

TRENDS IN THE WATER ENERGY FOOD NEXUS OF CALIFORNIA'S CENTRAL VALLEY:

DRIVERS OF VULNERABILITY WITHIN THE NEXUS OF OIL PRODUCTION, AGRICULTURE AND WATER USE
IN KERN COUNTY

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Introduction

Groundwater is an important natural resource for both human and environmental benefit. It can be used for drinking water or irrigation, and it can be accessed according to localized demand without the need for substantial infrastructure (Giordano, 2009). Groundwater serves as a critical reserve for agriculture in times of drought (Famiglietti et al., 2011), and is of vital importance to water security for rural communities (Taylor, et al., 2012).

Many major aquifers globally, especially in arid and semiarid climates, are in decline because abstract rates exceed natural recharges to support irrigated agricultural practices. There are several socioeconomic factors contributing to this so-called “Global Groundwater Crisis” (Famiglietti, 2014), including fundamental science that is needed to better characterize the volume of groundwater that may be sustainably withdrawn (Famiglietti, 2014; Taylor et al., 2012). At the same time, drivers of groundwater use are complex and multi-faceted. Here, drivers mean “factors that cause a particular phenomenon to happen or develop” (Oxford English Living Dictionaries, 2016). Economic growth, urbanization, and increased demand for irrigation or energy development place increased pressure on groundwater resources worldwide (Hoff, 2011). Climate change is predicted to increase the frequency and duration of droughts, especially in semi-arid regions, which will intensify groundwater demand (Taylor et al., 2012).

The Water-Energy-Food Nexus (hereafter WEF Nexus) is a useful framework to understand the dynamic relationships between these sectors to improve their collective management (Rasul and Sharma, 2015). Kern Basin, the southernmost end of the Central Valley of California that lies within Kern County (**Figure 1**), represents a uniquely vulnerable geography in the WEF Nexus. Kern Basin, with an area just over 3,000 square miles, has an arid hot climate with less than 12 inches of annual rainfall (DWR 2006). Kern Basin supported a population of 700,323 in 2010 (DWR 2003), and is one of the

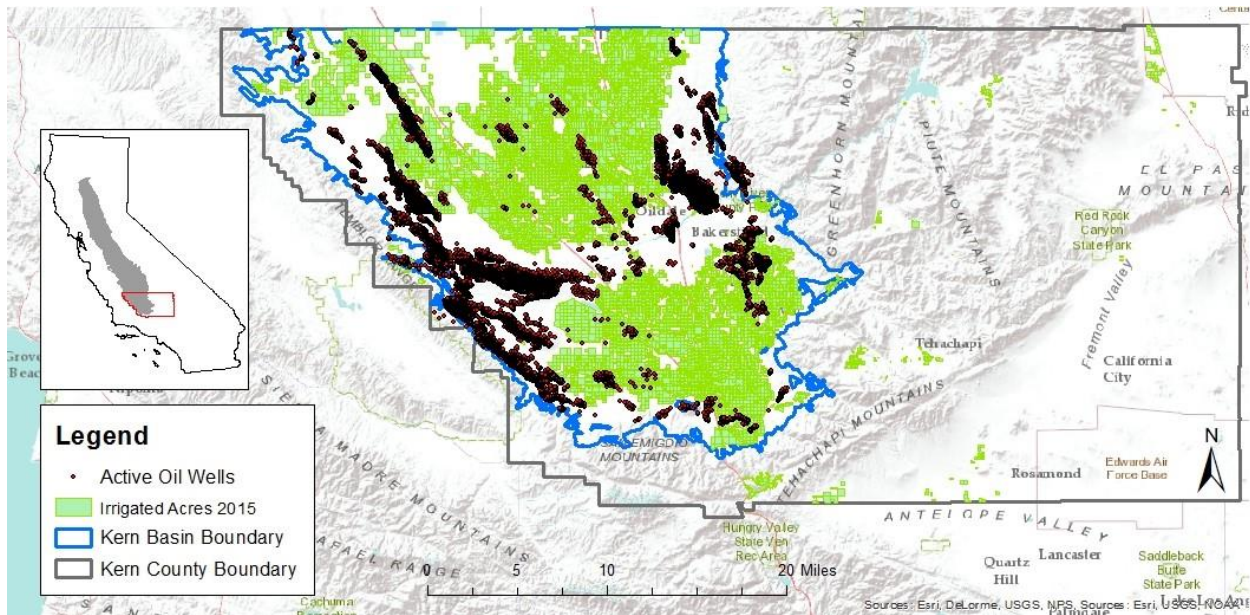


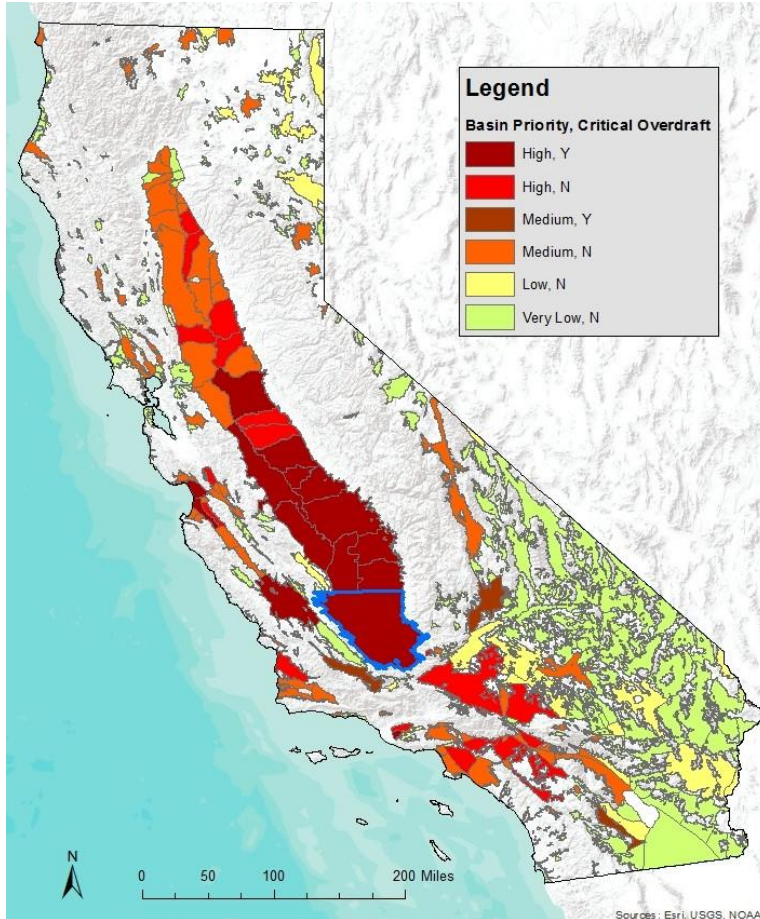
Figure 1. Map of Kern Basin, the southernmost section of the Central Valley Aquifer, located in Kern County. Data Sources: US Census 2014, US Census 2015, CDOC 2016a, Kern County Department of Agriculture 2016, DWR 2016a.

country's top agricultural counties, growing over 250 crops and the leading producer of almonds, grapes, and citrus in the United States (US) (USDA, 2015). Additionally, eighty-five percent of hydraulic fracturing for oil in California occurs in just four oil fields in Kern Basin (Long, et al., 2015b). Kern Basin is dependent on surface water deliveries from Northern California via the California aqueduct and the Friant-Kern canal (Water Association of Kern County, 2016a). Groundwater makes up 36 percent of Kern County's water supply in an average year (Water Association of Kern County, 2016a). Groundwater levels have declined for decades (Faunt et al., 2009), two surface lakes have dried up, and the basin has subsided as much as 9 feet in some places (Faunt and Sneed, 2015; Ireland, et al., 1984). Land subsidence is a gradual or sudden sinking of the Earth's surface due to subsurface movement of earth materials (Galloway and Riley, 1999). Compaction of sediments in unconsolidated aquifer systems that can accompany excessive groundwater pumping is the single largest cause of subsidence (USGS, 2000).

The Sustainable Groundwater Management Act (SGMA) was passed by the California State Legislature in 2014, in the midst of the state's driest 4-year period in recorded history (DWR 2016f).

SGMA requires groundwater to be managed sustainably in order to avoid six undesirable results, including groundwater decline, groundwater quality degradation, and land subsidence (DWR 2016f).

