Once again, this large decrease shows that steady long-term pumping rates greatly reduces fluxes within aquifers underneath UL.

4.3.3.5 Gross Water Volumes and Fluxes To and From Aquifers by 2050, Assuming High Pumping from Only the Dockum Aquifer

By 2050, in the scenario where 0% recycling is assumed (2HH), 9.73x10^6 m^3 of water enters and 9.12x10^6 m^3 exits the aquifers. The influx will be the same as if we assumed low pumping (2HL), and the efflux will be slightly reduced, resulting in a net flux of +1.60x10^4

m^3/yr. However, if we assume 30% of recycling (2LH), the amount entering and exiting is reduced to 9.57×10^6 and 8.98×10^6 m^3 (Fig. 28). The influx will not change, but the efflux will be 2.30×10^5 m^3/yr. This is a net flux of $+1.50 \times 10^4$ m^3/yr.

The influx values from the impacts of low (2HL) and high (2HH) pumping rates were the same for both forecast models, and the efflux values were the only ones that were impacted by the different pumping rates. This means that pumping has a larger effect on the efflux than on the influx of water within the lower Ogallala and Dockum aquifers.

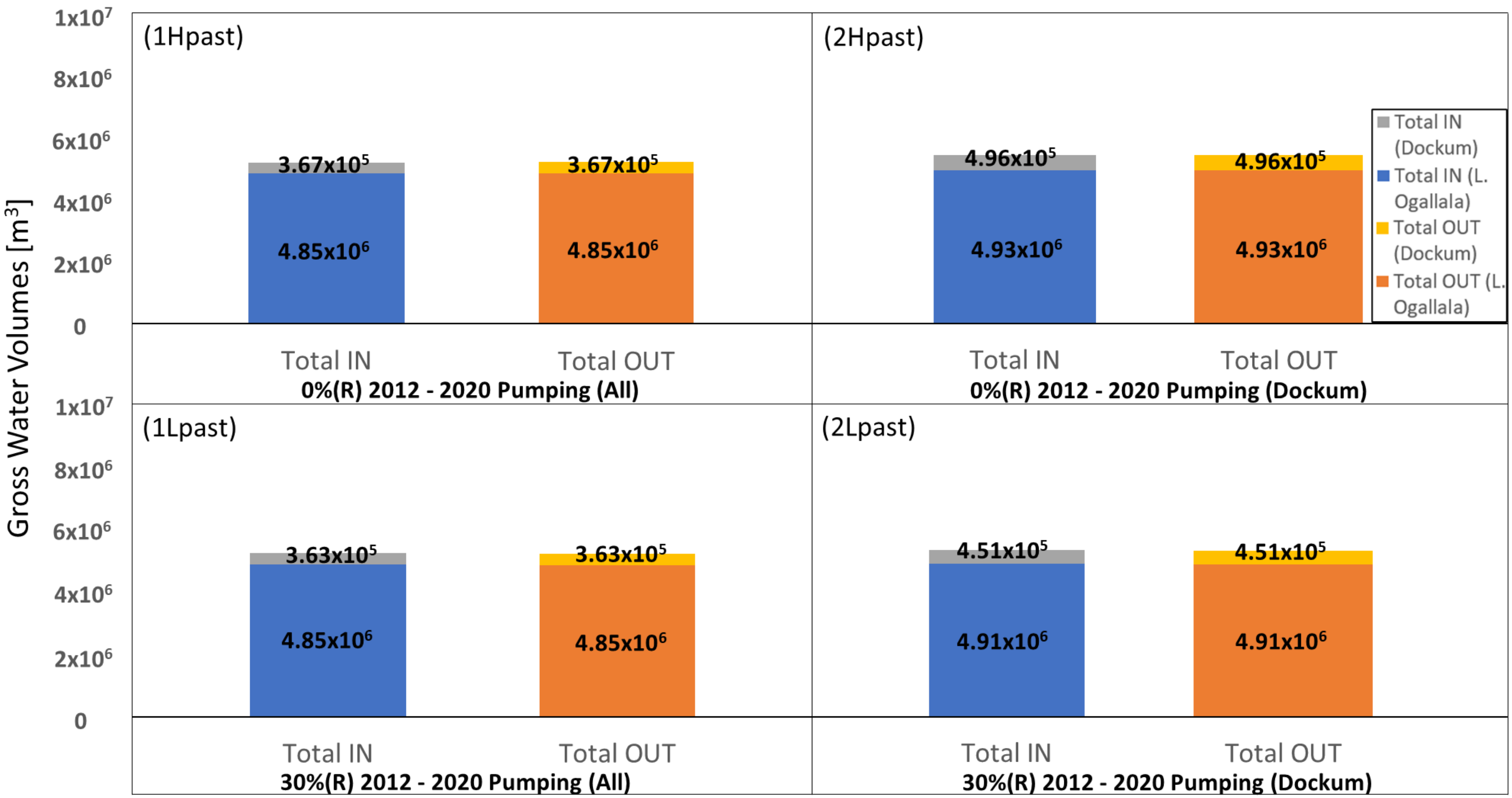


Figure 27: Total water volumes entering and exiting the lower Ogallala and the Dockum aquifers underneath the three UL regions (2012 – 2020), assuming (1Hpast) 0% recycling, pumping from all aquifers; (2Hpast) 0% recycling, pumping from Dockum aquifer; (1Lpast) 30% recycling, pumping from all aquifers; (2Lpast) 30% recycling, pumping from Dockum aquifer.

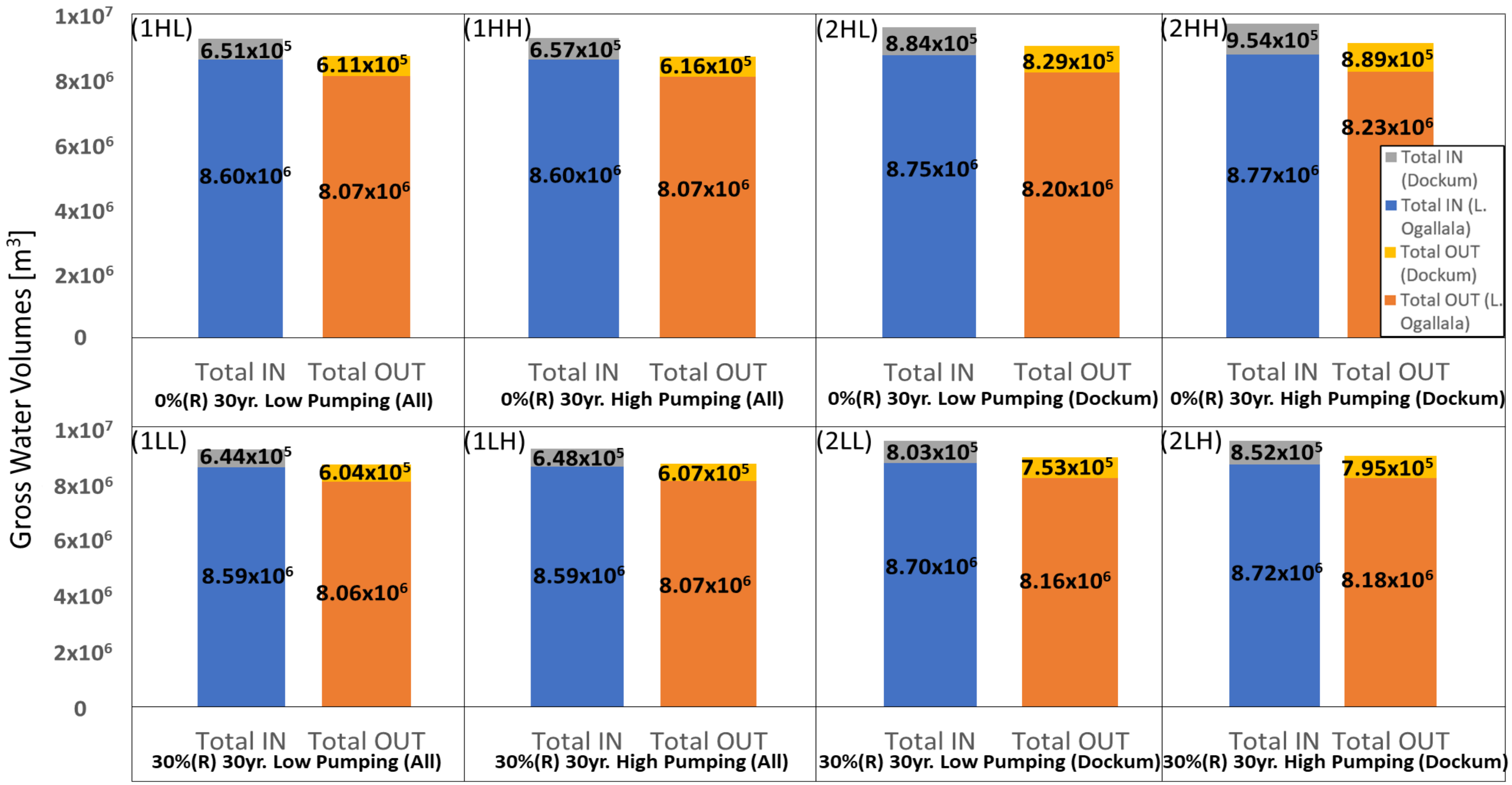


Figure 28: Forecast of total cumulative water volumes entering and exiting the lower Ogallala and the Dockum aquifers underneath the three UL regions (2012 – 2050), assuming (1HL) 0% recycling, low pumping from all aquifers; (1HH) 0% recycling, high pumping from all aquifers; (2HL) 0% recycling, low pumping from the Dockum aquifer; (2HH) 0% recycling, high pumping from the Dockum aquifer; (1LL) 30% recycling, low pumping from all aquifers; (1LH) 30% recycling, high pumping from all aquifers (2LL) 30% recycling, low pumping from Dockum aquifer; (2LH) 30% recycling, high pumping from Dockum aquifer.

4.3.4 Gross Water Fluxes Between Aquifers in Response to Pumping for HF Supply

Gross water fluxes between the lower Ogallala and the Dockum aquifers underneath the three UL regions are used to determine the general vertical flow of water between the two aquifers. The gross water fluxes between these aquifers were the result of aggregating the water fluxes reported for each time step in the same water budget zones. This was described in section 4.3.3, starting since 2012 for the duration of the past and future study periods. These water fluxes are affected by pumping for HF supply, as well as by the water supply wells built in the GAM (Ewing, et. al., 2008). The exclusion of pumping schedules from all the unaccounted other sector wells means these results are underestimating the impacts of gross water fluxes between aquifers underneath UL. The results below are further analyzed in the discussion.

4.3.4.1 Gross Water Fluxes Between Aquifers by 2020

By the end of 2020, in the case where we assume 0% recycling of flowback water and pumping from all aquifers (1Hpast), 2.76×10^5 m^3 of water flowed upwards into the lower Ogallala from the Dockum, and a smaller amount of 2.67×10^5 m^3 of water flowed downwards. If we assume 30% recycling (1Lpast), then 2.77×10^5 m^3 of water flowed upwards, and 2.65×10^5 m^3 flowed downwards into the Dockum (Fig. 29). When we change the assumptions to pumping only from the Dockum with 0% recycling (2Hpast), 2.65×10^5 m^3 of water flowed upwards, and a larger amount of 3.37×10^5 m^3 flowed downwards. Similarly, when we assume 30% recycling (2Lpast), 2.68×10^5 m^3 of water flowed into the overlying Ogallala, and 3.14×10^5 m^3 flowed downwards into the Dockum (Fig. 29). This demonstrates that pumping exclusively from the Dockum for HF supply will draw more water from the Ogallala aquifer into the Dockum.

4.3.4.2 Gross Water Fluxes Between Aquifers by 2050, Assuming Low Pumping from All Aquifers

By the end of 2050, forecasted total water fluxes between the lower Ogallala and the Dockum aquifers underneath UL (2021 – 2050), assuming 0% recycling of the flowback water and low water demand from all aquifers after 2020 (1HL), shows that $4.88\text{x}10^5$ m^3 of water flowed upwards while a smaller amount of $4.79\text{x}10^5$ m^3 flowed downwards into the Dockum (Fig. 30). If we assume 30% recycling (1LL), the volumetric flux of water that will flow upwards into the lower Ogallala and downwards into the Dockum are $4.90\text{x}10^5$ and $4.75\text{x}10^5$ m^3, respectively.

The impacts from the assumption of recycling 30% (1LL) of water compared to no recycling (1HL), would increase the gross water flux upwards into the lower Ogallala by 0.4%, and decrease downward flux into the Dockum by 0.8%.

4.3.4.3 Gross Water Fluxes Between Aquifers by 2050, Assuming High Pumping from All Aquifers

When all else was kept constant while switching from low (1HL) to high water demand for HF supply and 0% recycling (1HH), the upward flux decreased to $4.86\text{x}10^5$ m^3 and the downward flux increased to $4.80\text{x}10^5$ m^3 (Fig. 30). However, if we assume 30% recycling (1LH), the upward and downward fluxes would be $4.89\text{x}10^5$ and $4.76\text{x}10^5$ m^3, respectively.

In summary, the impacts from the assumption of recycling 30% (1LH) of water compared to no recycling (1HH), would increase the gross water flux upwards into the lower Ogallala by 0.6%, and decrease downwards into the Dockum by 0.8%.

4.3.4.4 Gross Water Fluxes Between Aquifers by 2050, Assuming Low Pumping from Only the Dockum Aquifer

By the end of 2050, the forecast of total (summed) upward and downward fluxes between the lower Ogallala and the Dockum aquifers underneath UL (2021 – 2050), assuming 0% recycling of the flowback water and low water demand from only the Dockum aquifer after 2020 (2HL), was 4.62×10^5 and 6.41×10^5 m^3, respectively (Fig. 30). If we assume 30% recycling (2LL), the upward and downward fluxes increase and decrease to 4.68×10^5 and 5.86×10^5 m^3, respectively.

The impacts from the assumption of recycling 30% (2LL) of water compared to no recycling (2HL), would increase the gross water flux upwards into the lower Ogallala by 1%, and decrease downwards into the Dockum by 9%. Now we can see that there is a greater impact in the downwards fluxes than the upwards fluxes from 30% recycling of flowback water.

4.3.4.5 Gross Water Fluxes Between Aquifers by 2050, Assuming High Pumping from Only the Dockum Aquifer

By 2050, when the assumption was changed to 0% recycling and high water demand from only the Dockum aquifer after 2020 (2HH), the amount of water that flowed upwards was 4.60×10^5 m^3, and 6.59×10^5 m^3 of water flowed downwards. However, if we assume 30% recycling (2LH), the amount flowing upwards into the lower Ogallala and downwards into the Dockum was 4.89×10^5 and 4.76×10^5 m^3, respectively (Fig. 30).

In summary, the impacts from the assumption of recycling 30% (2LH) of water compared to no recycling (2HH), would increase the gross water flux upwards into the lower Ogallala by 1%, and decrease downwards into the Dockum by 8%. These results also show that recycling of flowback water will have a greater impact on the downwards fluxes than the upwards fluxes, and if pumping is assumed from only the Dockum aquifer, then these impacts will be even greater.

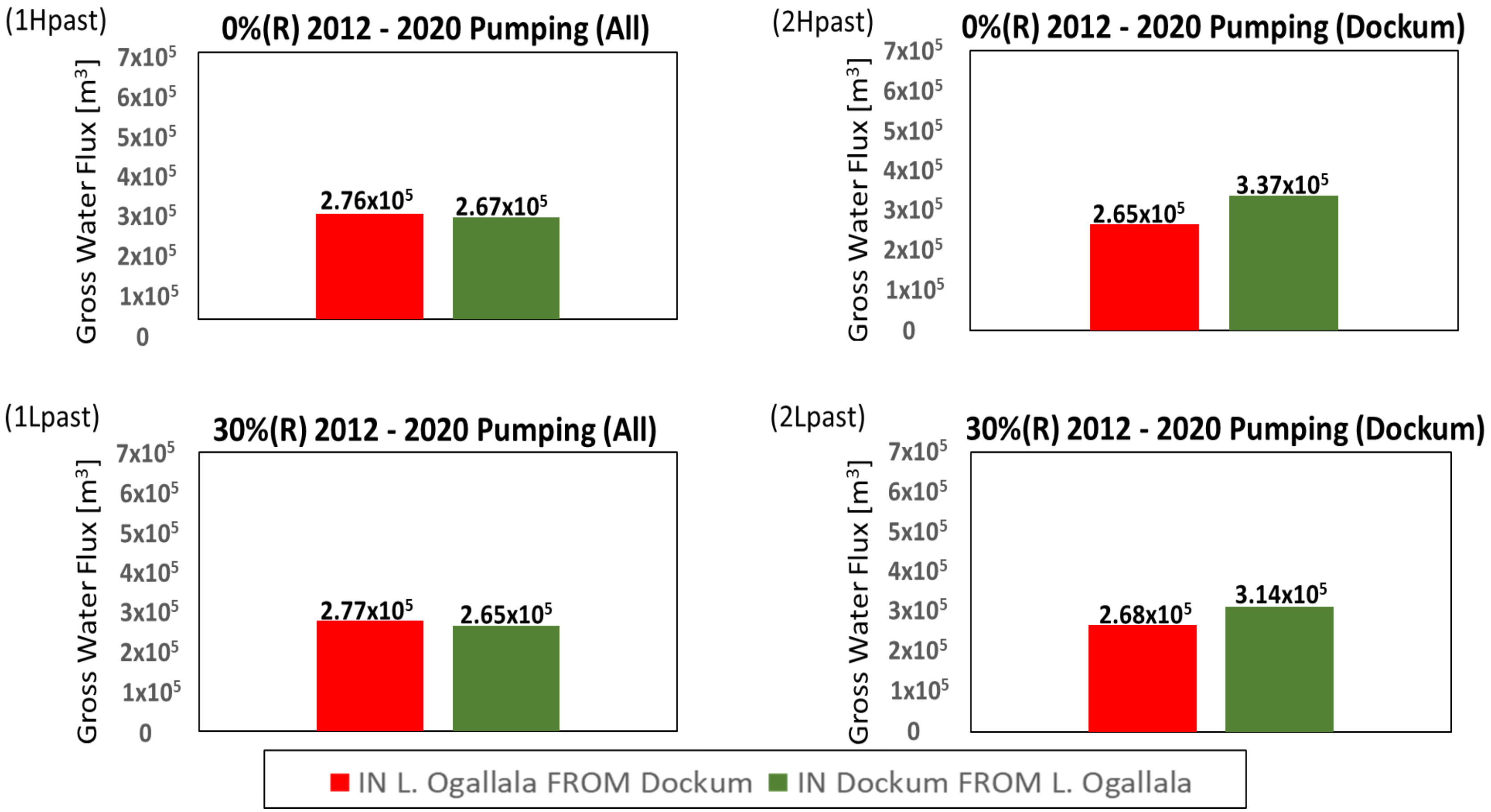


Figure 29: Total water fluxes between the lower Ogallala and the Dockum aquifers underneath the three UL regions (2012 – 2020), assuming (1Hpast) 0% recycling, pumping from all aquifers; (2Hpast) 0% recycling, pumping from Dockum aquifer; (1Lpast) 30% recycling, pumping from all aquifers; (2Lpast) 30% recycling, pumping from Dockum aquifer.