SGMA works in concert with existing water codes and previous efforts by DWR to manage groundwater.



Kern Basin has been considered critically overdrafted since 1980

(Figure 2) (DWR 2016c).

Relationships between water, climate, energy, oil production and agriculture are complex and varied. Interactions between these sectors within the physical, economic, and policy realms drive groundwater depletion and related vulnerabilities. The relationships within the WEF Nexus will be identified and evaluated for Kern County Basin to determine

Figure 2. Groundwater basins in California by management priority and critical overdraft. Sources: DWR 2016a; DWR 2016c; DWR 2016d; US Census 2015.

the drivers of vulnerability. Three undesirable results defined under SGMA—groundwater overdraft, groundwater quality degradation, and land subsidence—are used collectively to refer to vulnerability in this study. This paper will examine how understanding drivers of vulnerability within the WEF Nexus could help inform sustainable groundwater management.

1.1 Background

The Sustainable Groundwater Management Act of 2014 (SGMA) includes three separate bills which for the first time in California's history attempt to manage California's groundwater for sustainability (DWR 2016f). SGMA outlines a statewide sustainable groundwater management plan that divides management powers between three main entities: local Groundwater Sustainability Agencies (GSAs), the California Department of Water Resources (DWR), and the State Water Resources Control Board (SWRCB). SGMA applies only to high- and medium-priority groundwater basins or subbasins (basins), and those basins also considered to be critically overdrafted have slightly shorter deadlines (DWR 2016f).

Under SGMA, all high- and medium-priority basins in California must form locally-controlled GSAs by June 30, 2017; low-priority basins are exempt from this requirement (DWR 2016f). Each GSA is responsible for developing and implementing a groundwater sustainability plan (GSP) to operate within its sustainable yield without causing six undesirable results, defined below (DWR 2016f). High- or medium-priority basins also deemed critically overdrafted must be managed under a GSP by January 31, 2020. All other high- and medium-priority basins must be managed under a GSP by January 31, 2022. Basins must achieve sustainable yield within 20 years of initial management, or by 2040 or 2042, respectively (DWR 2016f).

Basin priority was first established in 2009 under the California Statewide Groundwater Elevation Monitoring (CASGEM) system. Groundwater basins were identified throughout the state and ecosystem health was assessed on a high, medium, and low priority scale. DWR determines the basin priority by evaluating eight conditions: 1) overlying population, 2) projected growth of overlying population, 3) the number of public supply wells that draw from the basin, 4) the total number of wells that draw from the basin, 5) overlying irrigated acreage, 6) reliance on groundwater as the primary

source of water (as a percentage), 7) impacts on the groundwater within the basin, including overdraft, subsidence, saline intrusion, and other water quality degradation, and 8) any other information determined to be relevant to the Department of Water Resources. (DWR, 2016d). Kern Basin has been considered a high-priority basin under these criteria since 2009 (DWR 2016f).

Previous to basin prioritization, in 1980 DWR was directed by the California State Legislature to develop a definition of critical overdraft and identify basins that were in a condition of critical overdraft (DWR 2016c). The DWR's definition of critical overdraft is:

“A basin is subject to critical conditions of overdraft when continuation of present water management practices would probably result in significant adverse overdraft-related environmental, social, or economic impacts.” (2016c).

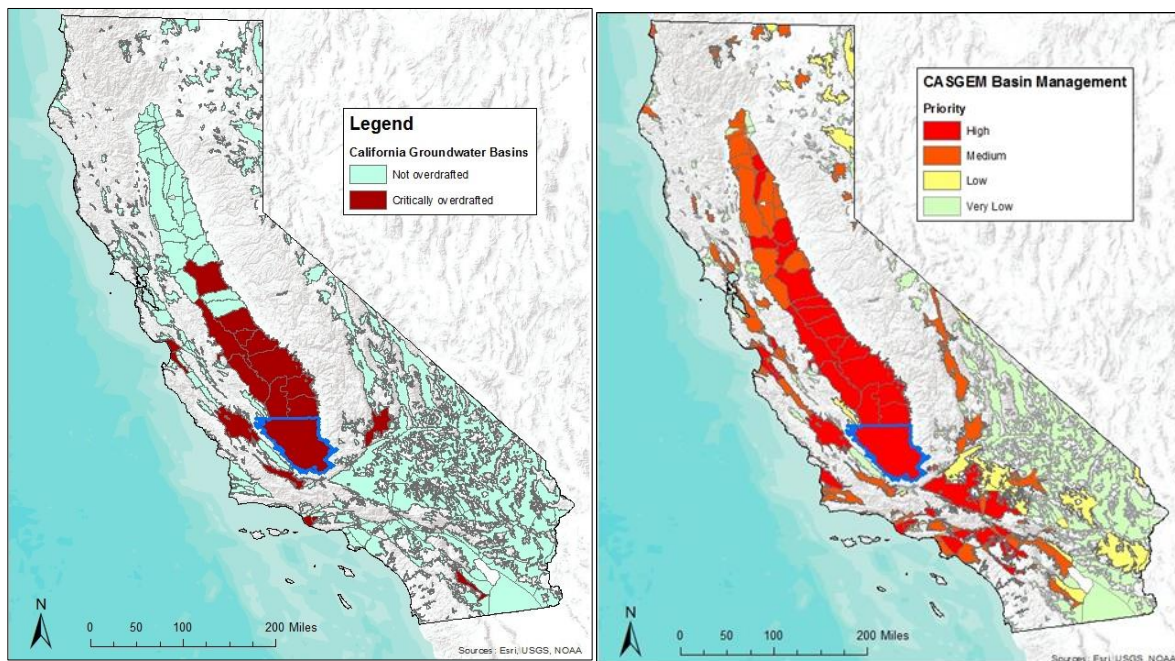


Figure 3. Previous groundwater management regulations in California. Basins subject to critical overdraft (left) and categorized by Priority for basin management under CASGEM (right). Sources: DWR 2016a; DWR 2016c; DWR 2016d; US Census 2015.

In 1980, 11 basins were identified as critically overdrafted including Kern Basin; in January 2016 this list was modified to include 10 more basins bringing the total to 21 basins (2016f).

Sustainable yield is defined by SGMA as “the maximum quantity of water, calculated over a base period representative of long-term basin conditions, that can be withdrawn annually from a groundwater supply without causing an undesirable result” (DWR 2016i). Basins subject to SGMA must be managed to achieve sustainable yield and avoid any of the following six undesirable effects: chronic lowering of groundwater levels, significant and unreasonable reduction of groundwater storage, significant and unreasonable seawater intrusion, significant and unreasonable degraded water quality, significant and unreasonable land subsidence, and depletions of interconnected surface water. (DWR 2016f).

2. Literature Review: The WEF Nexus

A review of the relevant WEF Nexus literature explores how the WEF Nexus can reveal drivers of groundwater vulnerability in Kern Basin. The WEF Nexus has emerged as an international framework for sustainable management of three essential resources for human economic development (Hoff, 2011). The WEF Nexus builds on previous studies which recognized the interdependence of resources, such as the water-energy nexus, the water-food-trade nexus and the energy-climate nexus (Endo et al., 2015; Allan et al., 2015). The WEF Nexus recognizes that water, energy production, and food production interact in complex ways across multiple spatial and temporal scales (Leck et al., 2015), and that managing these resources collectively could avoid the negative results of siloed approaches (Rasul and Sharma, 2015).

A number of factors drive vulnerability within the WEF Nexus. Global population is expected to reach 9.7 billion by 2050, (UN DESA, 2015) with most growth occurring in developing countries where the demand for water and food already exceeds supply (Rasul and Sharma, 2015). Climate change already impacts the global hydrological cycle, and is expected to increase the severity of both droughts in dry areas and floods in temperate areas, making agricultural production more difficult and

unpredictable (Trenberth, 2011) and water resources management more challenging at local to global scales.

The WEF Nexus approach has arisen at a time when human alterations of earth's life-enabling systems have crossed several safe thresholds for sustaining life—atmospheric carbon dioxide levels, the rate of biodiversity loss, and increased available nitrogen (Rockstrom, et al., 2009). All three transgressions are either a direct or indirect result of human activities within the nexus of energy production and/or consumption, food production, and water use. Likewise, the crossing of these three thresholds threatens the future viability of human activities within the WEF Nexus.

Water, energy and food production interact in complex ways. The single greatest human use of freshwater resources worldwide is to support irrigated agriculture (Siebert et al., 2010). However, water is also required in the production of electricity as an essential cooling agent in thermoelectric plants and thermonuclear plants (Maupin et al., 2014). Water is an essential ingredient in petroleum refining, and with the rise of hydraulic fracturing water has also become essential to the production of natural gas and oil (Gold, 2014). Energy is required to pump, treat and transport water for human use, and industrial agriculture is highly dependent on energy for all levels of food production, processing and transportation (National Intelligence Council, 2012). Agriculture, in turn, interacts with the surrounding physical environment and has resulted in the degradation of many ecosystems and ecosystem services (Hoff, 2011). Irrigated agriculture impacts water supplies by lowering the natural groundwater levels. Nitrate from fertilizers and concentrated animal wastes infiltrates aquifers (Gurdak and Qi, 2006), and

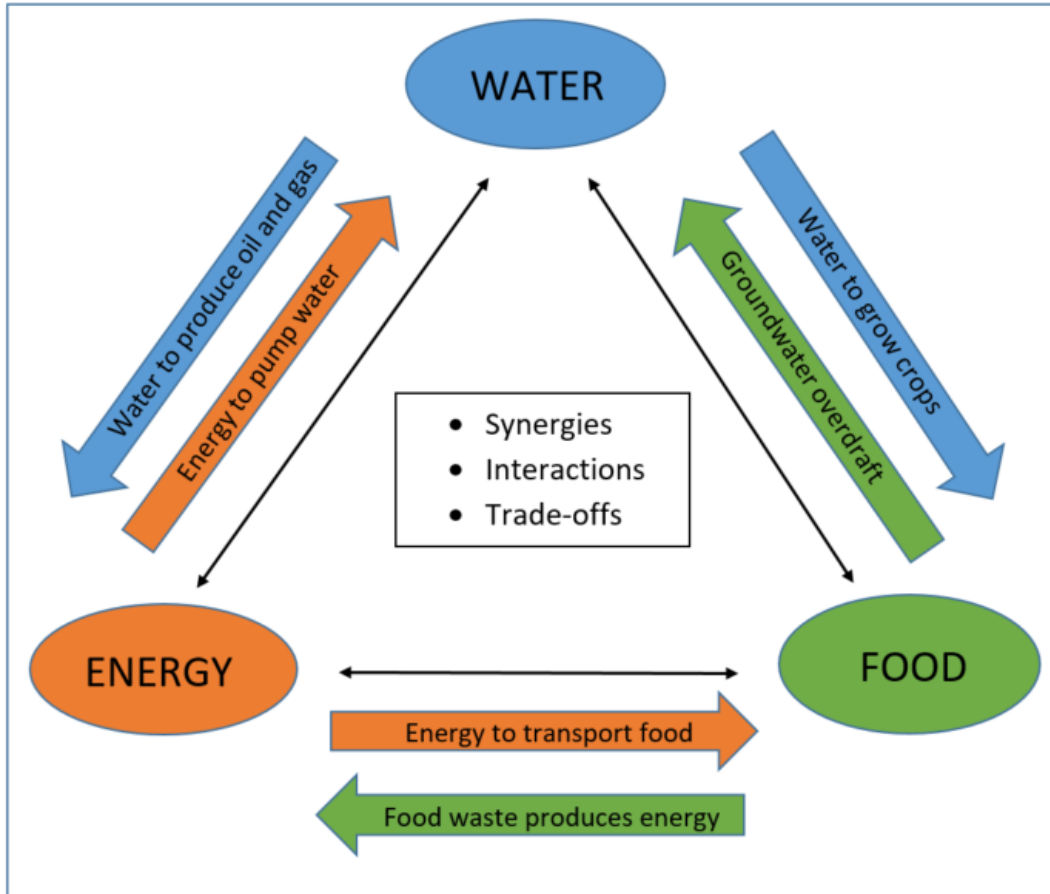


Figure 4. Simplified conceptual model of relationships within the WEF Nexus. Source: modified from Rasul and Sharma, 2015.

runoff to streams and rivers causes aquatic life to die off when high nitrogen concentrations cause eutrophication (Nixon, 1995).

Water is the most important resource in the WEF Nexus and the main limiting factor since both energy production and agriculture require water, for which there is no substitute. **Figure 4** shows a simplified conceptual model of interactions within the WEF Nexus. Relationships among these three resources can be characterized as synergies, interactions, or trade-offs. For this study, synergies (or linkages) are defined as relationships between water, energy, or food resources where no resource is consumed or degraded in producing another resource (such as in-stream micro hydroelectric power generation) or where there are mutual benefits or co-production of resources (such as methane digesters in dairy production). Interactions are defined here as relationships between water, energy,

and food resources where one resource is altered but not degraded as a result of producing another resource (such as water that is heated in the process of cooling reactors in a nuclear power plant). Trade-offs or conflicts may be where one resource is consumed or degraded in the production of another resource, or where one resource is produced at the expense of another (e.g., biofuel production competes with agriculture; irrigation pumping results in groundwater overdraft; water used for hydraulic fracturing returns too polluted to be reused for any purpose).

By examining the relationships within the WEF Nexus, the intent is to identify trade-offs so they can be mitigated or avoided altogether, while encouraging the development or discovery of synergies. A WEF Nexus approach to managing common resource use may help avoid policy pitfalls that exacerbate vulnerability to climate change, food, or energy insecurity. In the Hindu Kush Himalayan region, for example, subsidized groundwater was intended to help cope with surface water shortages and uncertainty in water availability; instead it led to overexploitation of localized groundwater and increased demand for energy (Rasul and Sharma, 2015).

The WEF Nexus is a relatively new framework for analyzing resource management, and methods for conducting research are still evolving. Many disciplines may be involved in assessing WEF Nexus metrics, including economics, geology, geography, policy studies, and others. Endo et al. (2015) lay out several suggested methods for WEF Nexus studies, but this is far from an exhaustive list. Some researchers critique the WEF Nexus on this basis, saying that attempts to analyze too many metrics, across three or more sectors, at multiple spatial and temporal scales is too ambitious to be practical or operational at current scales of management (Leck et al., 2015). At the same time, these researchers and others point out that the potential of the WEF Nexus to enable interdisciplinary and cross-disciplinary research, particularly in Geography, is a distinct advantage of the approach (Leck et al., 2015; Scott et al., 2015).

The complexity of the relationships within the WEF Nexus of Kern Basin is illustrated in **Table 1**. Each relationship is dynamic across space and time, and depends on multiple other factors which may include climate, geology, hydrology, precipitation, economic conditions, population dynamics, market incentives, and other factors. Quantifying any particular relationship within this nexus necessarily depends on many other factors. For example, the amount of groundwater extracted for irrigation in Kern County Basin depends on the annual precipitation for that year, the amount of surface water available, the crop type, and irrigation method. These factors may in turn be affected by the cost of electricity, access to drilling or irrigation technology, crop prices, and environmental or economic policies. Some of these factors may change infrequently, while others may be dynamic on a yearly basis.

The WEF Nexus framework can be applied to help answer resource management questions. Quantifying every possible relationship in the WEF Nexus across space and time is an interesting challenge. Since so many different relationships exist, the WEF Nexus analysis is site specific and will focus on those relationships that pertain to the most relevant research question at the scale of interest. For example, a study focused on synergies between water and energy production might aim to quantify in-stream electricity production, or the potential irrigation demand reduction from soil conservation practices for a particular temporal and spatial scale, considering different climate, pricing, and/or policy scenarios. A study of transport losses might quantify the amount of food or water lost over various distances given different dependent variables. A recent water-energy nexus study found that significant greenhouse gas emissions reductions, as well as economic savings, could be realized by fixing leaky pipes in urban settings, because of the energy savings that resulted (Stokes et al., 2013).