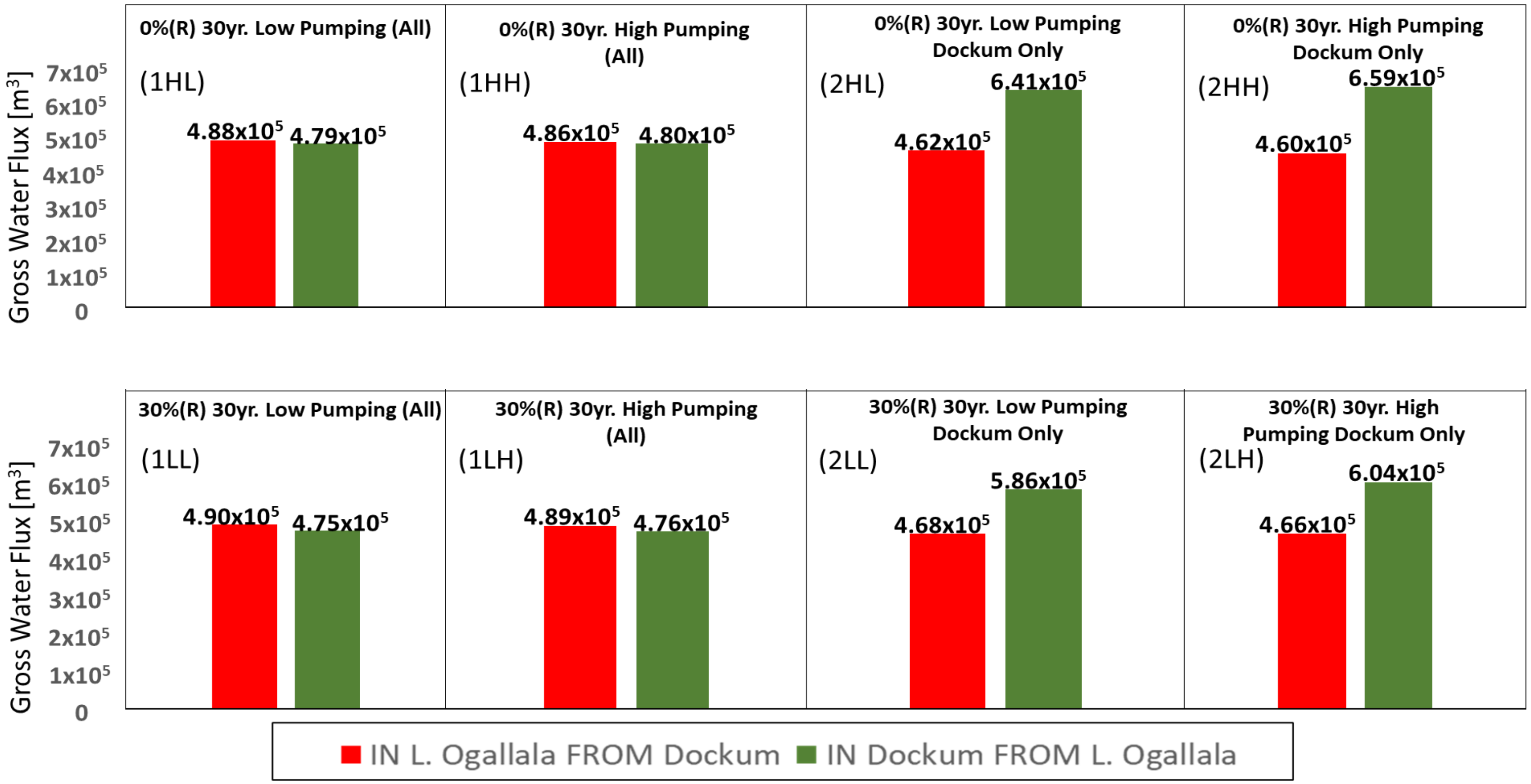


Figure 30: Forecasted total water fluxes between the lower Ogallala and the Dockum aquifers underneath the three UL regions (2012 – 2050) , assuming (1HL) 0% recycling, low pumping from all aquifers; (1HH) 0% recycling, high pumping from all aquifers; (2HL) 0% recycling, low pumping from Dockum aquifer; (2HH) 0% recycling, high pumping from Dockum aquifer; (1LL) 30% recycling, low pumping from all aquifers; (1LH) 30% recycling, high pumping from all aquifers (2LL) 30% recycling, low pumping from Dockum aquifer; (2LH) 30% recycling, high pumping from Dockum aquifer.

5. DISCUSSION

5.1 Research Objectives

The overall goal of this thesis is to understand the impact of water use for HF on the water levels, fluxes, and stored volumes of water in aquifers beneath UL's property which have been the site of HF activity for over 10 years. The specific research objectives are to assess the: (1) distribution of groundwater quality for the aquifers underlying UL acreage; (2) impacts from pumping for HF on the hydraulic heads of the Dockum aquifer; (3) gross water volumes that enter and leave storage; and (4) gross water fluxes within and between the Dockum and lower Ogallala aquifers. This discussion is organized in the order listed above, beginning with the assessment of the distribution of groundwater quality for the aquifers underneath UL.

5.2 Assessment of the Distribution of Groundwater Quality for the Aquifers Underneath University Lands

The Pecos Valley, Edwards-Trinity (Plateau), and Dockum aquifers provided water for HF at UL prior to 2021. At least one of each one of these aquifers is underneath the entire extent of the Northern Midland, Delaware & Central, and Southern Midland regions. The Dockum is under the entire extent of Northern Midland, the Pecos Valley is under the entire extent of the D&C, and the Edwards-Trinity (Plateau) is under the entire extent of Southern Midland (Fig. 2).

5.2.1 Northern Midland

The extent of the property blocks that make up the Northern Midland region overlaps partially with the Pecos Valley and Edwards-Trinity (Plateau) aquifers, but entirely with the Dockum aquifer, which is expected to contain fresh and brackish water (Fig. 11). Blocks 11 and 12 are the only ones that overlap with the extent of the Pecos Valley, which is expected to contain fresh water (Fig. 7). Blocks 1 and 9 are the only ones that overlap with the Edwards-Trinity (Plateau), which is expected to contain very fresh water (Fig. 9).

5.2.2 Delaware & Central

The extent of the blocks that make up the D&C region overlaps partially with the Dockum aquifer, but entirely with the Pecos Valley aquifer, which contains very fresh to brackish water (Fig. 7). The Edwards-Trinity (Plateau) does not underlie the D&C region. Blocks 18, 19, 20, 21 and 30 are the ones that partially overlap with the extent of the Dockum aquifer, which is expected to contain fresh to very fresh water underlying the D&C (Fig. 11).

5.2.3 Southern Midland

The extent of the blocks that make up the Southern Midland region overlaps partially with the Dockum and Pecos Valley aquifers, but entirely with the Edwards-Trinity (Plateau) aquifer, which is expected to contain from very fresh to brackish water (Fig. 9). Blocks 16, 24, and 26 are the ones that partially overlap with the extent of the Pecos Valley aquifer, which is expected to contain brackish water (Fig. 7). The Dockum aquifer overlaps with the Southern Midland region's blocks 1 through 15, 29, 40, and 43 through 51. Water quality in this part of the Dockum ranges from fresh to brackish (Fig. 11). Block numbers are only mentioned above as a spatial reference (a map of UL property with the labeled block sections can be found in the Appendix section A7) and were left out of water quality maps to avoid having too much information displayed in them that was covering up the results.

5.3 Assessment of the Impacts on the Hydraulic Heads of the Dockum Aquifer Underlying University Lands

The impacts on the hydraulic heads in the Dockum aquifer due to pumping for the Rig/Frack supply well sector was experienced by other sector wells within the three UL regions.

If water levels drop drastically (>15 m), then it is likely for a well to burn out by drawing air instead of getting cooled down by the temperature of the groundwater (Washington State Department of Health, 2009). As mentioned in section 3.4.5, a list (made in Excel) of selected (1×1 mile grid) cells covering the UL regions (Northern Midland, D&C, and Southern Midland Basin) was used to define the area where drawdown results will be extracted from the exported GMS text file. The following sections will assess the impacts on hydraulic heads by 2020 and by 2050, under the assumptions of 0% and 30% recycling of flowback water, and low or high pumping rates. Results for 30% recycling are similar to the results for 0% recycling and are thus not discussed. There are only 70 other sector wells screened in the Dockum aquifer that are within the three UL regions, and this low number of wells is likely due to the fact that it is more expensive to drill a deeper well and there is generally lower water quality than in the Pecos Valley, Edwards-Trinity (Plateau), and lower Ogallala aquifers.

5.3.1 Impacts on Hydraulic Heads by 2020 (1Hpast, 2Hpast)

By 2020, the impacts on drawdowns when we assumed pumping from all aquifers impacted 8 out of 34 other sector wells by lowering water levels in those wells by median drawdowns of 2 m (7 ft) in Northern Midland region. In the D&C region 4 out of 12 other sector wells were impacted by median drawdowns of 1.5 m (5 ft). Only 1 out of 24 other sector wells was impacted with 0.3 m (1 ft) drawdown, at Southern Midland. Maximum drawdown impacts are only reported if its value is different from the median drawdown impact. These are minimal impacts which should have no impact on the well owners. In comparison, when we assume pumping from only the Dockum aquifer, the same wells mentioned above experienced up to 6 m (20 ft), in Northern Midland. In the D&C region, 7 out of 12 other sector wells were impacted by median drawdowns of 3 m (10 ft) of drawdown, but 3 out of those 7 wells experienced maximum drawdown impacts of 30 to 60 m (100 to 200 ft). In Southern Midland, 4 out of 24 other sector wells were impacted by median drawdowns of 3 m (10 ft). Unfortunately, it is likely that the pumps in wells experiencing 30 to 60 m (100 to 200 ft) drawdowns burnt out, or the well owners were forced to pay a higher price to pump the groundwater or were forced to pay to deepen their well(s) (Obkirchner, 2019).

5.3.2 Forecasted Impacts on Hydraulic Heads by 2050, Assuming Low Pumping Rates from All Aquifers (1HL)

Forecasted impacts on hydraulic heads assuming low pumping rates will impact the same wells affected by 2020, by median drawdowns of 2.5 m (8 ft) in Northern Midland; and in Southern Midland 3 out of the 24 other sector wells will be impacted by median drawdowns of 1 m (3 ft). Interestingly, within the D&C region the hydraulic head will recover, showing no impact on hydraulic head in wells that were previously impacted by 2020. When pumping ceases, or is reduced, the lateral inflow of water in the aquifer continues, and the water table gradually recovers towards equilibrium (Buddemeier, 2000). The impacts in the affected regions are likely to force well owners to pay a higher price to pump (USGS, 2021).

5.3.3 Forecasted Impacts on Hydraulic Heads by 2050, Assuming High Pumping Rates from All Aquifers (1HH)

In comparison, when we assume high pumping rates, the 9 out of 34 other sector wells impacted at Northern Midland will experience median drawdowns of 2.5 m (8 ft), as the area of influence, from the spreading local cone of depression, grows. Drawdowns in aquifers suggest the presence of a cone of depression – the land area above a cone of depression is referred to as the area of influence – and the spreading of a cone of depression can be enhanced by well interference when two or more overlapping cones of depression are present (Raymond, 1988). In

D&C, the wells impacted by 2020, will be impacted by median drawdowns of 1.8 m (6 ft), with the addition of 1 more other sector well. In Southern Midland, 3 out of 24 other sector wells will be affected by median drawdowns of 1 m (3 ft). This also suggests that the well owners who will be affected are likely to pay a higher price to pump (USGS, 2021).

5.3.4 Forecasted Impacts on Hydraulic Heads by 2050, Assuming Low Pumping Rates from Only the Dockum Aquifer (2HL)

In contrast, forecasted impacts on hydraulic heads will impact 9 out of 34 other sector wells by median drawdowns of 3 m (10 ft) in Northern Midland. At D&C, 6 out of 12 other sector wells will be impacted by median drawdowns of 2 m (7 ft). Interestingly, that means that the water levels will be able to recover substantially from the 30 to 60 m (100 to 200 ft) drawdown experienced by 2020, by lowering the pumping rates (Buddemeier, 2000). In Southern Midland, 15 out of 24 other sector wells were affected by median drawdowns of 3 m (10 ft), and 3 out of those 15 were impacted by maximum drawdowns of 15 to 18 m (50 to 60 ft). Unfortunately, the well owners who were affected the most under these assumptions will suffer a pump burnout, will be forced to pay a higher price to pump the groundwater or forced to pay to deepen their well(s) (Obkirchner, 2019).

5.3.5 Forecasted Impacts on Hydraulic Heads by 2050, Assuming High Pumping Rates from Only the Dockum Aquifer (2HH)

In comparison, when we assume high pumping rates, all the wells impacted at Northern Midland when assuming low pumping rates will be affected by median drawdowns of 10 m (30 ft), and 1 of these 9 wells will experience a maximum drawdown of 15 to 18 m (50 to 60 ft). At D&C, 7 out of 12 other sector wells will be impacted by median drawdowns of 3 m (10 ft), and 3 of these 7 will experience maximum drawdown impacts of 30 to 60 m (100 to 200 ft). In

Southern Midland, 10 out of 24 other sector wells will be impacted by median drawdowns of 1 m, and maximum drawdown impacts of 2.5 m will be experienced by 3 of these 10 wells. Drawdowns will be greatly enhanced by well interference when the high pumping rates are assumed within Northern Midland and D&C (Raymond, 1988). This also suggests that the well owners who were affected the most in each region will suffer a pump burnout, will be forced to pay a higher price to pump the groundwater or forced to pay to deepen their well(s) (Obkirchner, 2019).

5.4 Assessment of the Gross Water Volumes that Entered and Left the Lower Ogallala and Dockum Aquifers Underlying UL, as a Single Grouping of Aquifers

Gross water volumes that entered and left the two aquifers underlying the three UL regions within the GAM were a new insight that has not been previously quantified. According to a report for the Texas Comptroller of Public Accounts written by Robert E. Mace (2019), there is no public database which contains pumping schedule data of wells supplying water for HF oil extraction in the Permian Basin. In the present study, the estimated annual pumping schedules used in each of the models were an attempt to estimate the impacts of supplying water for HF on these aquifers in the Permian Basin.

5.4.1 Assessment of Gross Water Volumes by 2020, Assuming 0% Recycling of Flowback Water (1Hpast, 2Hpast)

The results suggests that there was natural groundwater flow from the areas surrounding UL that was able to push water in and out of the aquifers within the regions underneath UL, and this happened in large enough quantities so that it seems as if all the water that came into both aquifers also left, but there is in fact a slight difference between the two which was insignificant compared to the total accumulated water volumes. Groundwater flows both vertically and laterally within the groundwater system (Winter, 1998). To try to isolate just the impact that pumping for HF supply on UL properties has on vertical fluxes across aquifers, the zones do not extend across the entire aquifer, but rather only lie directly below UL properties which were grouped into three regions. This ignores the impacts of pumping on lateral fluxes into the sides of the aquifer and this study also notably does not model pumping for HF supply occurring all around UL properties. Therefore, the impacts described here are far less than the overall impacts of the entire HF industry in the Permian Basin. With this limitation explained, if we compare the results of the models between pumping from all aquifers and pumping only from the Dockum, we can see there was a 35% increase in the amount of water flowing in and out of the Dockum, and a 1% increase for the lower Ogallala. Therefore, UL's Water Plan of switching pumping for HF supply to the Dockum has immediate effects on volumetric fluxes.

5.4.2 Assessment of Gross Water Volumes by 2020, Assuming 30% Recycling of Flowback Water (1Lpast, 2Lpast)

When we compare what happens if we assume 30% recycling when pumping from all aquifers, then there is only a 1% reduction in water flowing through the Dockum compared to when there is no recycling, and an insignificant reduction through the lower Ogallala. When recycling is implemented in the case of pumping only from the Dockum, there is a 10% reduction in water flowing through the Dockum, and <1% reduction through the lower Ogallala. This means that the gross water volumes that entered and left the Dockum aquifer, in the three UL regions, were impacted much more than the lower Ogallala by the different pumping rate and recycling assumptions. In other words, the Dockum aquifer experienced a higher percentage increase when pumping is only from the Dockum compared to when it is from all aquifers, as well as a larger reduction when 30% of the water was recycled compared to when there is no recycling of flowback water.