Nexus	Water Production (for Ag)	Water Transport	Energy Production	Energy Transport	Food Production (Agriculture)	Food Transport
Water Consumption (Nexus)	Groundwater extraction amounts/rates vs. groundwater recharge rates (snowpack/rainfall)	Evaporation in flood irrigation techniques; evaporation in surface water deliveries (open canals)	Freshwater consumed (unrecovered and/or polluted beyond treatment) used to frack for oil or gas.	Indirect consumption, if counting water used to produce transport fuel (transport oil to refineries)	Irrigation amounts; evapotranspiration rates; groundwater recharge; run-off	Indirect consumption, if counting water used to produce transport fuel (transport harvest to markets)
Water Alteration (Interaction)			Water (freshwater) used in thermoelectric plants for cooling		Nitrate contamination of groundwater; evapotranspiration	
Water Linkage (Synergies)			In stream micro-hydroelectric energy production (potential)		Soil conservation practices like mulching, intercropping, and use of compost reduce water demand	
Water Transport					Nitrate leaches to groundwater over time; groundwater levels affected (up or down)	
Energy Consumption	Electricity consumed in extracting water for agriculture (KWh per AF)	Groundwater pumping; water piped to fields; aerial sprinklers; pressure in pipes;	Energy consumed in fracking for oil or gas	Oil consumed in transport of oil to refineries	Energy used in irrigation and transport of water to fields. Energy used to produce and spread fertilizers.	Oil consumed in transport of harvest to markets.
Food Consumption			Kilocalories of food consumed as energy			Food wasted during transport or processing
Water Production			Water released from rock during hydraulic fracturing, called "produced water"			
Energy Production		Hydroelectric production.	Energy Produced from oil production.		Fracking wastewater disposed in shallow irrigation wells; Produced water used for irrigation.	

Table 1. Water-Energy-Food Nexus relationships within Kern County Basin. Orange squares show relationships with the most direct effect on groundwater vulnerability. Yellow squares show relationships with indirect effects on groundwater vulnerability.

Nexus relationships are dynamic, thus the WEF Nexus framework can be used to demonstrate temporal trends that may either drive vulnerability or reveal potential management synergies or trade-offs. Trends in agricultural practices were examined in the High Plains aquifer to determine potential drivers of groundwater decline and economic vulnerability through a WEF Nexus analysis (Smidt, et al., 2016). In their analysis, the authors quantified irrigated and non-irrigated crop yields, crop acreage change over time, aquifer volume decline, changes in irrigation technology, and the economic value of irrigation by crop type (Smidt, et al., 2016).

The WEF Nexus framework may be especially useful to model scenario-based outcomes to measure the effect of policy on resource management. For example, a recent (2016) study of the Pajaro Valley in coastal California modeled the value of avoiding sea level intrusion for the Pajaro basin by irrigating with surface water from the College Lake project to reduce seawater intrusion for the Pajaro basin by supplant groundwater withdrawals (Wada et al., 2016). Results from the model demonstrated the economic benefits to growers of using College Lake water with several crop scenarios based on a stylized groundwater management model (Wada et al., 2016). Similarly, Scott (2011) conducted a nexus study on the effect of different climate, population, and electricity pricing on predicted future groundwater drawdown in 280 water districts in Mexico. Scott calculated the outcomes for six different scenarios based on these variables and results demonstrated that higher electricity pricing for irrigation could reduce groundwater drawdown in nearly every basin (Scott, 2011).

A study that models future scenarios must understand how the dynamic relationships within the WEF Nexus enable synergies or drive vulnerabilities. The purpose of this study is to examine and quantify trends and interactions within the WEF Nexus of groundwater, irrigated agriculture, and hydraulic fracturing for oil to determine drivers of groundwater vulnerability in Kern Basin over dynamic climate and economic contexts.

3. Methods

3.1 Study Area

The scale of this study is limited to the Kern Basin, which is the southernmost reach of the Central Valley Aquifer in Kern County (**Figure 5**). Many drivers within the WEF Nexus, including physical, socio-economic, and policy drivers, act on a larger scale than the Kern Basin.

3.1.1 Physical

California's Central Valley is a large structural trough between the Sierra Nevada to the East, and the Coastal Ranges to the West, filled with sediment of Jurassic to Holocene age, ranging from 3 miles deep in the San Joaquin Valley to 6 miles deep in Sacramento Valley (Faunt et al., 2009). Most of the

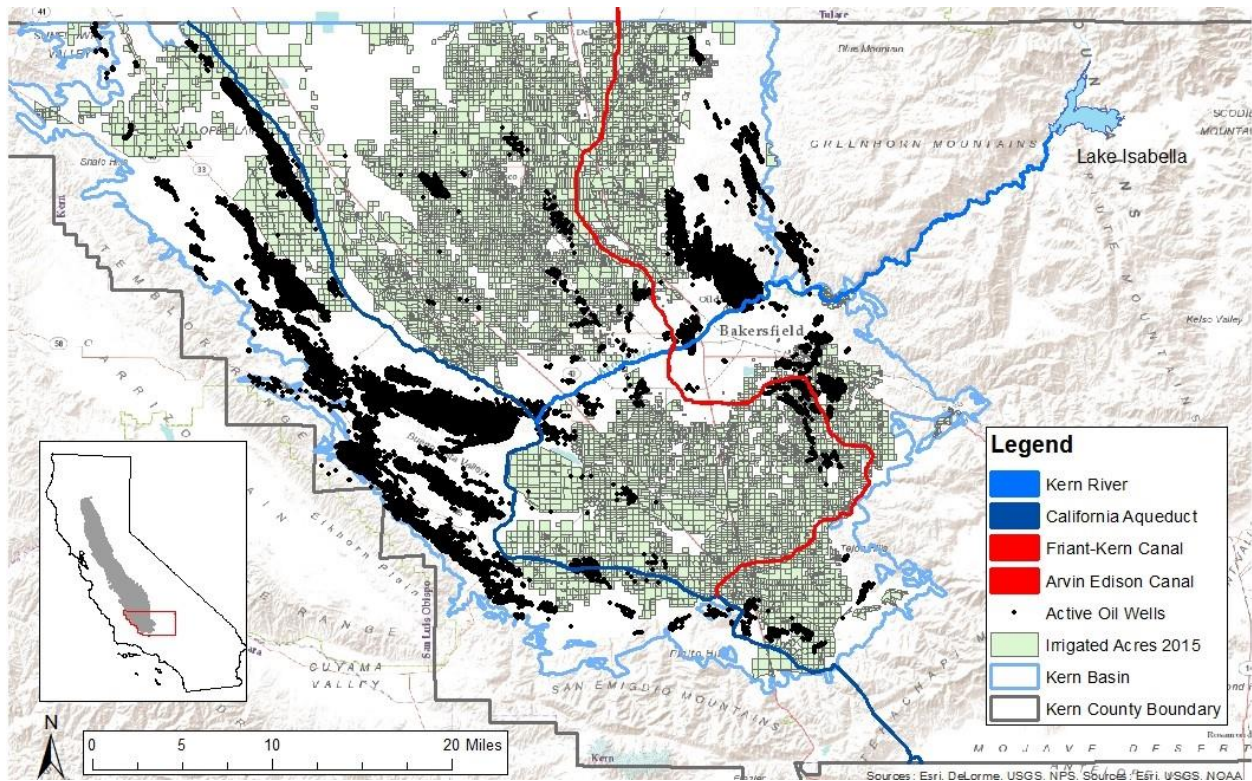


Figure 5. Kern Basin irrigated agriculture in 2015, active oil wells, and major canals. Sources: US Census 2014; US Census 2015; DWR 2016a, CDOC 2016a, Kern County Department of Agriculture 2016; Kern County ESPS 2016.

freshwater is contained in the upper part of the sediments, with saturated thicknesses ranging from 1,000 to 3,000 feet (Faunt et al., 2009). The Central Valley aquifer is an unconsolidated and semi-

consolidated sand and gravel aquifer (Maupin *et al.*, 2014). The aquifer is unconfined or semi-confined; a laterally extensive lacustrine clay known as the Corcoran Clay is distributed throughout the central and western San Joaquin valley at depths that range in thickness up to 160 feet. The Corcoran Clay confines a deeper aquifer system comprised of fine-grained sediments and older deposits of both sediment and water (Galloway and Riley, 1999). The base of fresh water is considered the bottom of the basin. (DWR 2003).

Approximately 800 million acre-feet of freshwater is reported to be stored in the upper 1,000 feet of sediments in the Central Valley (Faunt *et al.*, 2009). This number and other estimates may be misleading because much of the water in storage cannot be extracted without serious consequences, as discussed below (Faunt *et al.*, 2009).

The Kern Basin (previously the subbasin 5-22.14 “Kern County”) is located in the Tulare Lake hydrologic region in the southern end of the San Joaquin Valley, the southernmost section of the Central Valley aquifer. The surface area of Kern Basin is 1,945,000 acres, (3,040 square miles) (DWR 2003). Kern Basin is an alluvial groundwater basin (DWR 2013), bounded on the north by the Kern County boundary and the Tulare groundwater subbasin, on the east and southeast by the granitic bedrock of the Sierra Nevada foothills and the Tehachapi mountains, and on the southwest and west by the marine sediments of the San Emigdio Mountains and Coast Ranges. The lateral boundaries of the basin are features that significantly impede groundwater flow, such as rock or sediments with very low permeability (DWR 2003).

3.1.2 Climate

The southern San Joaquin Valley has an arid hot climate (DWR 2006). Average precipitation ranges from 5 inches at the Kern Basin interior to 9 to 13 inches at the subbasin margins to the east, south, and west, with 95 percent falling from October through April (DWR 2003). Temperatures in July in the mid-valley reach over 100 degrees Fahrenheit (DWR 2006). Before agricultural development, land

cover was alkali desert scrub with some grassland and wetland areas including two shallow lakes, Kern Lake and Buena Vista Lake (**Figure 6**). Principal rivers and streams include Kern River and Poso Creek. Active faults include the Edison, Pond-Poso, and White Wolf faults (DWR 2006).

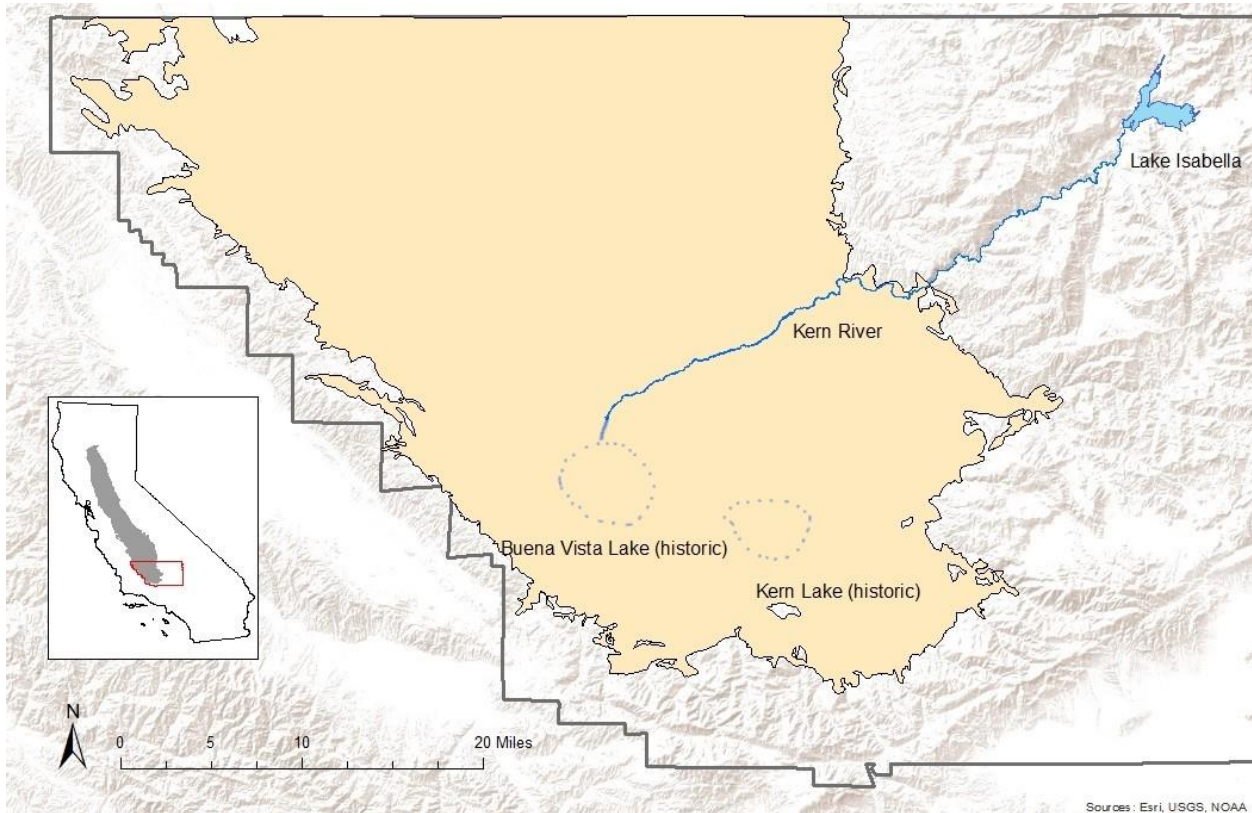


Figure 6. Approximate locations and extents of Kern Basin historic lakes. Sources: US Census 2014; US Census 2015; DWR 2016a; Kern County ESPS 2016; Faunt et al., 2009.

3.1.3 Hydrology

The Kern River originates in the Inyo and Sequoia national forests and Sequoia National Park, and flows southward into Lake Isabella. In wet years, with high-discharge, water will spill into the ancient Buena Vista/Kern Lake bed. Kern Lake previously covered 8,300 acres during wet periods, and was connected by a slough to Buena Vista Lake, which could reach 4,000 acres in size. Historically, and in very high water years, Buena Vista Lake overflowed into Tulare Lake via sloughs and floodwater channels (DWR 2013).

Kern Basin has a dry climate, therefore agriculture, oil production, and urban residents depend on water sources from outside of the valley. One source is Kern River, which originates in the Southern Sierra (DWR 2013). Water deliveries from the State Water Project and Central Valley Project provide over a third of the total water supplies in a year of average rainfall (Water Association of Kern County, 2016a). Groundwater supplies 36% in a year of average rainfall; some residents rely exclusively on groundwater for their water supply (Water Association of Kern County, 2016a). Average assumptions for water use and amounts are given below from the Water Association of Kern County. AF stands for acre-feet, the amount of water needed to cover an acre of land a foot deep (Water Association of Kern County, 2016a).

Water Uses	
Municipal and Industrial	166,000 AF
Agricultural	2,294,000 AF
Total	2,460,000 AF

Source	Percent
Kern River	20%
State Water Project (California Aqueduct)	26%
Federal Central Valley Project (Friant-Kern Canal)	12%
Local Streams and Other Sources (Poso Creek, and others)	6%
Groundwater	36%
Total	100%

Table 2. Modified from: Water Association of Kern County, 2016a. www.wakc.com

3.1.4 Population and Urban Centers

The population living within the Kern Basin boundary is 700,323, which represents 83 percent of the total Kern County population (839,631) as published in the most recent census (US Census 2010; DWR 2016d). Most of Kern Basin is a rural agricultural area with a low population, with the exception of Bakersfield, the county seat, where roughly half the population resides (US Census 2010). Kern Basin is

considered a high priority for management in part because the population of Kern County has seen rapid growth since 2000 (US Census 2010), and is projected to continue to grow by 40 percent from 2010-2030 (DWR 2016d).

3.1.5 Economy: Oil and Agriculture

The economy of Kern County revolves around agriculture and petroleum extraction, which both date back to the 1890's in Kern Basin. Kern County is one of the most productive agricultural regions in the United States, and a top producer of specialty crops like almonds and grapes (Kern County Department of Agriculture, 2014). More than 880,000 acres of land in Kern Basin produce over 150 types of agricultural products—vegetables, fruits and nuts, field crops, and specialty crops worth over \$7.5 billion in 2014 (Kern County Department of Agriculture, 2014). Crops produced in Kern County are exported to urban areas in California, the eastern United States, and internationally. As a region, San Joaquin Valley produces 40-50% of the produce consumed in the United States (CDFA, 2015).

Kern County has a long history of oil production, which means the oil no longer gushes to the surface. Several types of well stimulation techniques are used to extract the heavy oil that remains, including steam injection, acidizing and hydraulic fracturing (fracking), all of which require water (Gold, 2014). Hydraulic fracturing accounts for about 90 percent of all well stimulations in California. Ninety-five percent of reported hydraulic fracturing operations in California occur in the San Joaquin Basin, nearly all in four Kern Basin oil fields: Lost Hills, North Belridge, South Belridge, and Elk Hills (Long, et al., 2015a). Agriculture and oil production have co-existed in Kern Basin for over a hundred years (Heberger and Donnelly, 2015).