5.4.3 Assessment of the Forecasted Gross Water Volumes by 2050, Assuming 0% Recycling of Flowback Water (1HL, 2HL, 1HH, 2HH)

The forecasted model results show that the Rig/Frack supply wells will pump a gross amount of water that is greater than was pumped by the end of 2020, permitting the difference between the gross water volumes going in and out of the lower Ogallala and the Dockum aquifers to be compared quantitatively and qualitatively. The results from all the models show that a larger amount of water will go into both aquifers than out of them. This means that the aquifers underlying UL can provide water for HF for many decades if the activity remains under the selected assumptions. When we compare the gross water volumes for low pumping from all aquifers and low pumping from only the Dockum aquifer, there is an increase in water going into the Dockum and the lower Ogallala underlying UL of 36%, and 2%, respectively. The amount of water that went out of the Dockum and lower Ogallala will also increase by the same percentage. In contrast, when we assume high pumping rates, the water volumes going into the Dockum and lower Ogallala will increase by 45%, and 2%, respectively; and the water volumes going out will increase by 44%, and 2%, respectively. These results are further discussed in the next section.

5.4.4 Assessment of the Forecasted Gross Water Volumes by 2050, Assuming 30% Recycling of Flowback Water (1LL, 1LH, 2LL, 2LH)

When we compared the results if we assume there is 30% recycling with 0% recycling for both low and high pumping scenarios from all aquifers, the aquifers will only experience water volume reductions of 1% for water going in and out of the Dockum, and <1% reductions for water going in and out of the lower Ogallala. However, when we assume low pumping rates from only the Dockum, there will be a reduction of 10% of water going into and out of the Dockum, and a reduction of <1% for the water going in and out of the lower Ogallala, compared to when assuming low pumping rates without recycling. Similarly, when we assume high pumping from the Dockum only, there is a 12% reduction in the water volumes going in and out of the Dockum, and <1% reduction for water volumes entering and leaving the lower Ogallala, compared to when assuming high pumping rates without recycling.

After further analysis of the results, it is important to note that all the pumping in these models came from within the Dockum aquifer, which it is hydraulically connected with the lower Ogallala aquifer (Ewing, 2008). The hydraulic connection between the two aquifers is good enough that if we increase the pumping rates of wells screened in the Dockum, to supply water for HF, then more water volumes will flow not only within the Dockum, but also within the lower Ogallala underlying UL as well. However, the annual rates at which these fluxes happen will decrease as a result from compression of the unconfined Dockum aquifer (USGS, 2013). In other words, water will enter and leave these aquifers underneath the three UL regions, but that flux will happen at slower rates. In the following section, we take a closer look at how these two aquifers exchange water.

5.5 Assessment of the Gross Water Fluxes Between the Lower Ogallala and Dockum Aquifers

The lower Ogallala has high quality fresh water, while the Dockum has lower quality brackish water. This means that to conserve the quality of the fresh water in the Ogallala, it would be better if more water is flowing downwards into the brackish waters of the Dockum, rather than flowing upward. This does not, however, conserve the quantity of that fresh water. For some perspective, we can assume that all the water in the lower Ogallala will be fresh (Ewing, et. al., 2008). If the regional annual pumping activity is allocated between all aquifers, then there is a possibility that more water (approximately 6,000 to 9,000 m^3) will flow up from the brackish Dockum into the high quality fresh water of the lower Ogallala. Fortunately, the UL policy of encouraging HF companies to use the lower quality brackish water from the Dockum (UL, 2012) has shown potential for conserving the high quality fresh water of the lower Ogallala, since much more water would end up flowing downwards than upwards. This is significant because based on a study of comparisons in hydraulic head and water chemistry, upward flow from the Dockum aquifer to the Ogallala aquifer is likely in some areas (Nativ 1988).

5.5.1 Assessment of Gross Water Fluxes Between Aquifers by 2020

The volume of water entering the lower Ogallala from Dockum during 2012 to 2020, when assuming pumping only from the Dockum, decreased by 4% compared to pumping from all aquifers. The amount of water flowing into the Dockum from lower Ogallala increased by 26%, compared to when pumping is assumed from all aquifers. If we assumed 30% recycling, the overall pattern is that water flux into lower Ogallala increased, and water flux into the Dockum decreased, for both high and low pumping rate assumptions.

5.5.2 Assessment of Forecasted Gross Water Fluxes Between Aquifers by 2050

For the low pumping scenario, the annual volume of water that will enter the lower Ogallala, when assuming pumping only from the Dockum, will decrease by 6%, and the amount of water that will flow into the Dockum from lower Ogallala will increase by 34%, compared to when pumping is assumed from all aquifers. Similarly, making the same comparison between just sourcing HF supply water from the Dockum vs. all aquifers in the high pumping scenario, water influx to the lower Ogallala will decrease 6%, and water influx into the Dockum will increase by 37%. The same overall pattern is also seen when we assume that 30% of water will be recycled – gross water fluxes into the lower Ogallala from Dockum will increase, while downwards flow into the Dockum from lower Ogallala will decrease. The lower Ogallala seems to readily act as a "water bank savings account" for the Dockum aquifer since recycling 30% of flowback water, which eases stress on the Dockum, lowered the amount of water that the Dockum received from lower Ogallala; and also because whenever the pumping is assumed to be only from the Dockum, which increased stress on the Dockum, then the lower Ogallala comes to the rescue by increasing the amount of water fluxed into the Dockum.

5.6 Model Weaknesses

5.6.1 Model Assumptions and Uncertainty

All the reported Rig/Frack supply wells from the UL water well database are assumed to be present and active throughout the entire study period starting in 2012. The UL database was downloaded during the summer of 2020, and these wells were drilled from at least 2001 to 2020, but only 15% of all the wells in the database reported a drilled date. It is likely that this bias will cause an overestimate of wells for every year since many wells were installed after the beginning of 2012, since HF was just getting started in the Basin. The exclusion of pumping schedules from all the unaccounted other sector wells means that these results are underestimating the impacts of gross water fluxes between aquifers and changes in hydraulic heads underneath UL. The pumping that was simulated on UL properties draws water in laterally from the aquifer surrounding UL. This will greatly diminish the vertical flux results, which would be much larger if there was competing pumping around UL properties. Importantly, pumping for HF supply does occur outside of UL properties, which means that any estimates of impacts from groundwater pumping for HF supply by UL operators is a conservative estimate compared to the overall impacts of the entire HF industry across the Permian Basin. It is important to note that these models are scenarios of exploration and are not calibrated past the year 1997, so any modeled results for the study period are not guaranteed to be observed in the field. The pumping schedules for the wells that came with the GAM were not edited or deliberately removed, and all the details of how the GAM was designed can be found in the official GAM report (Ewing, et. al., 2008). The official GAM report also states that the hydraulic connection of water that flows from the lower Ogallala into the Dockum is dominated by the vertical hydraulic conductivity in the Dockum, which was estimated using literature values for sand and clay combined with percentage of sand and clay in the Dockum (Ewing, et. al., 2008).

In this study, we generally assumed that the databases contain accurate information including well locations and depths, depth to water levels, water quality parameters, water demands from HF oil production wells. All the findings in this project depend on the accuracy of the databases used. For example, if the wells are not in the right location, then the spatial distribution of the impacts could be completely different, and the same is valid for the rest of these model inputs like the reported water volumes demanded for each HF event, or the timing of these events. The degree of uncertainty is increased in most cases by the lack of sufficient data, such as the missing drill dates mentioned above, and errors in observed data used also contribute to uncertainty in the estimated values of model parameters (Bear, et. al., 1992).

A major uncertainty in this study is that HF oil producers do not know where the reported water volumes used are sourced from. This is why the sensitivity analysis was performed by considering the impacts on the modeling results from changing between two main ways that water could have been (and will) be sourced: by region, and by aquifer. It was clear that the third approach that allocated water source to the nearest well, as had been done previously in the more densely populated and drilled Eagle Ford Shale (Obkirchner, 2019), did not produce realistic outcomes since many of the assumed HF supply wells (any water supply wells found in the SDR database containing at least one HF event within their catchment area) dried out the grid cells within the pumped aquifer underneath UL properties. This means that the maximum drawdowns over time in a given well commonly exceeded the aquifer thickness. The first two approaches to allocate water by region and by aquifer on an annualized basis, however, produced more realistic outcomes. Maximum drawdowns reached up to 60 m in some wells. Annualized pumping for HF supply smooths episodic, intensive pumping periods, over an entire year thereby diminishing the calculated drawdown experienced within several km of the pumping well. Therefore, annualizing the pumping rates probably underestimated the amount of drawdown which occasionally occurred in other sector wells located within several km of HF supply wells (Obkirchner, 2019).

5.6.2 Future Research Direction and Opportunities

Since the water demand for HF supply was annualized and then evenly allocated to all the Rig/Frack supply wells, the model could be improved if the regional pumping schedules were allocated on a weekly basis to assess the short-term impacts of groundwater pumping for HF supply on the lower Ogallala and Dockum aquifers. This could achieve a deeper understanding of how pumping aquifers in the Permian Basin to supply water for HF is impacting other sector well owners within UL in the short term, and in the long run (Obkirchner, 2019). This could be achieved by designing a code to combine databases and assign each region's weekly pumping schedule to all the Rig/Frack supply wells within the Northern Midland, D&C, and Southern Midland regions. Another way to enhance our understanding of the impacts from pumping from the Dockum aquifer would be to manually update all the databases and calibrate the model to reduce uncertainty, include any unaccounted wells, and remove outdated information.

5.7 Groundwater Competition Between HF Supply and Other Water Supply Sectors

The other water supply sectors within UL acreage that are competing for groundwater with the HF industry the most, are the livestock and municipal sectors. In total, there are 3,870 groundwater wells in the UL database, including the 744 (19%) monitoring/testing wells. Out of the 3,112 water supply wells, 1,520 (49%) were Rig/Frack supply wells providing water for oil & gas operations during the time period from 2012 to 2020. However, 987 wells (32%) were reported for livestock supply, and 307 wells (10%) were reported for municipal supply. Together, these three industries account for approximately 90% of all the water supply wells within UL.

In the Texas regional water planning area F, the permitted groundwater pumping volumes for the year 2020 for livestock and municipal supply are 0.3 and 2.5 times the permitted pumping volumes for HF, respectively (TWDB, 2016). This means we could expect that within UL, the livestock supply wells will pump at lower rates than the Rig/Frack supply wells. Likewise, we could expect that the municipal supply wells will pump at higher rates than the Rig/Frack supply wells, despite only accounting for 10% of the water supply wells in the UL groundwater database. These new insights describe how approximately 90% of the water supply wells within UL are competing for groundwater. The reasons behind this groundwater competition are all driven by economic gains.

The livestock industry in Texas was valued at $12.3 billion, in 2017 (Miller, 2021). Livestock has been a major Texas industry throughout history. However, water in Texas oilfields is enormously valuable, and the opportunity to sell HF water and disposal services allows ranchers to make millions of dollars more per year in returns than they did raising cattle (Collins, 2017). Ranchers who are leasing UL acreage are no exception to this economic opportunity, and will likely be tempted to provide water for HF. In the Permian Basin, a ranch that fills a $5x10^5$ bbl “frack pit” twice per month with fresh water could realistically generate $3 million per year in profit ($0.25/bbl), which is the same profit as selling nearly 11,000 feeder cattle annually ($272.73/cattle) (Collins, 2017). This economic opportunity is significant and could slow down the future development of recycling treated produced water, since ranchers want to maximize water revenues. Ranchers who fear the loss of water sales and disposal revenues in many cases will likely either: a) refuse to renegotiate surface use agreements to allow recycling; or b) seek to renegotiate them by asking for a “recycling royalty” that recaptures a significant portion of the water sales revenues and disposal fees that would otherwise be lost because of increased produced water recycling (Collins, 2017). Ranchers are not the only ones competing for groundwater, the municipal water suppliers are also competing.

The cities of Midland and Odessa are among the fastest growing metropolitan areas in the US, and this growth is likely driven by the HF industry. These two cities are within the Texas region F water planning area. This water planning region’s population is expected to increase 43% by 2070, increasing the water demand by 2% (TWDB, 2016). Even though these cities are not within UL acreage, they do compete for groundwater since they own municipal water supply wells that are in the UL groundwater database.

5.8 Comparison with Relevant Studies

One study evaluated the impacts of HF water supply wells located near domestic groundwater wells. This study found that groundwater wells located closer to HF wells (within 2 km) are more likely to be exposed to contaminants derived from on-site spills and well-bore failures (Jasechko and Perrone, 2018). They analyzed the proximity between drinking water supply wells and HF wells constructed between 2000 and 2014, across 14 states (including

Texas). Their main highlight relevant to this study, shows that in the Permian Basin approximately 75% of drinking water supply wells located are within 2 km of at least one HF well (Jasechko and Perrone, 2018). This means that the drinking water supply wells within 2 km of HF wells in UL (approximately 75%) should be closely monitored since they are at risk of being contaminated by on-site spills and well-bore failure, should they occur. Understanding how frequently HF operations impact groundwater quality is important to drinking water safety in areas where HF is common (Jasechko and Perrone, 2018). Two other relevant studies were also compared to this thesis.

A relevant water management study was done for the Eagle Ford Shale in northeast Mexico in which they predicted the impacts on groundwater supply from developing underdeveloped shale plays from 2015 to 2017 (Hernandez-Espiriu, et. al., 2019). As in the approach used in this thesis, the volume of water used per HF well increased progressively each year based on volumes recorded in the FracFocus database. The water use per HF well increased 2.5-fold from 2011 to 2017, and water intensity (water volume used per unit lateral length of HF wells) increased 2.3-fold in the Eagle Ford Shale of north-eastern Mexico (Hernandez-Espiriu, et. al., 2019). If we apply this new insight to this thesis, then we can assume that water intensity in the Permian Basin will increase, as it did for the Eagle Ford Shale.

Another relevant similar study to this thesis was done over water issues related to transitioning from conventional to unconventional oil production in the Permian Basin (Scanlon, et. al., 2017). Results from their study show that HF wells account for 10% of produced water in the basin, the rest comes from conventional, and this water can be reused to enhance oil recovery. HF wells in the Delaware Basin generate 2.8 times more produced water than in the Midland Basin (Scanlon, et. al., 2017). There is a high potential for reuse of produced water because treatment requirements are minimal; and produced water disposed in deep saltwater disposal zones is enough to meet HF water requirements, based on an analysis of 2014 data (Scanlon, et. al. 2017). In the future work section, 3 out of 6 gaps in their study of the Permian Basin were addressed by this thesis: (1) identifying water sources used for HF; (2) assessing groundwater availability for HF; and (3) monitoring impacts of HF on groundwater resources.

6. CONCLUSIONS

6.1 Summary

The main objectives of this study are to evaluate the impacts of the recent groundwater pumping for HF supply on the hydraulic heads, gross water volumes that enter and leave storage, and gross volumetric fluxes within and between the Dockum and lower Ogallala aquifers in the Permian Basin, in West Texas. The study area covers three regions where the UL holds properties: Northern Midland Basin, Delaware & Central Basins, and Southern Midland Basin. The locations of the Rig/Frack supply wells and HF oil production wells were collected from databases hosted by the Texas Water Development Board (TWDB), Texas Commission of Environmental Quality (TCEQ), FracFocus, and UL. Three approaches were developed to assign the water source for HF supply across known Rig/Frack supply wells: 1) the annual water demand for HF within a region was evenly allocated to all Rig/Frack supply wells registered with UL in that same region; 2) the annual water demand for HF within a region was evenly allocated only to UL Rig/Frack supply wells that are screened in the Dockum aquifer in that same region; 3) the nearest water supply well to a HF event was assumed to supply all the water for that HF event. The 1st and 2nd approach were then forecasted for the next 30 years by anticipating groundwater pumping by oil and gas and other sectors reliant on groundwater in this region. The exclusion of pumping schedules from all the unaccounted other sector wells means that these results are underestimating the impacts of gross water fluxes between aquifers and changes in hydraulic heads underneath UL. Importantly, pumping for HF supply does occur outside of UL properties, which means that any estimates of impacts by groundwater pumping for HF supply by UL operators is a conservative estimate compared to the overall impacts of the entire HF industry across the Basin.

This thesis advances the understanding of the impact UL's water management plan on the hydraulic heads, stored water volumes, and fluxes within and between the aquifers beneath their property which have been the site of HF activity for over 10 years. Water quality across the aquifers in the study area varies significantly, ranging from very fresh to saline and TDS varies from 10 to 10,000 mg/L. Changes in hydraulic heads owing to the pumping for HF supply was, in very small number of cases, large enough that well owners may have suffered from a burned out pump, were forced to pay a higher price to pump the groundwater, or were forced to pay to deepen their well(s) (Obkirchner, 2019). The impacts on the gross water volumes entering and leaving the Dockum and lower Ogallala underlying UL showed that substantial amounts of groundwater flows both vertically and laterally within the groundwater system (Winter, 1998). The gross water volumes which entered and left these aquifers in the 39 year study period accounts for approximately 0.3% of the estimated stored water available within the lower Ogallala ($3.13\text{x}10^9$ m^3), in region F of the regional water planning areas of Texas (TWDB, 2016). Also, these gross water volumes were impacted much more within the Dockum than the lower Ogallala by the different assumptions, experiencing a higher percentage increase when pumping is only from the Dockum compared to from all aquifers, as well as a larger reduction when 30% of the water was recycled compared to 0% recycling. The hydraulic connection between the two aquifers (Dockum and lower Ogallala) is good enough that if we increase the pumping rates of wells screened in the Dockum, to supply water for HF, then more water volumes will flow not only within the Dockum, but also within the lower Ogallala underlying UL as well. However, the annual rates at which these fluxes happen will decrease as a result from compression of the unconfined Dockum aquifer (USGS, 2013). In other words, water will enter and leave these aquifers underneath the three UL regions, but that flux will happen at slower rates. Fortunately, the UL policy of encouraging HF companies to use the lower quality brackish water from the Dockum (UL, 2012) has shown potential for conserving the high quality fresh water of the lower Ogallala, since much more water would end up flowing downwards than upwards. Finally, the lower Ogallala seems to readily act as a “water bank savings account” for the Dockum aquifer since recycling 30% of flowback water, which eases stress on the Dockum, lowered the amount of water that Dockum received from lower Ogallala; and also, because whenever the pumping is assumed to be only from the Dockum, which increased stress on the Dockum, this increases the flux from the lower Ogallala to the Dockum.