3.1.6 Historic and Current Vulnerabilities

The Kern basin has historically been subject to groundwater overdraft, land subsidence, and water quality degradation, three of the undesirable results SGMA seeks to avoid (DWR 2013; DWR

2016f). Although the DWR's CASGEM has monitored groundwater levels in the Central Valley since 2009, coverage is not complete; monitoring well densities vary by county (Faunt et al., 2009). It is well known that the Kern basin and Central Valley more broadly have been subject to overdraft, but amounts must be modelled, since not enough data are available and groundwater withdrawals are not usually metered (Faunt et al., 2009; Galloway and Riley, 1999). Faunt and others calculated that the Central Valley aquifer had lost an average of 1.4 million AFY (acre-feet per year) from 1962-2003 based on a complex water model (Faunt et al., 2009). Water budgets can be calculated for groundwater and may be useful, but models are preferred, since they are considered to be more accurate (Bredehoeft, 2002; Devlin and Sophocleous, 2005). The DWR calculated a groundwater budget for Kern Basin based on average inflows and outflows using data from 1958-1966, which showed a surplus each year of nearly 134,000 AFY. Meanwhile, the water budget calculated by Kern County Water Agency (KCWA) indicated the average change in storage for Kern Basin was minus 325,000 AFY from 1970-1998 (DWR, 2006). The differences between these two budgets could be due to different time periods.

While there have been periods of overdraft and periods of recharge over the history of Kern Basin (Faunt et al., 2009), the first water budget by the DWR may raise questions because it indicates average increases in groundwater levels during a time of known land subsidence in Kern Basin (Borchers and Carpenter, 2014). Between 1926 and 1970, groundwater extraction resulted in more than 8 feet of subsidence in the north-central portion of the Kern basin, and approximately 9 feet in the south-central area (Ireland et al., 1984). Land subsidence has not been observed in Kern Basin in more recent decades, although it is occurring at historically high rates in other subbasins within the San Joaquin Valley (Sneed et al., 2013). Land subsidence could resume in Kern basin if overdraft continues (DWR 2013). Famiglietti and others have measured recent and rapid groundwater decline in the San Joaquin Valley, including in Kern basin, using remote sensing images from twin satellites (Famiglietti, et al., 2011). Recent and historic overdraft has also degraded groundwater quality, in part from cross-

contamination of water above the confining layer and more saline water in the deeper confined aquifer, via well boreholes (Faunt et al., 2009).

Other groundwater vulnerabilities present in Kern Basin but not explored in this study include degradation from nitrate which migrates through sediment layers under agricultural acreage (Gurdak and Qi, 2006). Hydraulic fracturing pollutes the freshwater used to stimulate oil wells, as well as the deep groundwater into which the wastewater is injected (Kang and Jackson, 2016). Other fracking wastewater disposal methods, such as open pit percolation, are known to cause groundwater contamination in other states, and may be phased out in California (Long et al., 2015b). Direct contamination of groundwater drinking or irrigation wells from hydraulic fracturing have not been measured, although injections in several areas that should have been protected are being investigated for possible contamination of groundwater (Long, et al., 2015b). Irrigation with fracking wastewater is a newly discovered vulnerability not considered under SGMA; its risks are not yet known (Stringfellow, et al., 2015).

3.2. Analysis

This study examines the drivers of groundwater vulnerability within the WEF Nexus of the Kern Basin through a novel synthesis of data, GIS analysis, and an in-depth review of the relevant literature. Three undesirable results defined under SGMA—groundwater overdraft, groundwater quality degradation, and land subsidence—are used collectively to refer to vulnerability in this study. This study uses a WEF Nexus framework to analyze dynamic relationships within Kern Basin that drive groundwater vulnerability. The study is a first attempt to evaluate drivers and trends in the WEF Nexus relationships within Kern Basin. All drivers at every spatial and temporal scale may not be included.

3.2.1. Archive Data Sources: Scales, Timeframe, and Assumptions

Archive data on water use, oil production, agricultural crop types, economic measures, and GIS shapefiles were compiled for Kern Basin, and for the years 2000-2015; data on water use and chemical use in oil production have only been available to the public since 2011, pursuant to the passage of Senate Bill 4 (Long, et al., 2015a). With the exception of DWR CASGEM data specific to Kern Basin, Kern County was the scale at which data were available. Since most of the oil production and virtually all the agricultural production in Kern County occurs in Kern Basin, the data available for Kern County for these metrics were assumed to represent the data for Kern Basin.

Pursuant to SGMA implementation, the DWR has completed a process of evaluating requests for redefining basin and subbasin boundaries as deemed necessary (**Figure 7**). The subbasin boundary of the southernmost Central Valley Aquifer in Kern County, subbasin 5-22.14, has been modified according to the following four basin boundary requests: The Delano-Earlimart Irrigation District and Devil's Den Water District requested boundary changes along the northern Kern basin boundary county line for jurisdictional internal reasons, since both of these districts cross county lines. The Olcese Water District requested minor modifications to the basin boundary in the northwest corner for scientific reasons because of physical changes in the subsurface landscape. Finally, the Tejon-Castac Water District requested a subdivision of the basin at the southernmost end of the valley at the White Wolf fault line, which they showed restricts subsurface groundwater movement (DWR 2016g). These modifications may be important for GSAs and GSPs in managing the basin and new subbasin for sustainable yield.

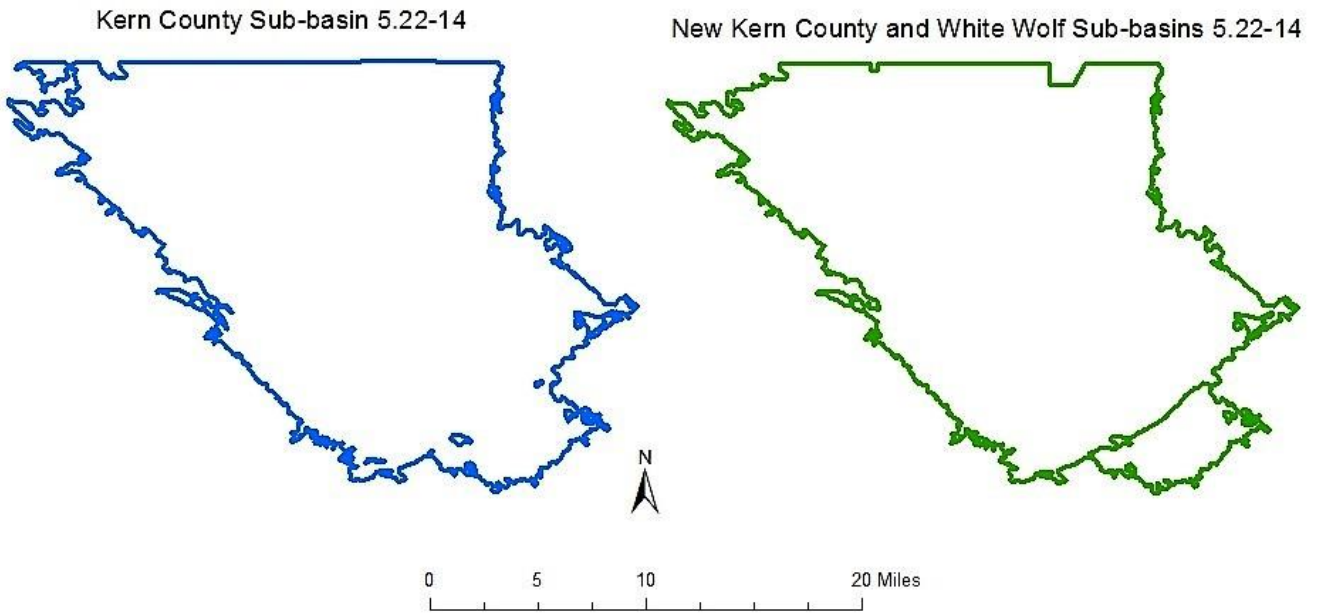


Figure 7. Map of basin boundary changes under SGMA. Study site is the previous basin boundaries shown at left. Source: DWR 2016a; DWR 2016b.

The boundaries of the study site are the physical hydrologic boundary of the Central Valley aquifer that exists within Kern County, and not the new basin boundaries defined under SGMA management. The WEF Nexus relationships that may drive groundwater vulnerability in Kern Basin are not confined to the regulatory authority of SGMA implementation, since they are influenced by land use practices and economic variables outside the scope of SGMA.

4. Data Analysis

This study focuses on demand-side drivers of groundwater use in Kern Basin. From the available models and data, it appears that groundwater levels have been declining on average for decades in Kern Basin, due to overdraft (Faunt et al., 2009; Sneed, 2013; Famiglietti et al., 2011 and others). Climate change models predict reduced snowpack in the Sierra and increased intensity and duration of droughts in California, both of which will impact groundwater recharge (DWR 2003; Taylor, et al., 2012). Based on reduction of surface deliveries in past droughts, it is assumed that surface water deliveries to Kern Basin

may be reduced in the future. Therefore, understanding what drives groundwater demand in Kern Basin may be important to managing groundwater for sustainable use.

This paper will synthesize the available data on water use within oil production and irrigated agriculture, examine drivers of land use change in agriculture and implications for groundwater vulnerability, and explore how relationships between water, oil production, agricultural land use change and drought drive vulnerability with regard to irrigation with produced oil water.

4.1 Water use in Oil Production

Commercial production of oil in Kern County dates to the 1860's, and even today four of the five largest and most productive oil fields in California are located in Kern County: Midway-Sunset Field, Kern River Field, Belridge South Field, and Elk Hills Field (US EIA, 2015). All four of these fields are in Kern Basin (**Figure 8**). Kern County is the largest oil producing region in California, accounting for about 75 percent of the state's total production (**Figure 9**), down from an historic peak of 400 million barrels in 1985 (CDOC, 2016b; US EIA, 2016a). Since 2010, California's production has remained at roughly 200 million barrels a year, largely because of enhanced oil production techniques using water (Long, et al., 2015a). Kern County's oil production declined to just over 141 million barrels in 2012, increasing to 145 million barrels in 2014 (CDOC, 2016b). Most of the hydraulic fracturing in Kern County occurs in the large fields on the west side of Kern Basin--Elk Hills, North and South Belridge, and Lost Hills (Long et al., 2015c).

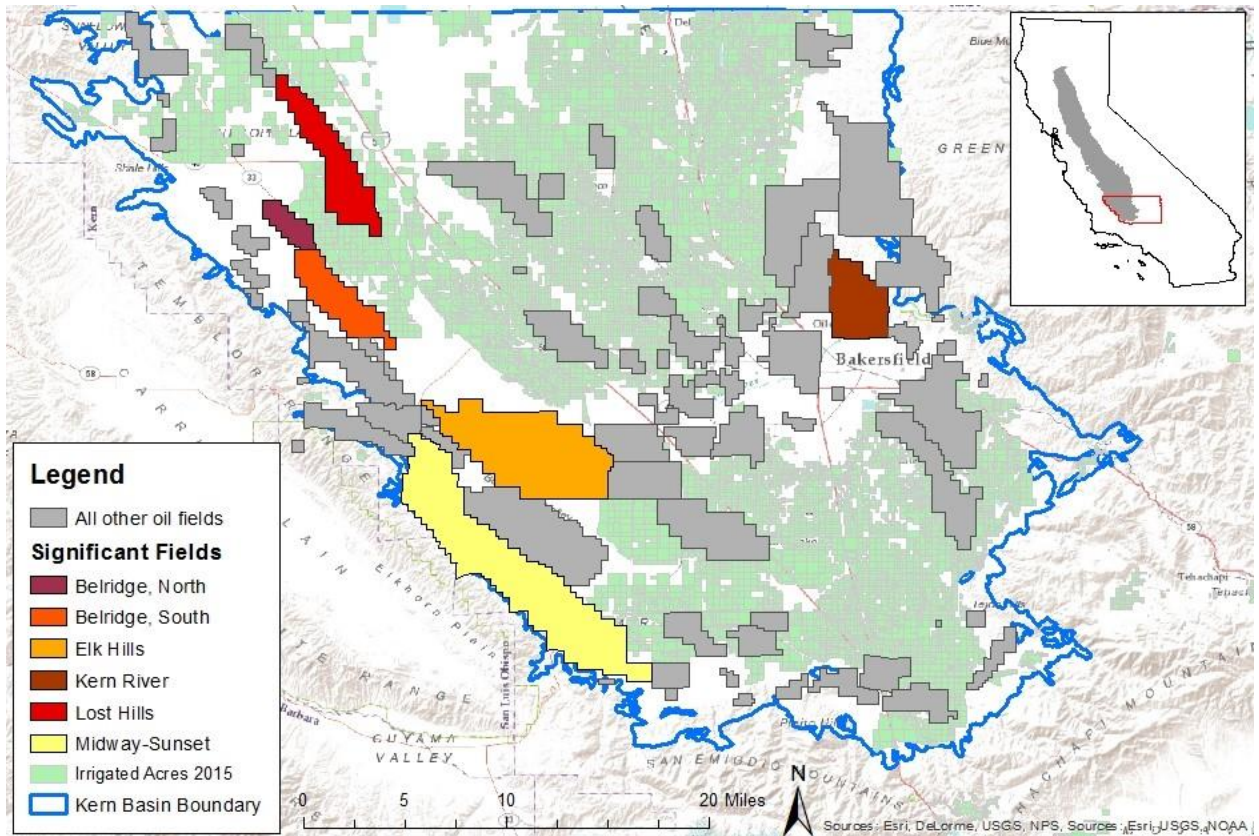


Figure 8. Oil fields in Kern County. Significant fields include the four largest producing: Midway-Sunset, Kern River, Elk Hills and South Belridge. North Belridge, South Belridge, Lost Hills, and Elk Hills account for 85 percent of all hydraulic fracturing in California. Sources: US Census 2014; US Census 2015; DWR 2016a; CDOC 2016a, Kern County Department of Agriculture, 2016; Long et al., 2015c.

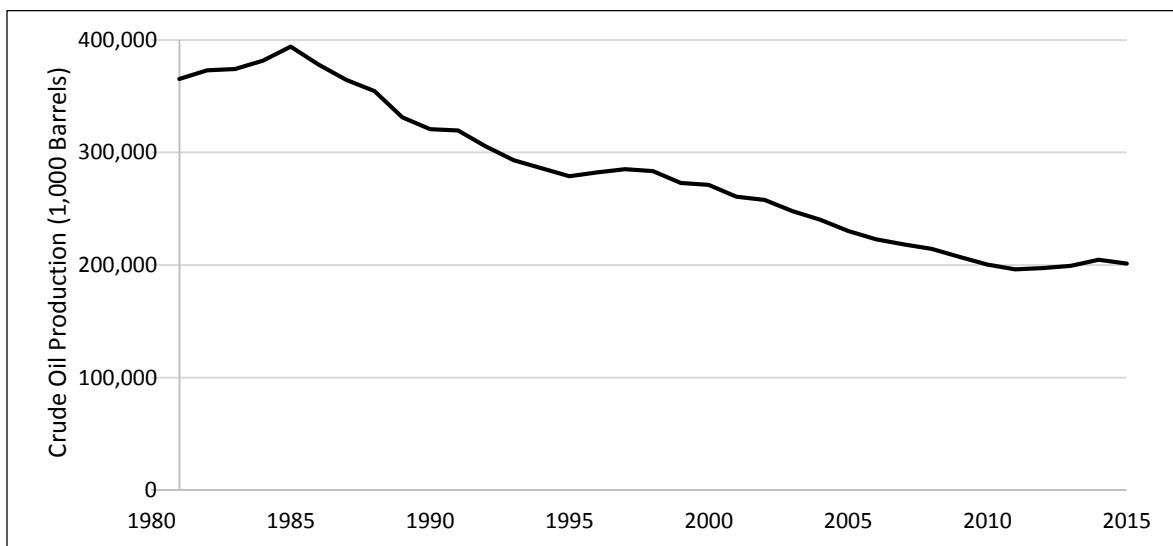


Figure 9. California field production of crude oil 1981-2015. Data Source: US EIA, 2016a.