6.2 Implications

The groundwater supply sectors within UL acreage that compete the most with HF supply are the livestock and municipal supply sectors. Together, these three sectors account for 90% of the water supply wells in the UL groundwater database.

Water in Texas oilfields is enormously valuable, and the opportunity to sell HF water and disposal services allows ranchers to make millions of dollars more per year in returns than they did raising cattle (Collins, 2017). However, this economic opportunity could slow down the future development of recycling treated produced water, since ranchers want to maximize water revenues.

UL annual regional pumping for HF has minor effects on the hydraulic heads of the Dockum aquifer. In contrast, the cities of Midland and Odessa have impacted water levels of the Dockum, showing drops in water levels of 10 to 20 m (30 to 65 ft) by 2012 since pumping began in 1950’s. These impacts remained relatively constant, the drawdowns only grew within the same range of 10 to 20 m during the period from 2012 onwards, and are expected to increase so long as the cities continue to pump and treat the water from the Dockum aquifer to supply the many people living within the two cities and surrounding areas.

The aquifers underneath UL properties can provide water for HF even if pumping remains high due to the large thickness and aerial extent of the aquifers, since the gross water volumes which entered and left these aquifers over the 39 year study period only accounts for approximately 0.3% of the estimated stored water available within the lower Ogallala ($3.13x10^9$ m^3), in the Texas regional planning area F (TWDB, 2016). If pumping volumes shift completely to be sourced from the Dockum aquifer, more water would flow downwards than upwards, therefore conserving the high quality fresh water of the lower Ogallala from deteriorating. Despite that, since the lower Ogallala is willing to give up its water to the Dockum, conserving the high quality fresh water comes at a price of risking a decline in the water levels of the unconfined lower Ogallala. The lower Ogallala is already an aquifer that is being mined (TWDB, 2016), so it makes sense that intensely pumping the hydraulically connected Dockum aquifer has potential to decrease water levels of the lower Ogallala as more water would flow downwards, which would prevent brackish water from flowing upwards. However, only the changes in hydraulic heads of the Dockum aquifer were measured for the purposes of this study.

6.3 Interdisciplinary Applications

This project aims to help professionals and decision makers understand how groundwater is affected by HF activity and lays down the methods to answer such a complicated question. This work was achieved thanks to the databases which kept track of water supply wells, their water quality (UL, TWDB), and reported water used for HF (FracFocus). Those databases that were just mentioned, provided all the critical information needed to put together all the puzzle pieces, including the GAM files.

Recent relevant studies have been compared to this thesis in section 5.8. They have shown that the drinking water supply wells within 2 km of HF wells in UL (approximately 75%) should be closely monitored since they are at risk of being contaminated by on-site spills and well-bore failure, should they occur (Jasechko and Perrone, 2018). Also, we can assume that water intensity in the Permian Basin will increase, as it did for the Eagle Ford Shale (Hernandez-Espiriu, et. al., 2019). Finally, in the Permian Basin there is a high potential for reuse of produced water because treatment requirements are minimal; and produced water disposed in deep saltwater disposal zones is enough to meet HF water requirements, based on an analysis of 2014 data (Scanlon, et. al. 2017).

There are many oil fields around the world, and they all have a need for water. The Permian Basin is only one of the many places in the world where HF takes place, and not every unconventional basin has been studied this extensively in terms of how the groundwater within aquifers will be impacted if it is used to supply water for HF. Groundwater management becomes increasingly more difficult if there is no direct line of communication between water supply well owners and groundwater databases. The methods developed in this thesis can be applied for any aquifer GAM, so long as the minimum data needs are reported and available. They can also be applied to assess the impacts of any type of water supply sector, provided that well owners would be willing to cooperate, which is not always the case as many people are afraid that they will be fined or found guilty of having contaminated water. However, if people get together and decide that all pumping activities are worth keeping track of, then we will be able to model aquifer pumping from any sector with accuracy and precision. This thesis helps advance the discussion on defining what sustainable water management means in an arid region with vast stored groundwater supplies, little recharge, and a growing industrial activity that crucially depends on that stored water along with the people who live there.

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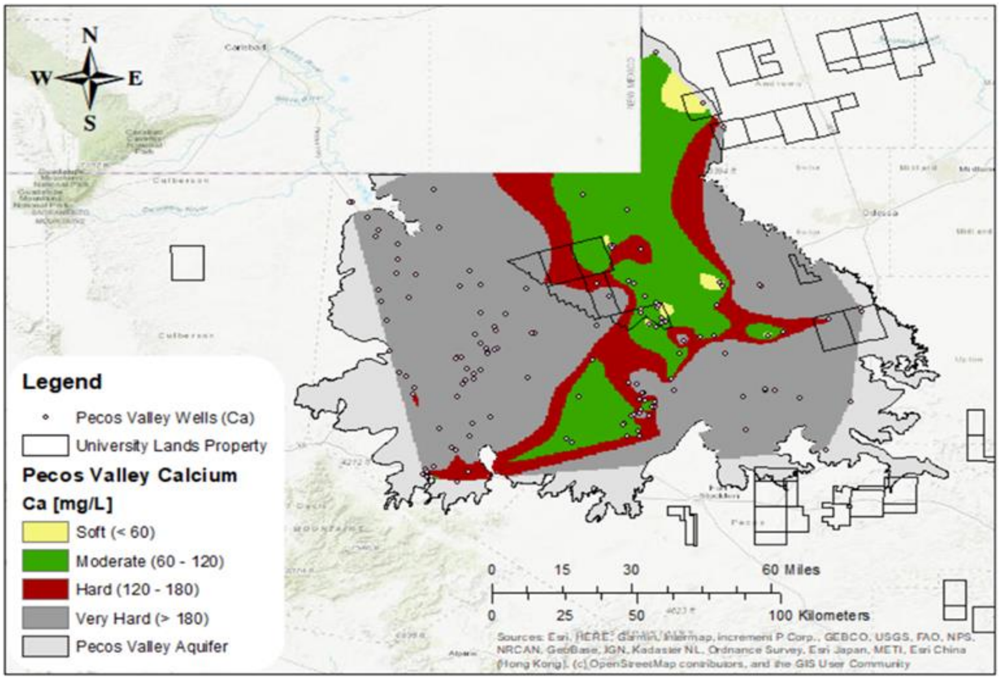
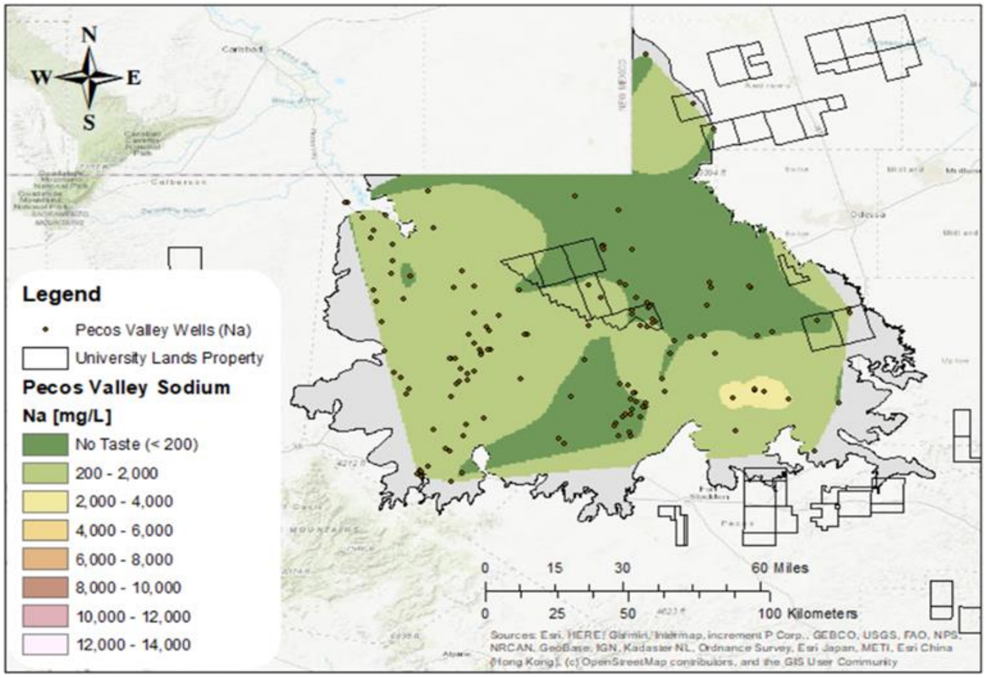
APPENDIX

Section A1: Ca, Na, Cl, and SO_4 [mg/L] water quality maps of the Pecos Valley, Edwards-Trinity (Plateau), and Dockum aquifers.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure A1: Pecos Valley Calcium concentration.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure A2: Pecos Valley Sodium concentration.

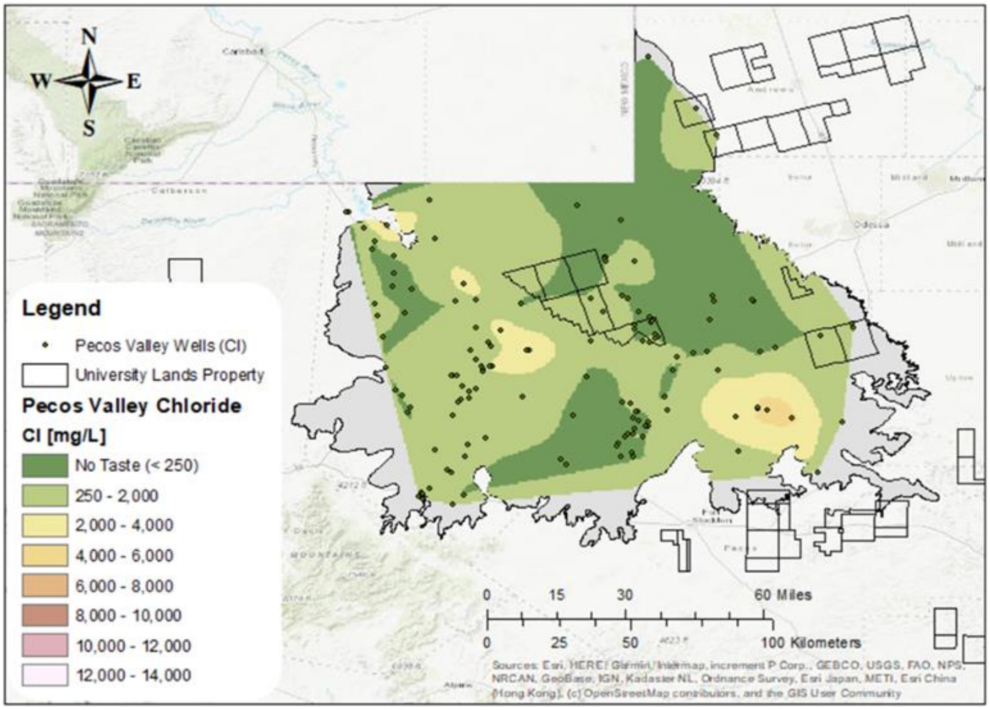


Figure A3: Pecos Valley Chloride concentrations.

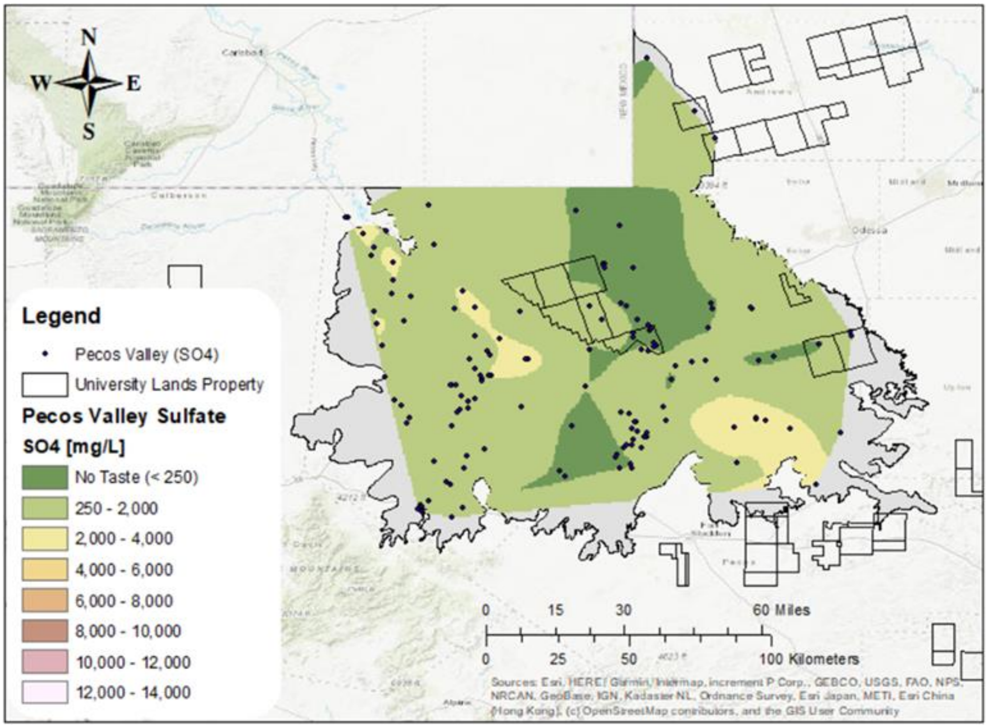


Figure A4: Pecos Valley Sulfate concentrations.

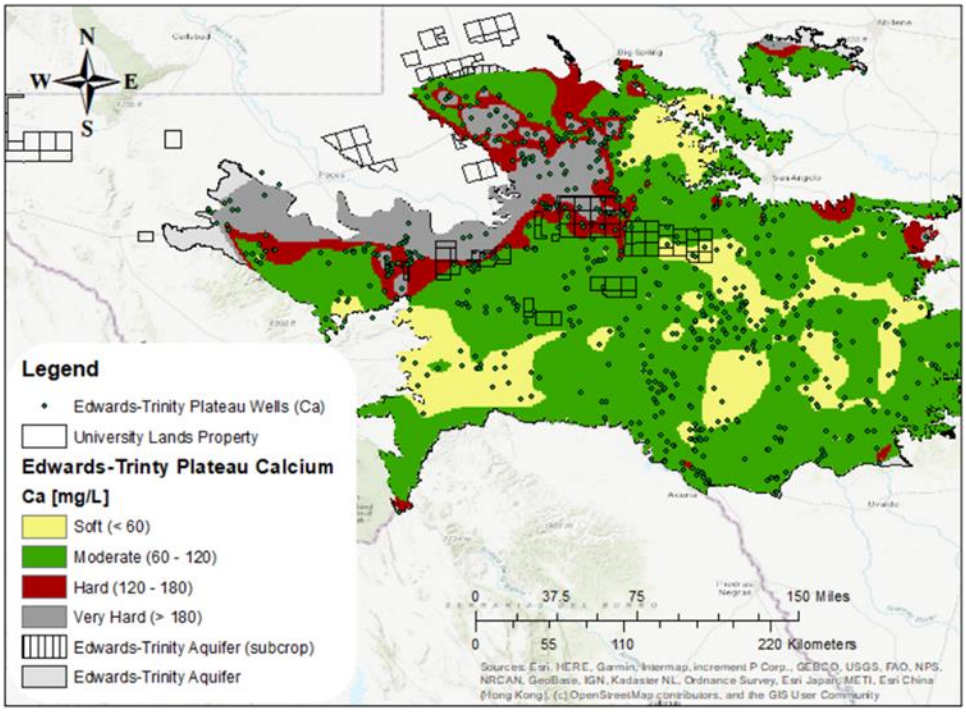


Figure A5: Edwards-Trinity (Plateau) Calcium concentrations.

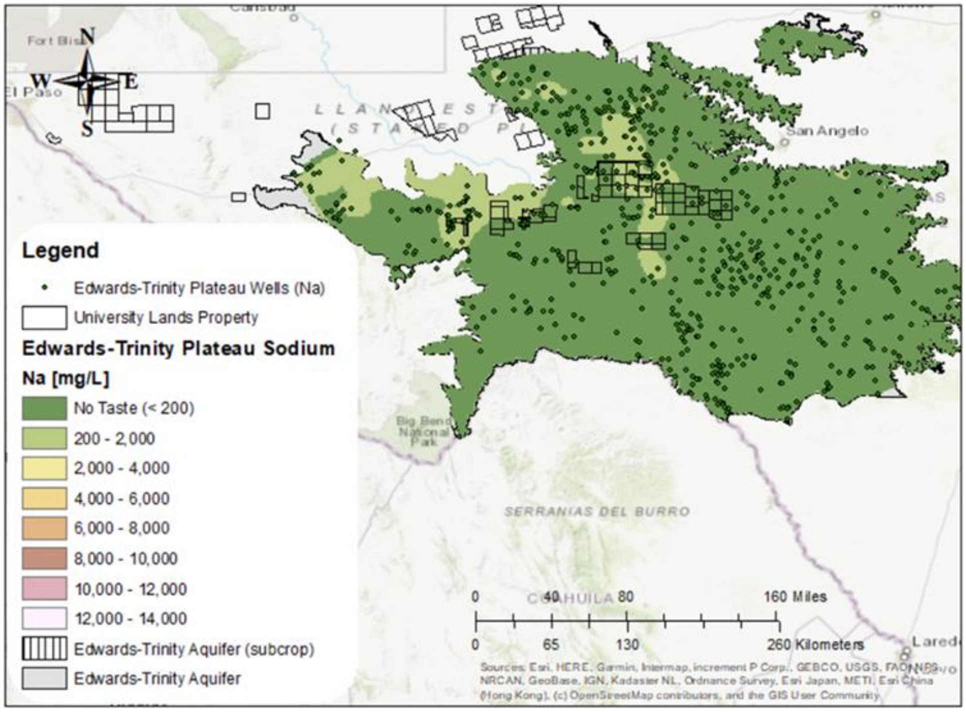


Figure A6: Edwards-Trinity (Plateau) Sodium concentrations.

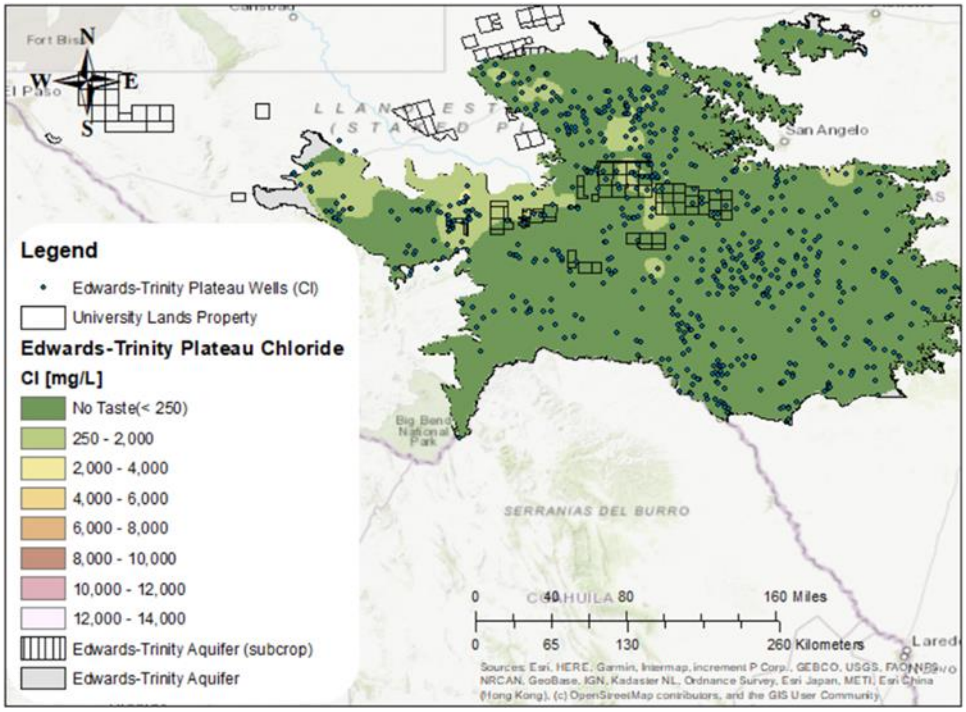


Figure A7: Edwards-Trinity (Plateau) Chloride concentrations.

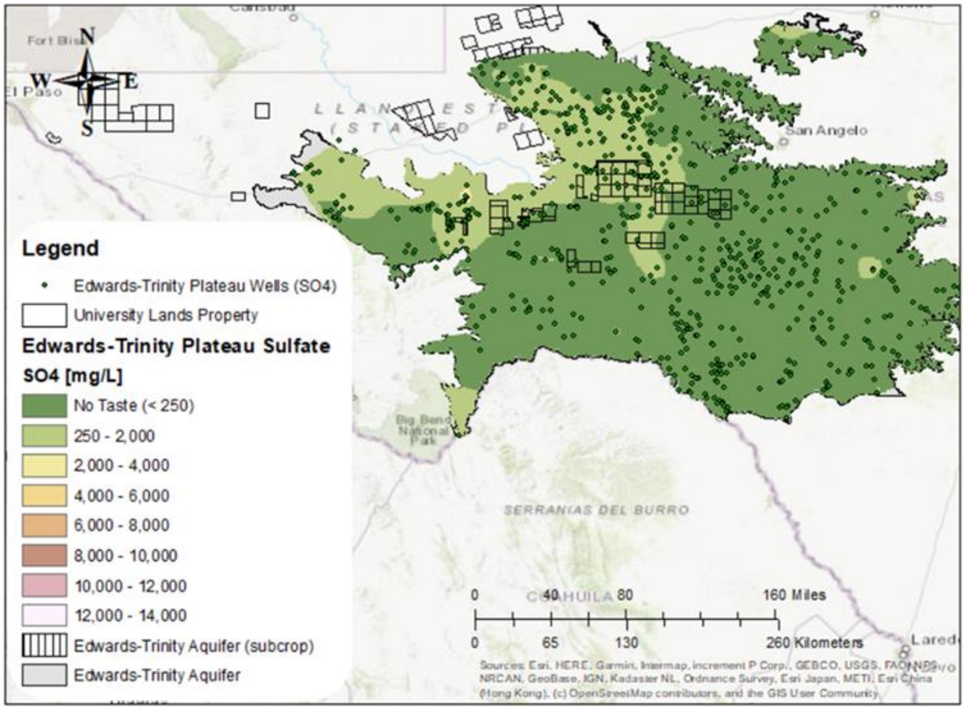


Figure A8: Edwards-Trinity (Plateau) Sulfate concentrations.

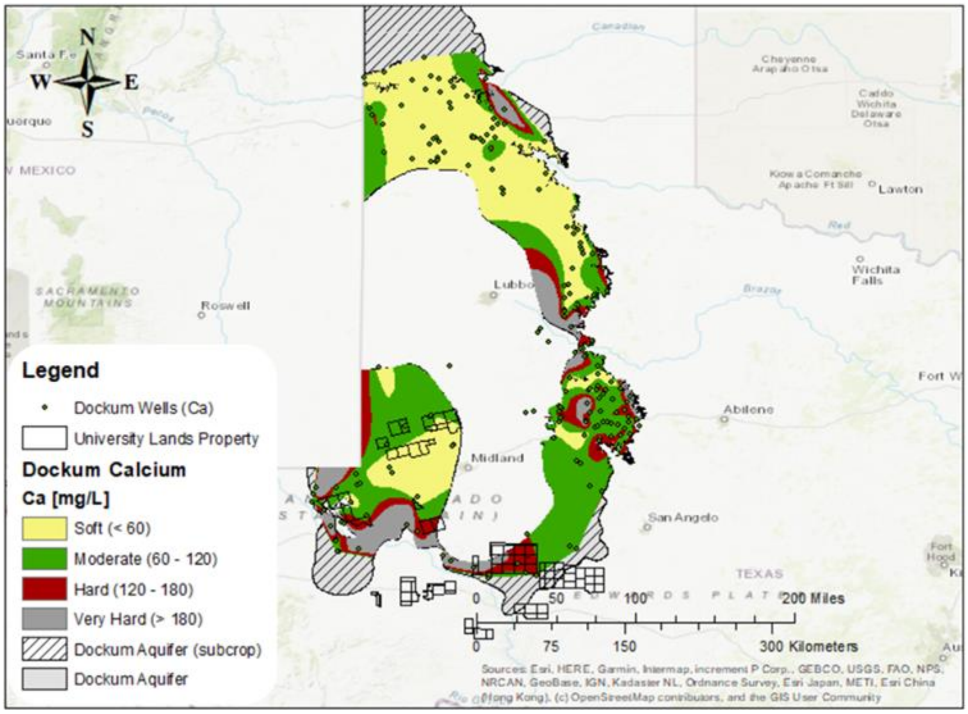


Figure A9: Dockum Calcium concentrations.

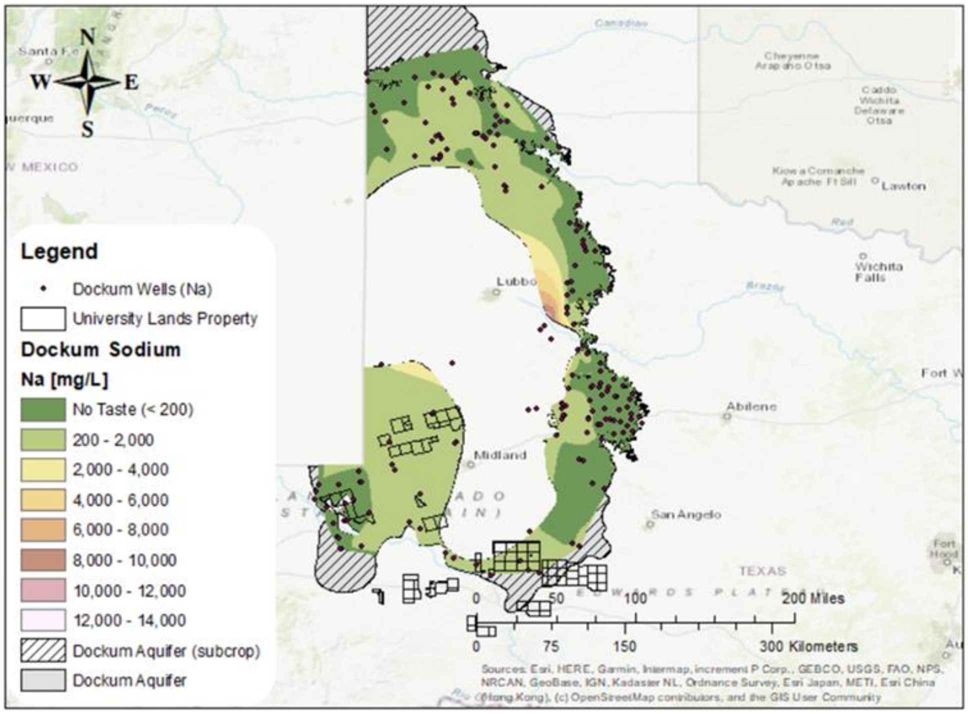


Figure A10: Dockum Sodium concentrations.

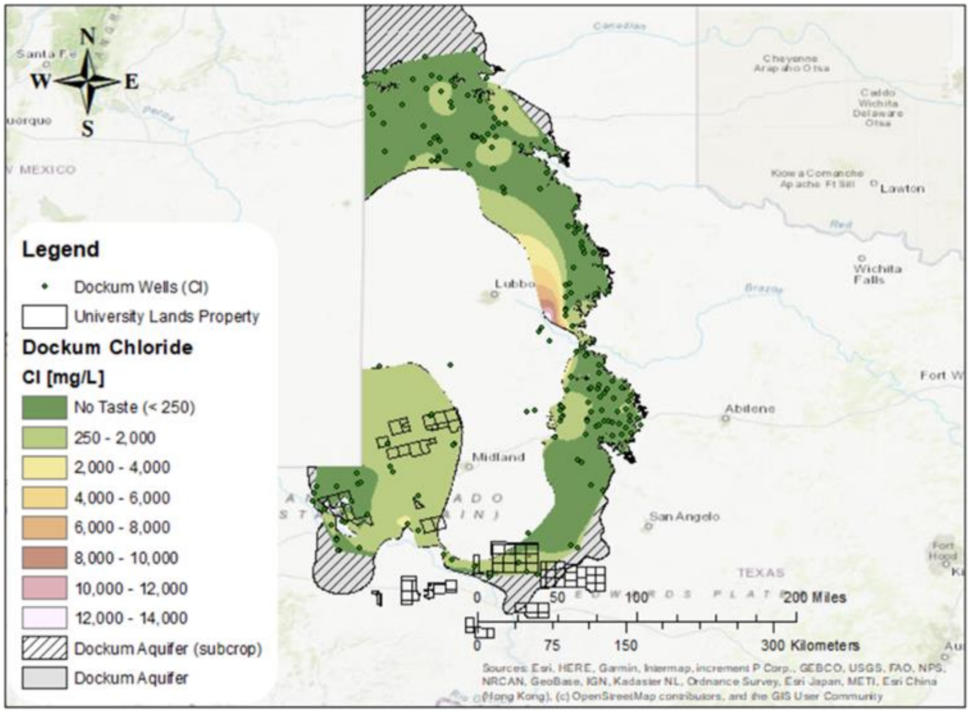


Figure A11: Dockum Chloride concentrations.

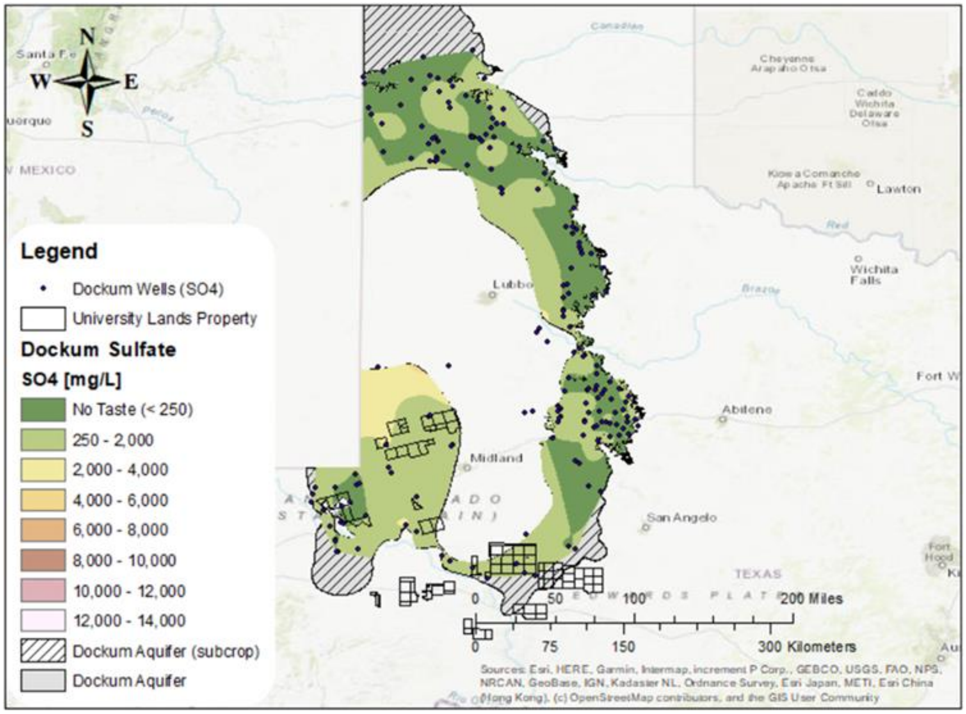


Figure A12: Dockum Sulfate concentrations.

Section A2: Piper Plot and Gibbs Diagram of the Pecos Valley, Edwards-Trinity (Plateau), and Dockum aquifers.

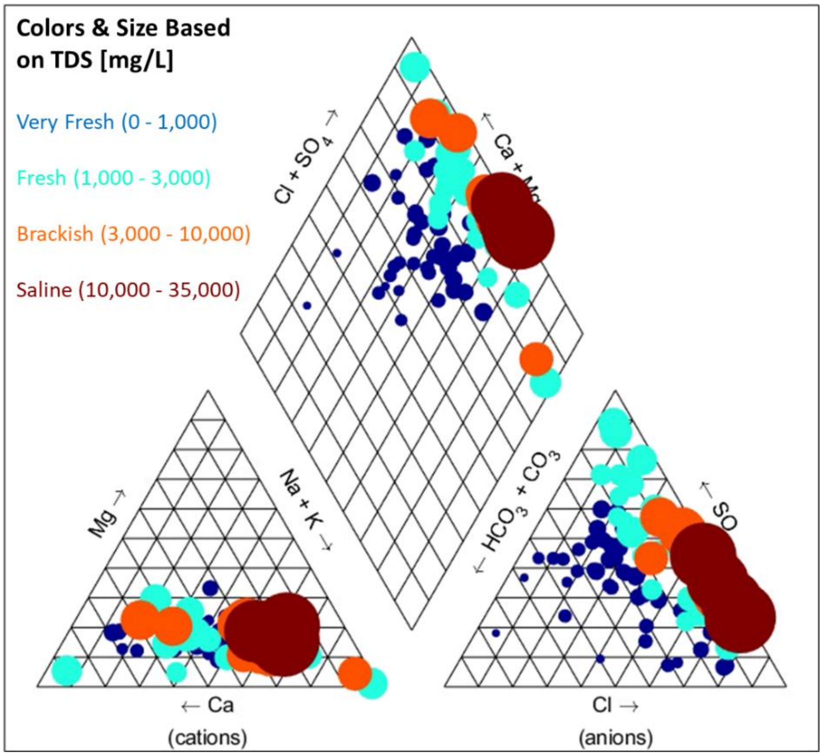


Figure A13: Pecos Valley Piper plot.

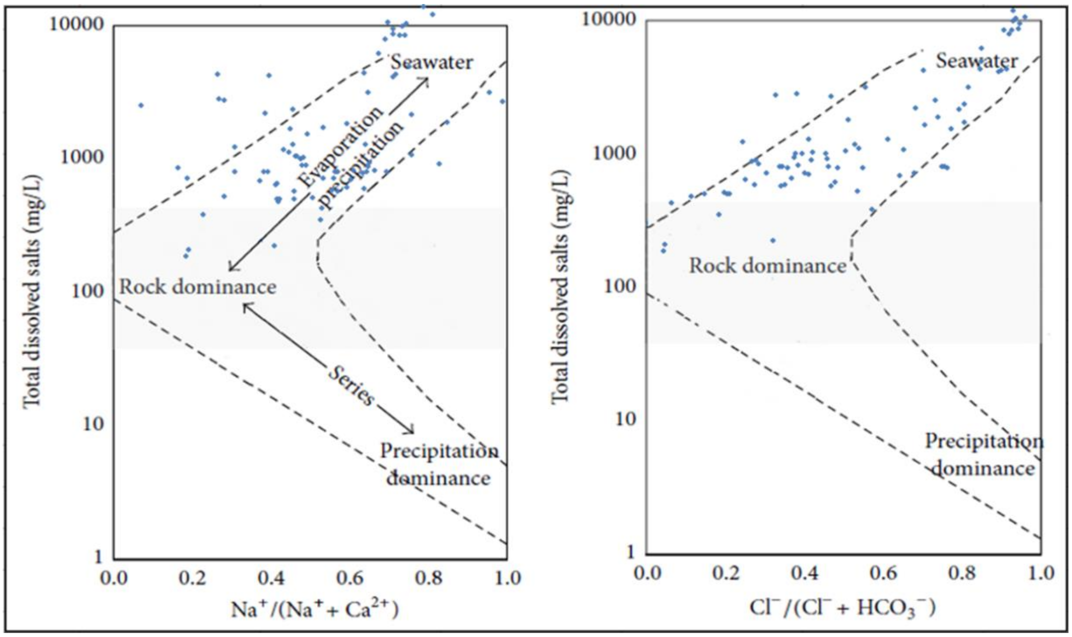


Figure A14: Pecos Valley Gibbs diagram.

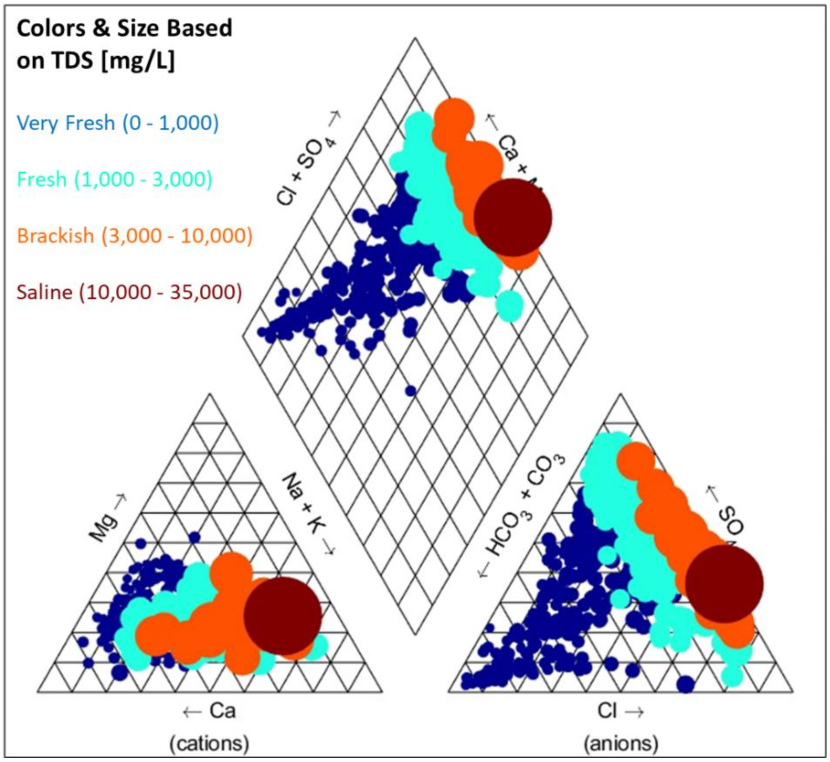


Figure A15: Edwards-Trinity (Plateau) Piper plot.

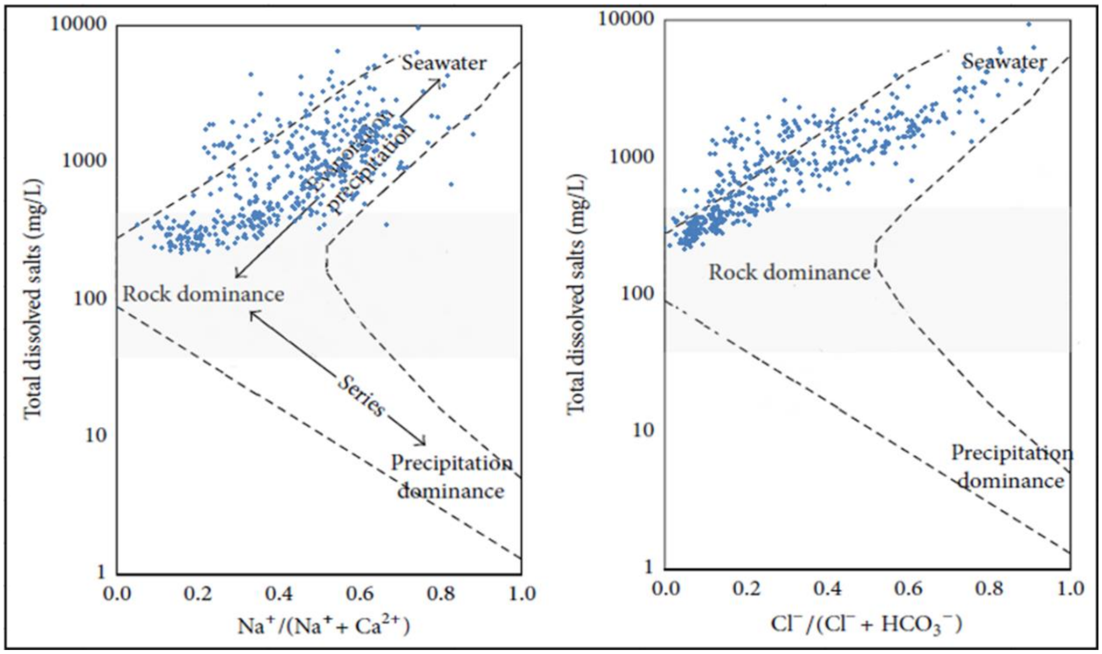


Figure A16: Edwards-Trinity (Plateau) Gibbs diagram.

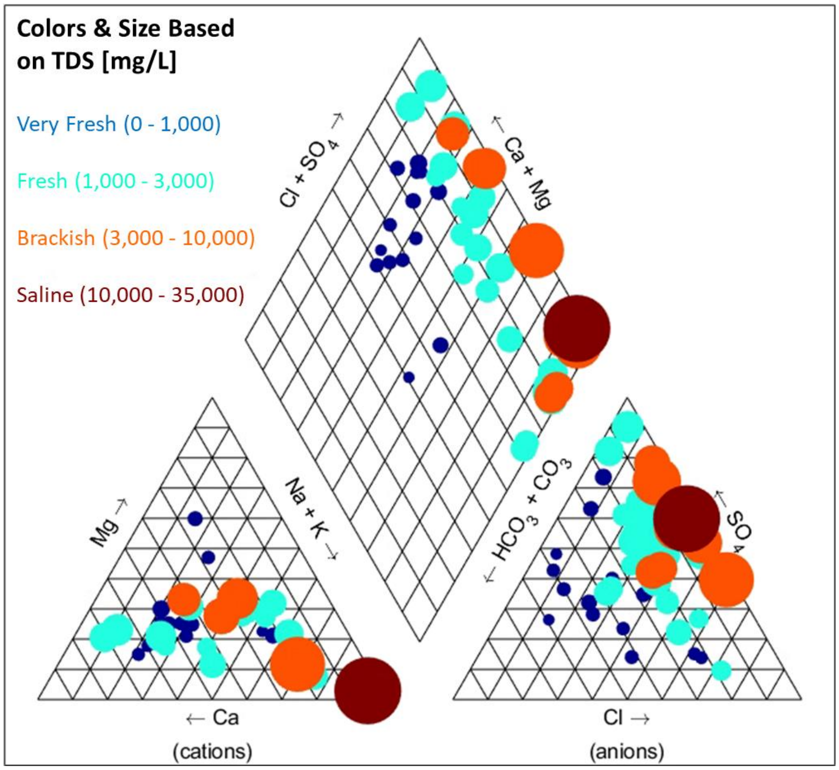


Figure A17: Dockum Piper plot.

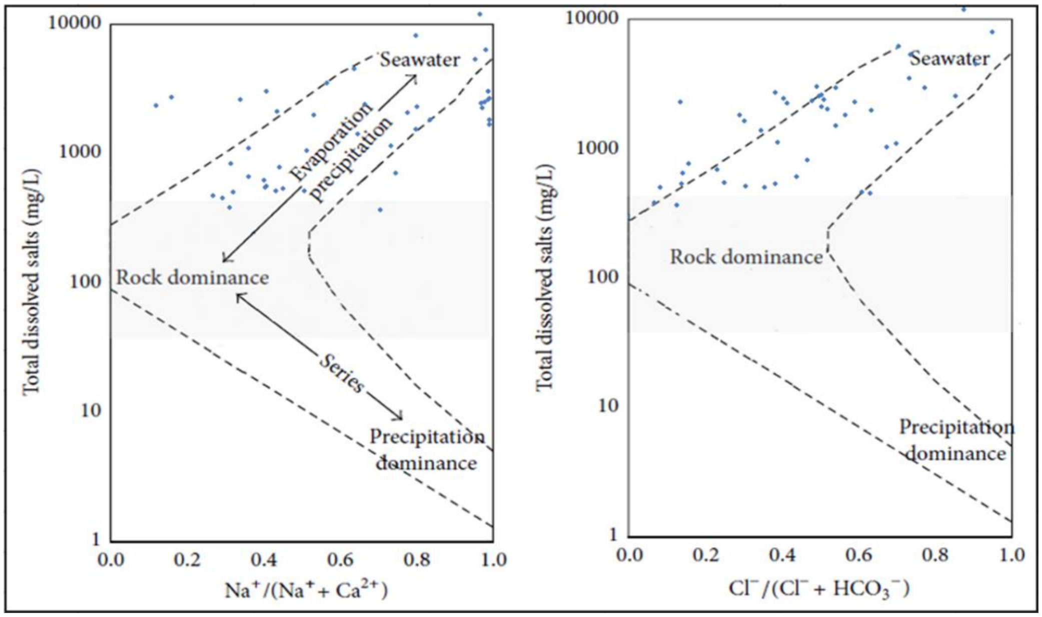


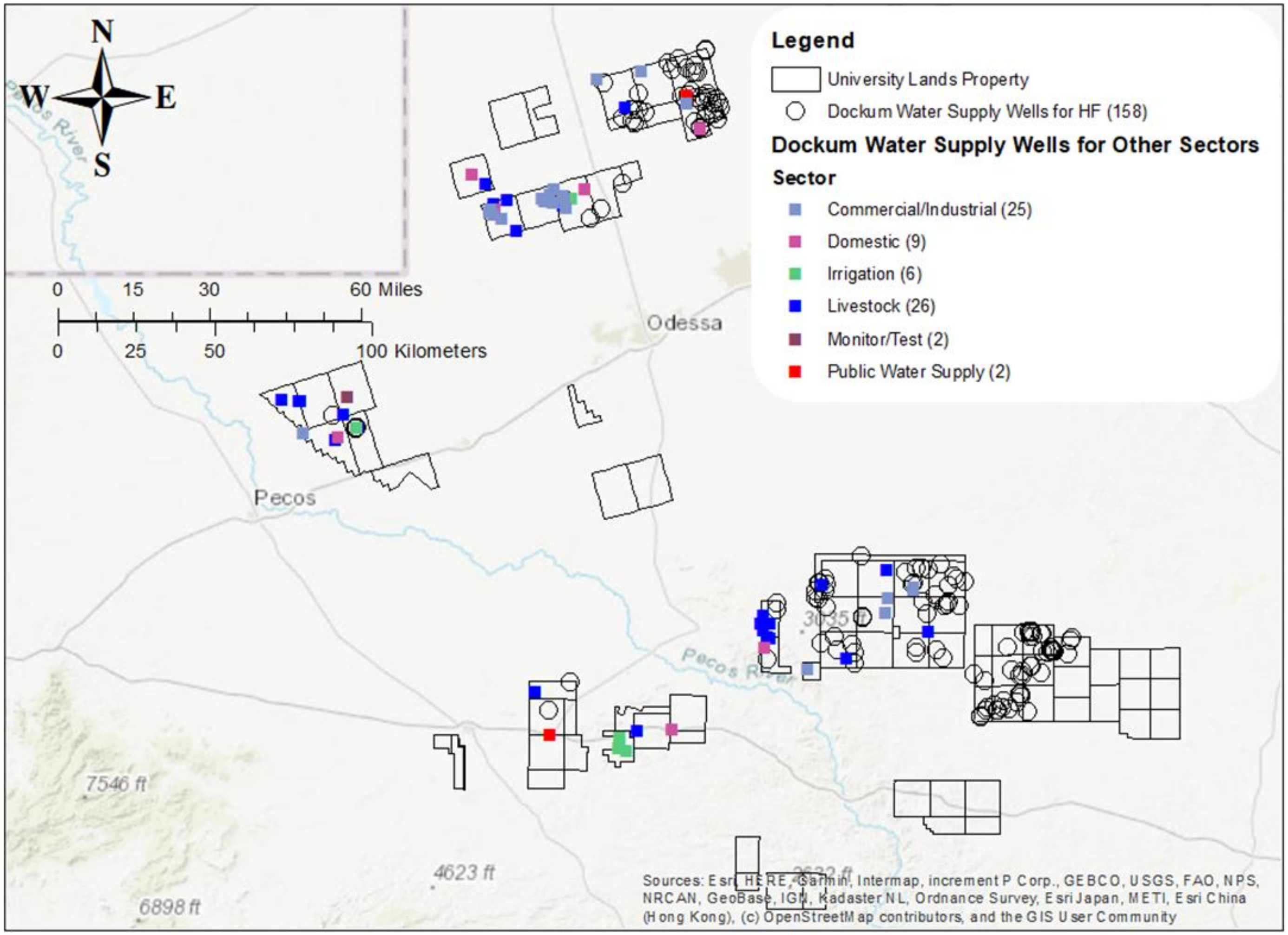
Figure A18: Dockum Gibbs diagram.

Section A3: Code used to assign water supply wells to aquifers based on their well depth.

Code A1: Excel code used to assign SDR water supply wells to aquifers based on their well depth.

```
“=IF(AND(well_depth< =(dem),well_depth>=(pecos_bottom)),"Pecos
Valley",IF(AND(well_depth<=(pecos_ bottom), well_depth >=(edw-
trin_bottom)),"Edwards Trinity Plateau",IF(AND(well_depth<=(edw-
trin_bottom),well_depth>=(dockum_bottom)),"Dockum",IF(AND(well_depth
<=(dockum_bottom),well_depth>=(rustler_bottom)),"Rustler",IF(AND(well_depth<=
(rustler_bottom),well_ depth>=(cap-reef_bottom)),"Capitan Reef
Complex",IF(AND(well_depth<=(dem),well_depth>= (edw-trin_bottom)),"Edwards
Trinity Plateau",IF(AND(well_depth<=(dem),well_depth>=(
dockum_bottom)),"Dockum","Check"))))))).”
```

Section A4: Water supply wells screened the Dockum aquifer.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure A19: UL water supply wells screened in Dockum aquifer, differentiated between sectors; null sector not included (52 wells).

Section A5: Drawdown impacts in the Dockum aquifer from historical pumping by 2012, relative to 1950.

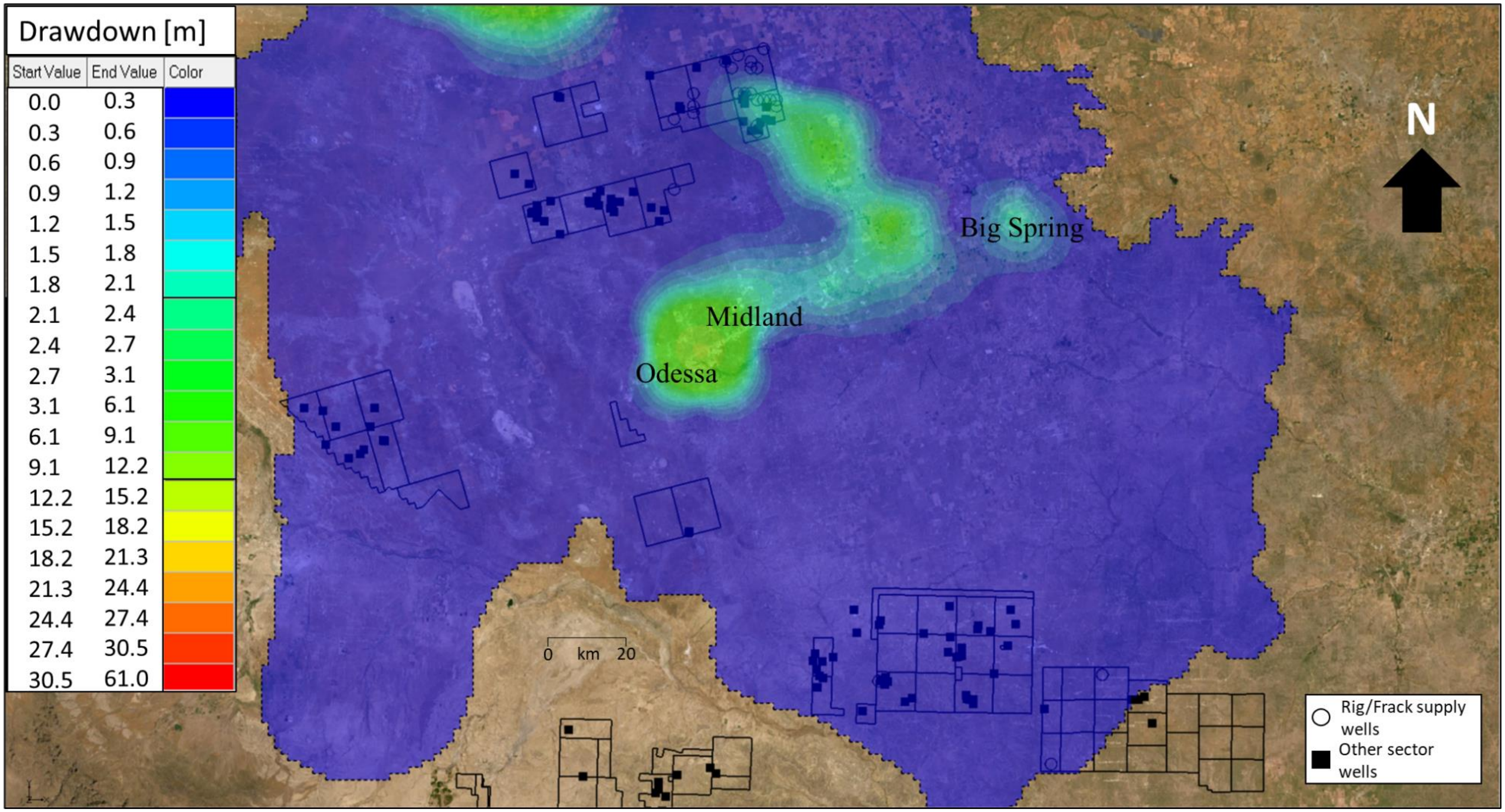


Figure A20: Upper Dockum drawdown impacts from historical pumping, 2012.

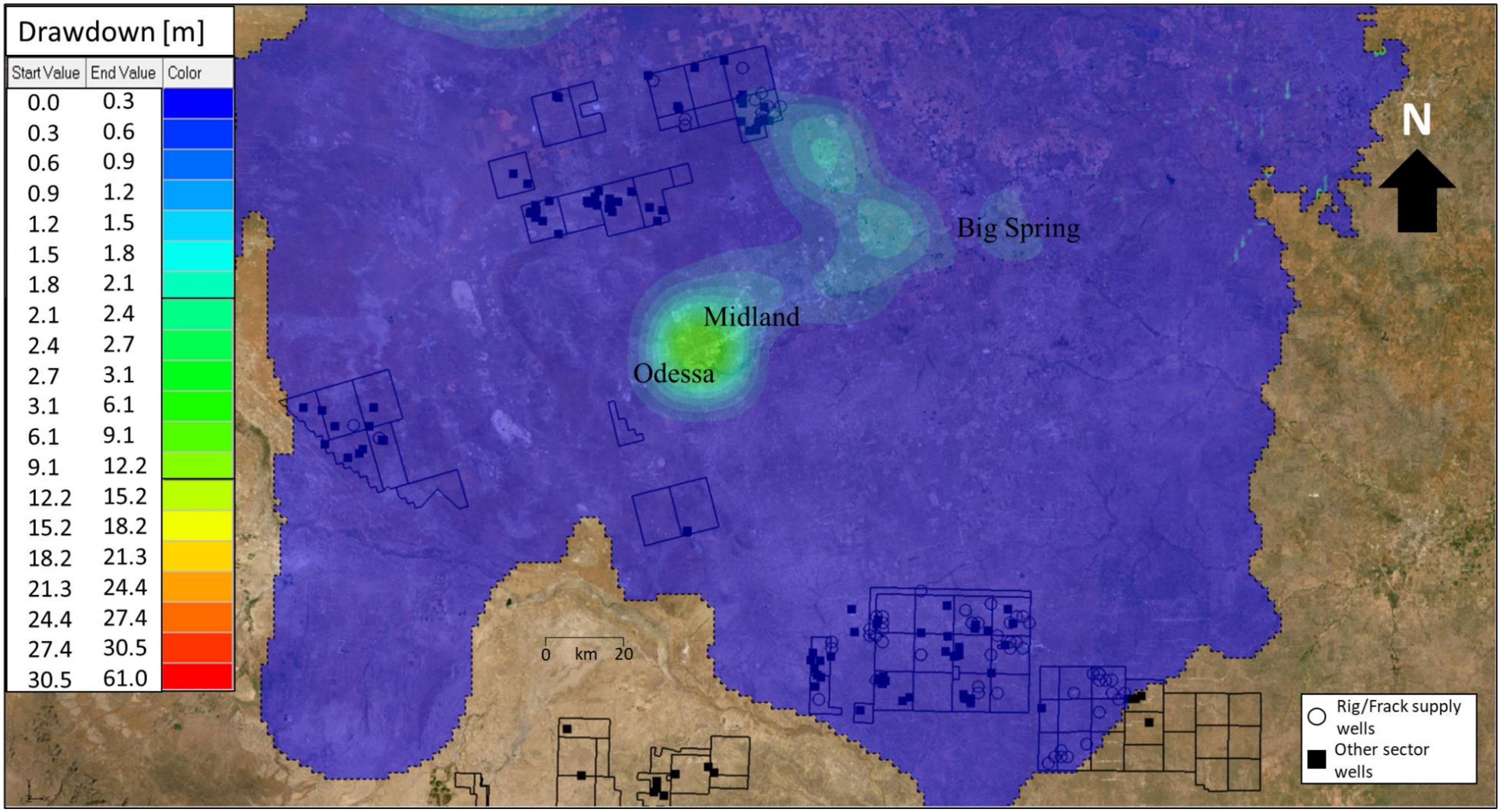


Figure A21: Lower Dockum drawdown impacts from historical pumping, 2012.

Section A6: Drawdown impacts in the Dockum aquifer assuming the nearest water supply well to a HF event supplied all the water for that event.

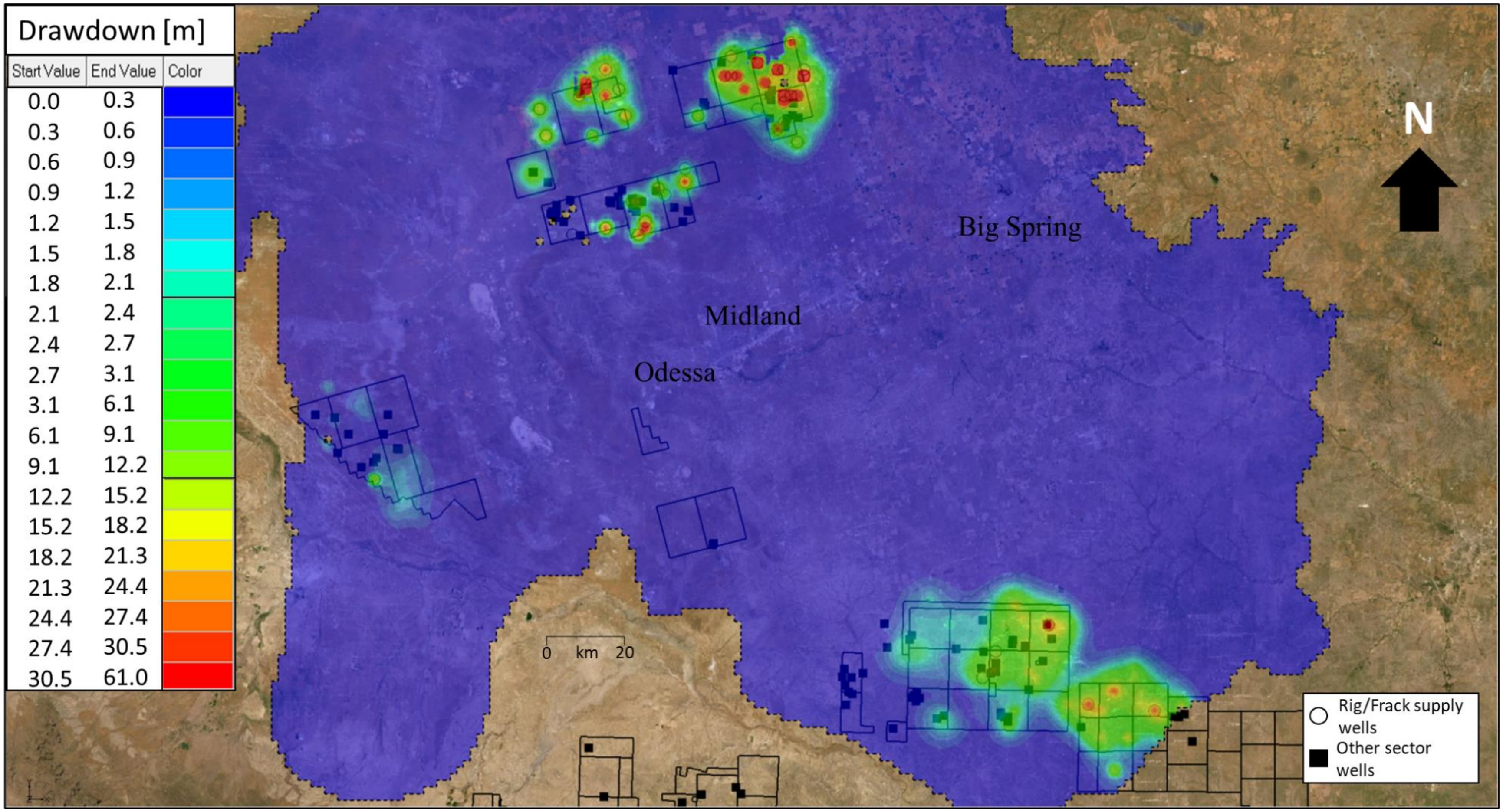


Figure A22: Upper Dockum drawdown impacts by 2020, assuming nearest water supply well to a HF event supplied all the water for that event.

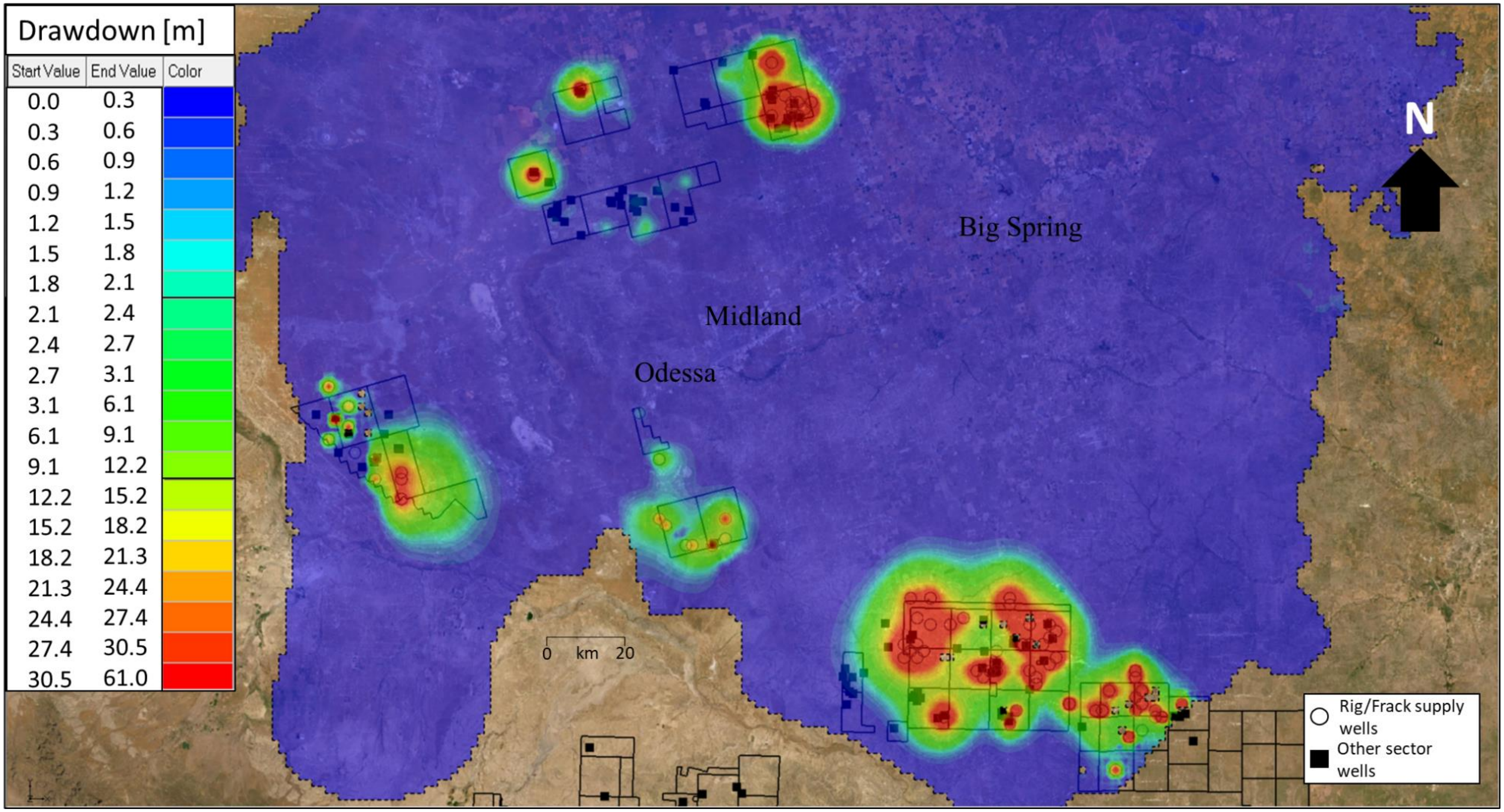
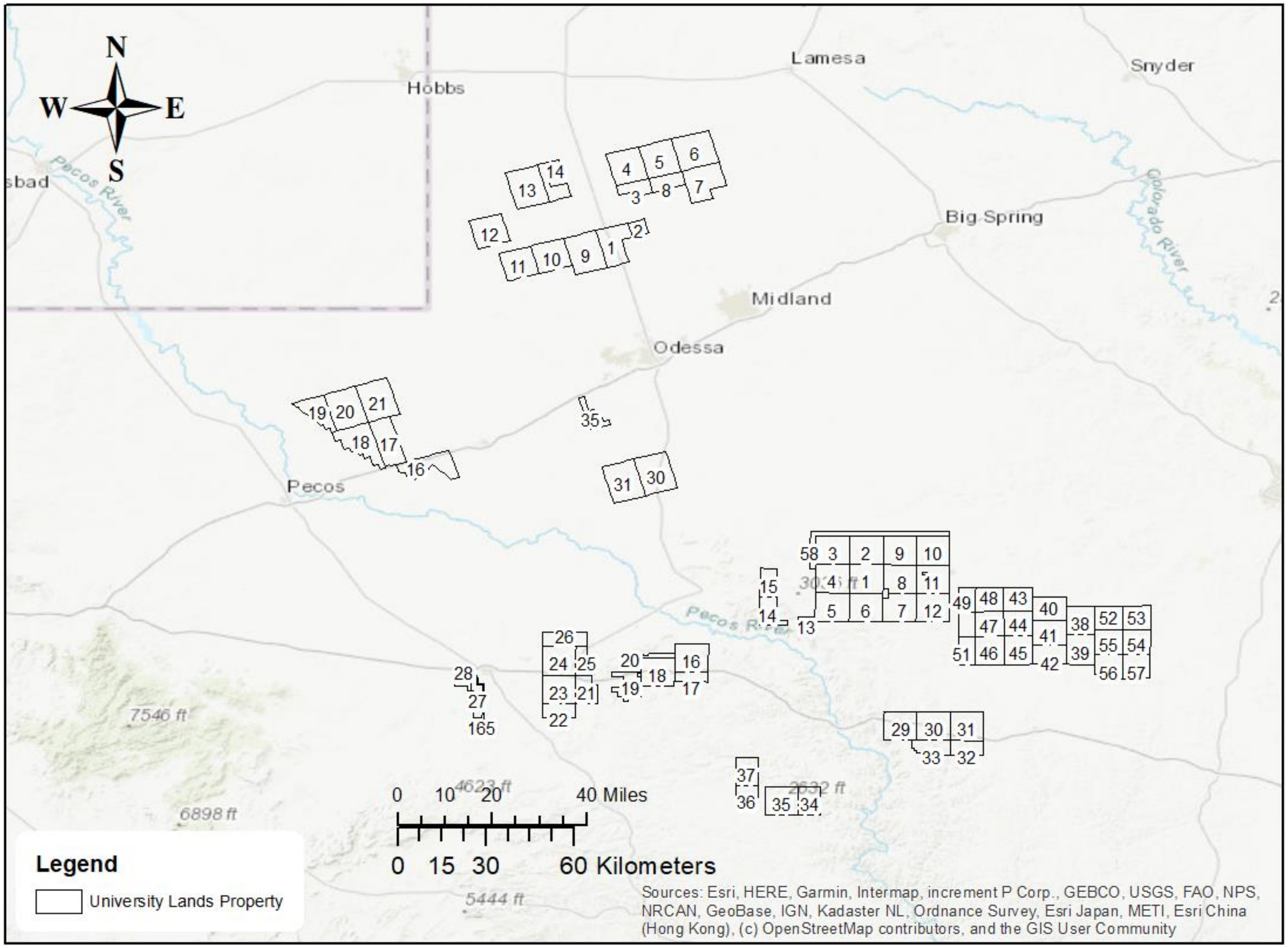


Figure A23: Lower Dockum drawdown impacts by 2020, assuming nearest water supply well to a HF event supplied all the water for that event.

Section A7: University Lands property displaying block numbers.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure A24: UL property displaying block numbers.

Section A8: Drawdown results from annualizing water pumping across Rig/Frack supply wells screened in all aquifers assuming 30% recycling of flowback water.

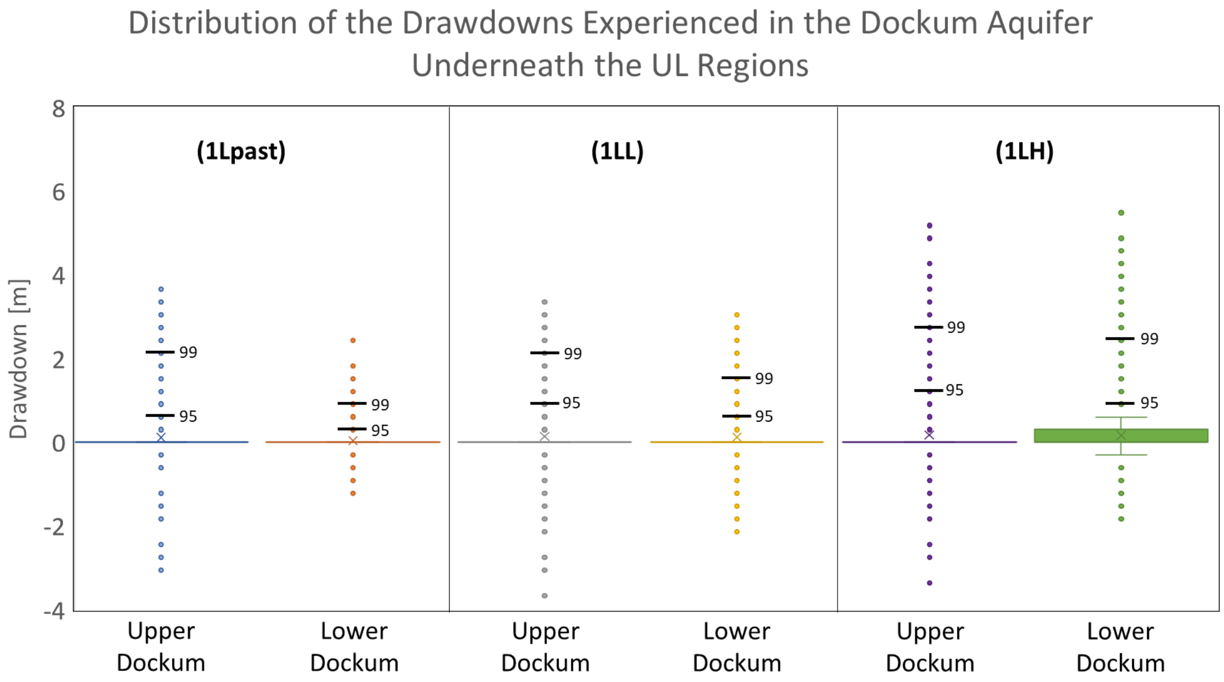


Figure A25: Summary of changes in hydraulic head from annualizing water pumping for HF across all Rig/Frack supply wells in each region screened in all aquifers assuming 30% recycling of flowback water.

Table A1: Drawdown results from annualizing water pumping for HF across all Rig/Frack supply wells in each region screened in all aquifers assuming 30% recycling of flowback water. (1Lpast) upper and lower Dockum; (1LL) upper and lower Dockum; (1LH) upper and lower Dockum.

Drawdown [m]	**1Lpast upper DKM**	**1Lpast lower DKM**	**1LL upper DKM**	**1LL lower DKM**	**1LH upper DKM**	**1LH lower DKM**
Maximum	3.66	2.44	3.35	3.05	5.18	5.49
99th percentile	2.13	0.91	2.13	1.52	2.74	2.44
95th percentile	0.61	0.30	0.91	0.61	1.22	0.91
Mean	0.12	0.04	0.14	0.13	0.18	0.16
Median	0.00	0.00	0.00	0.00	0.00	0.00
Minimum	-3.05	-1.22	-3.66	-2.13	-3.35	-1.83

Section A9: Drawdown frequency histogram from annualizing water pumping across Rig/Frack supply wells screened in all aquifers.

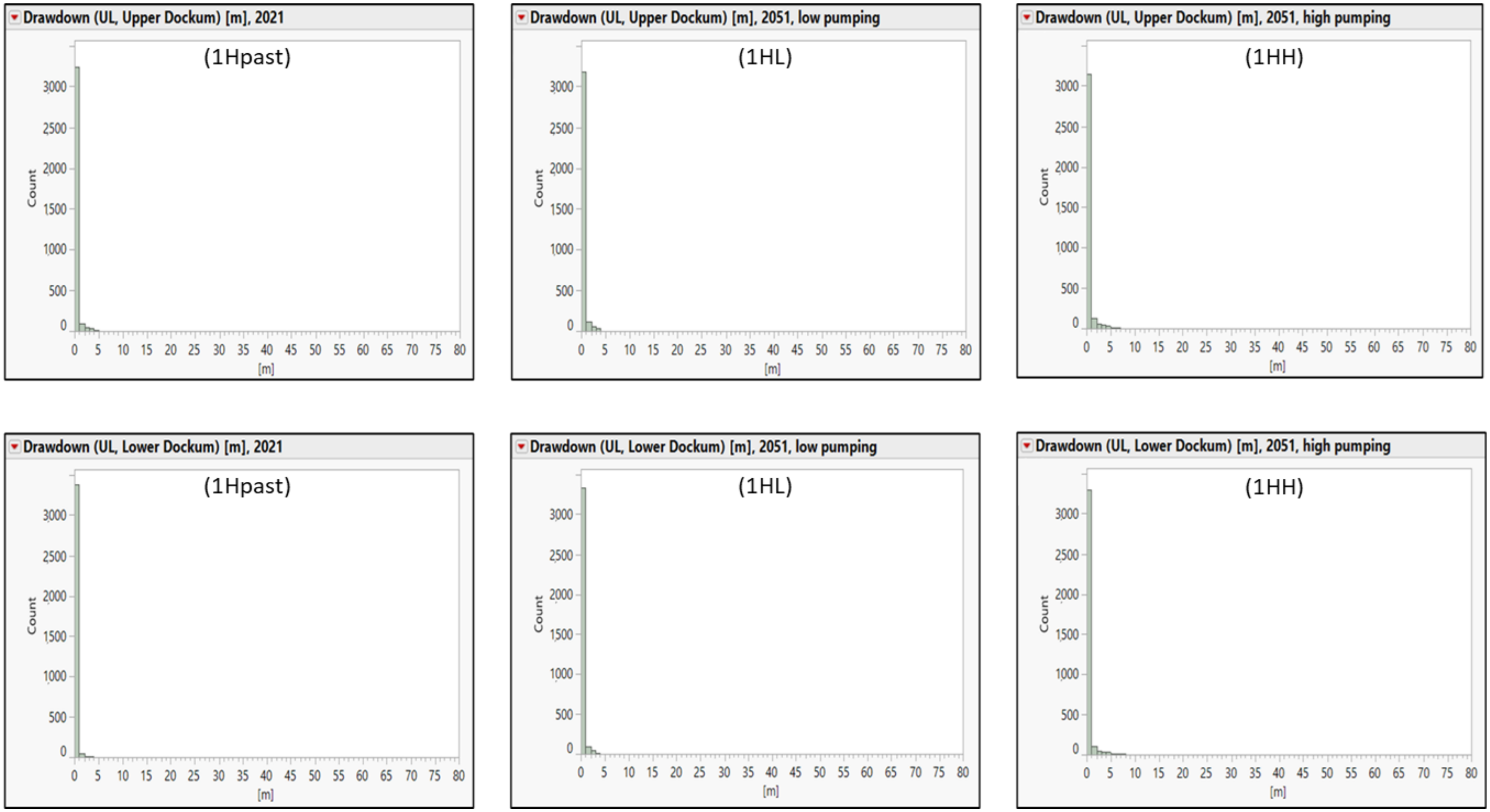


Figure A26: Drawdown frequency histogram results from annualizing water pumping for HF across all Rig/Frack supply wells in each region screened in all aquifers. Upper Dockum (1Hpast) by 2020; (1HL) by 2050, low pumping; (1HH) by 2050, high pumping; and lower Dockum (1Hpast) by 2020; (1HL) by 2050, low pumping; (1HH) by 2050, high pumping.

Table A2: Drawdown results from annualizing water pumping for HF across all Rig/Frack supply wells in each region screened in all aquifers. (1Hpast) upper and lower Dockum; (1HL) upper and lower Dockum; (1HH) upper and lower Dockum.

Drawdown [m]	1Hpast upper DKM	1Hpast lower DKM	1HL upper DKM	1HL lower DKM	1HH upper DKM	1HH lower DKM
Maximum	4.27	3.35	3.96	3.65	6.40	7.01
99th percentile	2.13	0.91	2.44	1.83	3.35	3.05
95th percentile	0.91	0.30	0.91	0.91	1.22	0.91
Mean	0.12	0.05	0.15	0.15	0.19	0.20
Median	0.00	0.00	0.00	0.00	0.00	0.00
Minimum	-3.04	-1.21	-3.35	-2.13	-3.35	-1.82

Section A10: Drawdown results from annualizing water pumping across Rig/Frack supply wells screened in the Dockum assuming 30% recycling of flowback water.

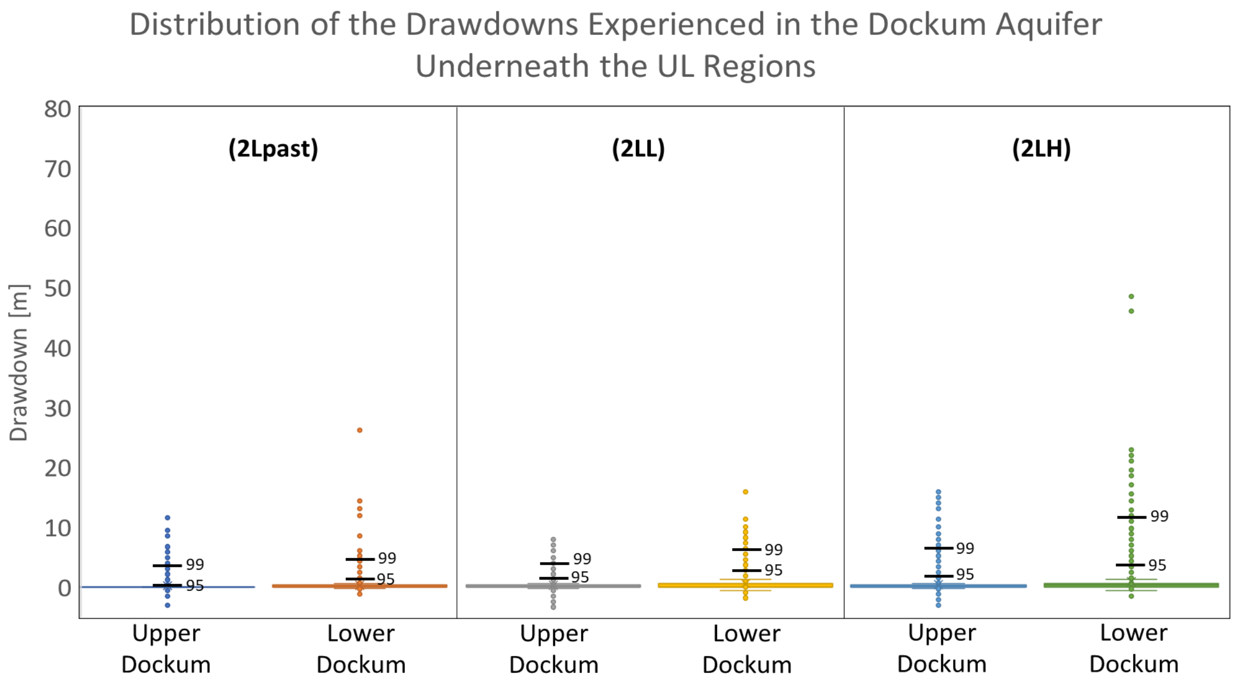


Figure A27: Summary of changes in hydraulic head from annualizing water pumping for HF across all Rig/Frack supply wells in each region screened in the Dockum assuming 30% recycling of flowback water.

Table A3: Drawdown results from annualizing water pumping for HF across all Rig/Frack supply wells in each region screened in all aquifers assuming 30% recycling of flowback water. (2Lpast) upper and lower Dockum; (2LL) upper and lower Dockum; (2LH) upper and lower Dockum.

Drawdown [m]	2Lpast upper DKM	2Lpast lower DKM	2LL upper DKM	2LL lower DKM	2LH upper DKM	2LH lower DKM
Maximum	11.6	26.2	7.92	16.2	15.9	48.5
99th percentile	3.66	4.27	3.80	6.10	6.71	11.6
95th percentile	0.91	1.22	1.52	2.74	1.83	3.66
Mean	0.20	0.29	0.25	0.54	0.38	0.83
Median	0.00	0.00	0.00	0.00	0.00	0.30
Minimum	-3.05	-1.22	-3.35	-1.83	-3.05	-1.52

Section A11: Drawdown frequency histogram from annualizing water pumping across Rig/Frack supply wells screened in the Dockum

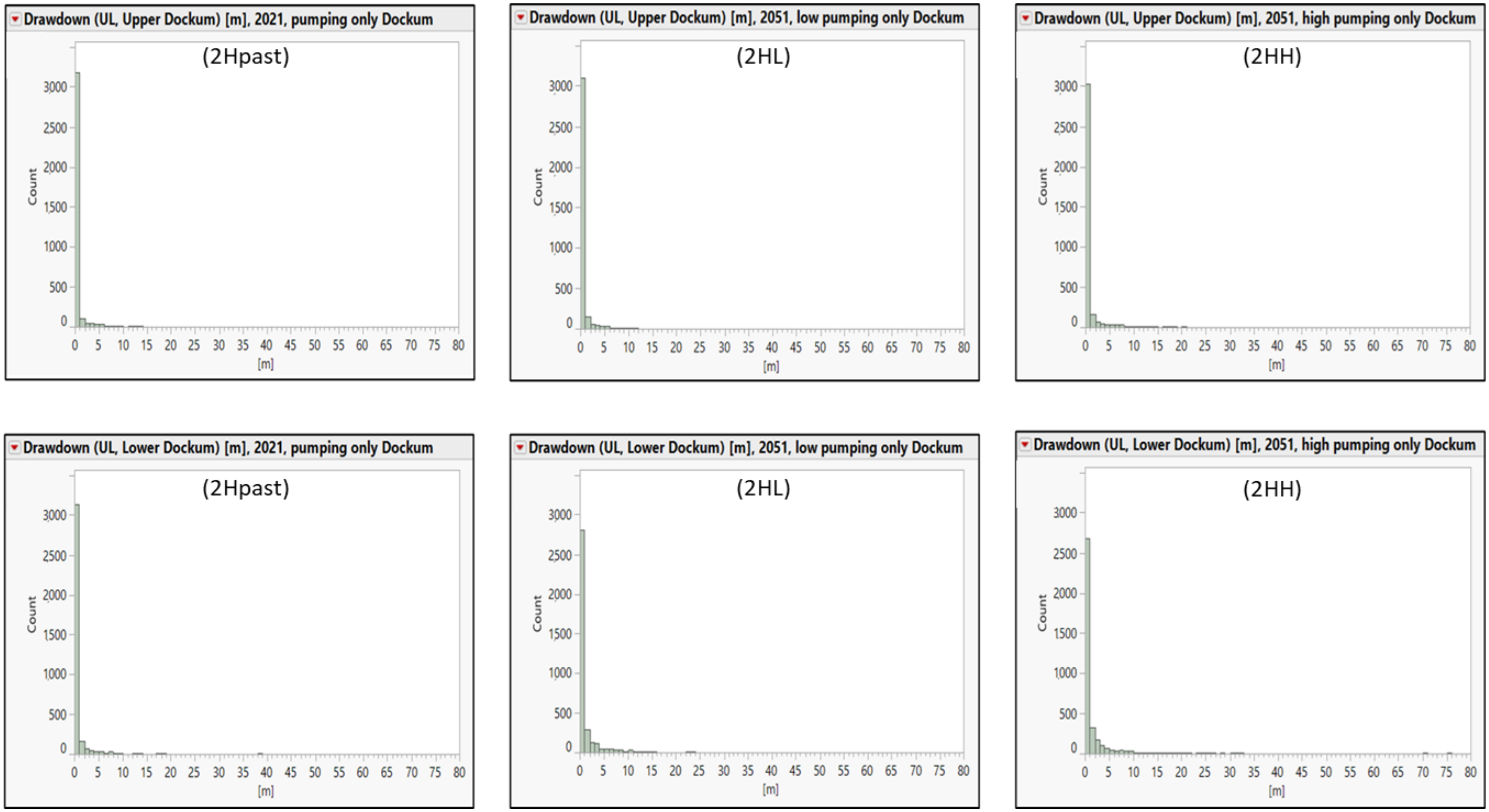


Figure A28: Drawdown frequency histogram results from annualizing water pumping for HF across all Rig/Frack supply wells in each region screened in the Dockum aquifer. Upper Dockum (2Hpast) by 2020; (2HL) by 2050, low pumping; (2HH) by 2050, high pumping; and lower Dockum (2Hpast) by 2020; (2HL) by 2050, low pumping; (2HH) by 2050, high pumping.

Table A4: Drawdown results from annualizing water pumping for HF across all Rig/Frack supply wells in each region screened in the Dockum aquifer. (2Hpast) upper and lower Dockum; (2HL) upper and lower Dockum; (2HH) upper and lower Dockum.

Drawdown [m]	2Hpast upper DKM	2Hpast lower DKM	2HL upper DKM	2HL lower DKM	2HH upper DKM	2HH lower DKM
Maximum	13.4	38.4	11.5	23.1	20.1	75.8
99th percentile	4.57	5.79	4.88	8.23	8.23	15.9
95th percentile	1.22	1.83	1.52	3.66	2.13	4.88
Mean	0.23	0.40	0.31	0.74	0.46	1.13
Median	0.00	0.00	0.00	0.30	0.00	0.30
Minimum	-3.04	-1.21	-3.04	-1.52	-2.74	-1.52