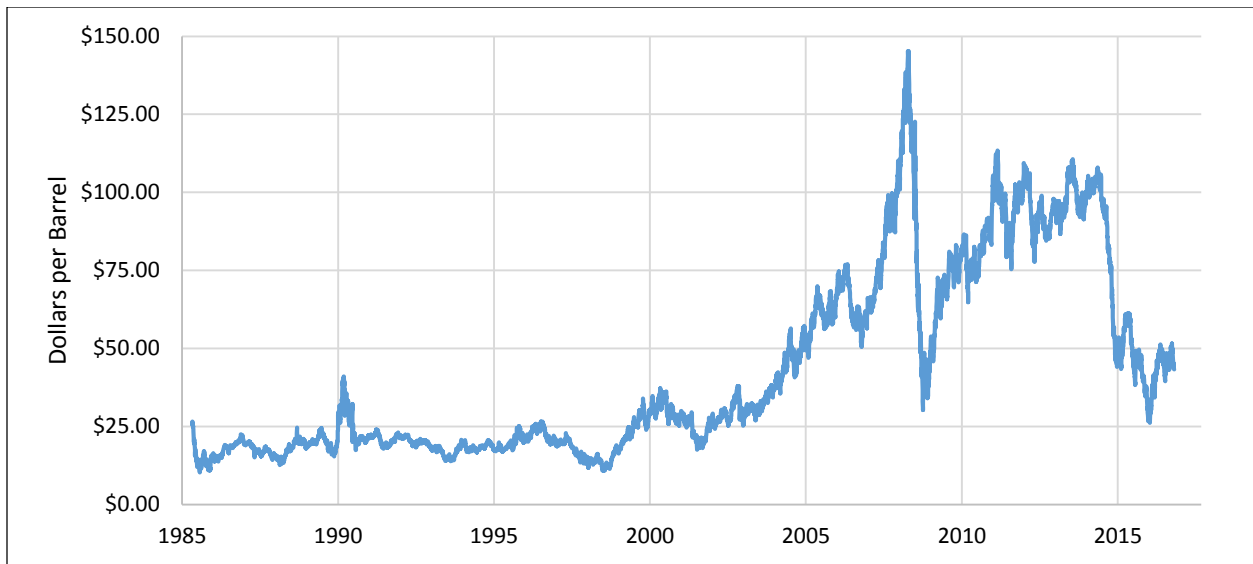


Figure 10. Daily Spot Price for West Texas Intermediate (WTI) Crude Oil. Prices not adjusted for inflation. Data Source: US EIA, 2016b.

Oil production in Kern County and elsewhere is influenced by wild swings in market prices, which affect the cost of production. **Figure 10** shows how the West Texas Intermediate (WTI) benchmark (used to price North American crude oil), changed daily since 1985. The price of oil fell most recently, and dramatically, in 2014.

Hydraulic fracturing (fracking) in California differs from the practice in the rest of the United States in a number of ways. First, fracking in California is conducted almost exclusively for the purpose of oil production, and not to produce natural gas (Long et al., 2015a). Fracking operations in states such as Texas and North Dakota employ high volume hydraulic fracturing (HVHD) techniques like horizontal drilling, in which multiple horizontal bores extend underground for miles in several directions from each oil well. (Gold, 2014; Long et al., 2015a). California’s unique geology has created multiple underground folds that make horizontal drilling impossible in most areas (Long et al., 2015a). California’s oil wells are generally shallower than oil or gas wells in other states, averaging 1,500 feet deep, compared to 6,000-10,000 feet in Texas, for example (Chen and Carter, 2016). **Figure 11** shows the comparison of water use per oil or gas well put into production through fracking. The average water use per well for fracking in California is about 128,000 gallons, compared to more than 7 million gallons per well used in West

Virginia (Chen and Carter, 2016). Water amounts used in oil production are usually recorded in cubic meters or million cubic meters. One gallon is about 1.7 cubic meters.

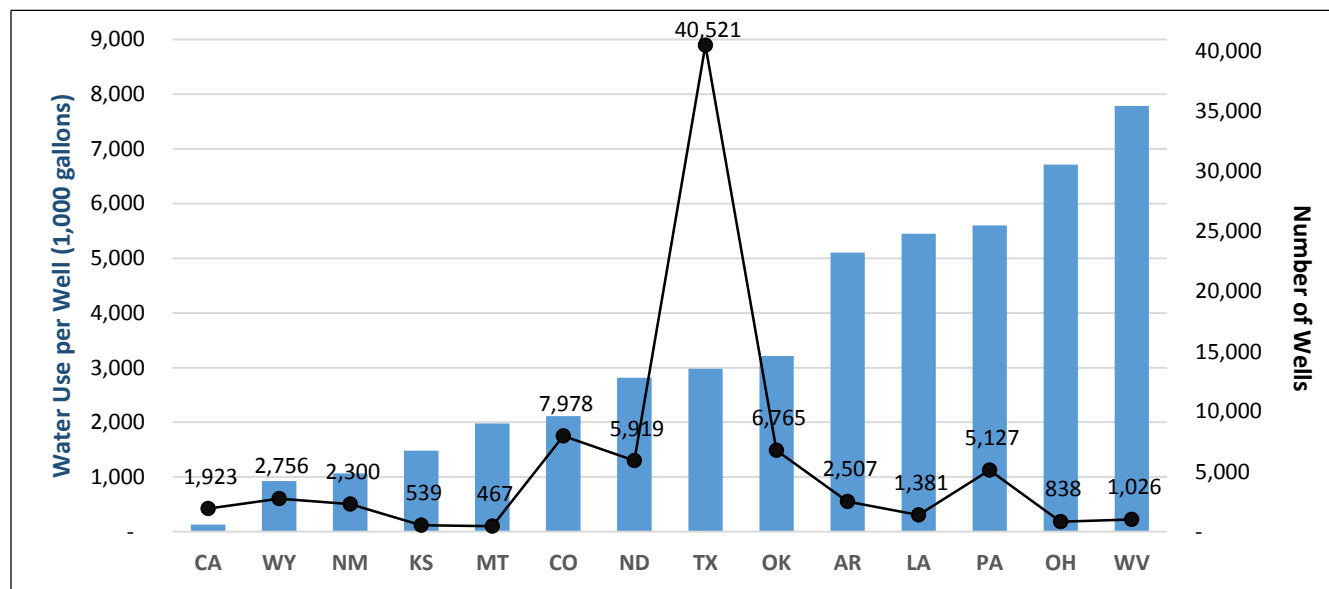


Figure 11. Comparison of water use per well for oil or gas wells put into production through hydraulic fracturing, 2008-2014. Data for some states here, including California, reflects wells fracked from 2011-2014. Data source: Chen and Carter, 2016.

Reporting on water amounts and chemicals used in fracking was not required in California until January 1, 2014, pursuant to the passage of Senate Bill 4, which also required an independent scientific study of hydraulic fracturing in the state (Long et al., 2015a). Voluntary reporting on water use in fracking prior to 2014 has been available since 2011 (FracFocus 2016), an industry sponsored site for national hydraulic fracturing chemical disclosure. A study by Lawrence Berkeley National Laboratories and California Center for Science and Technology estimated the average amount of water used for all three well stimulation types in California to be about 800 AFY, or 1 million cubic meters (Stringfellow, et al., 2015). The authors' estimates, shown in **Table 3**, were based on the average water intensity per stimulation treatment type and average operations per month from January 2011 to June 2014. The range of values reflects the data uncertainty due to voluntary reporting before 2014 (Stringfellow, et al., 2015).

	Number of operations per month	Average Water Intensity per well (m ³ per operation)	Estimated Annual Water Use (m ³)	Estimated Annual Water Use (AF)
Hydraulic fracturing	125-175	530	800,000-1,100,000	640-900
Matrix acidizing	15-25	300	54,000-90,000	44-73
Acid fracturing	0-1	170	0-2,000	0-2
Total			850,000-1,200,000	690-980
			Estimated Annual Average	800

Table 3. Estimated annual average water use for well stimulation treatments for oil production in California. Source: Modified from Stringfellow, et al., 2015.

Reported water use for well stimulation for most of 2014 was significantly lower than this estimate, however. Water sources for 480 well stimulation completion reports submitted between January 1, 2014 and December 10, 2014 are shown below in **Table 4** (Stringfellow, et al., 2015). All but two of these stimulations were for operations in Kern County, which overwhelmingly (83%) used water from the Belridge Water Storage District originally sourced from the State Water Project (Stringfellow, et al.,

Water Source	Number of Operations	Percent of Total Water Volume	Water Volume (AF)
Irrigation district	399	68	95
Produced water	43	13	18
Own well	28	13	18
Municipal water supplier	9	4	6
Private landowner	1	1	2
Total	480	100%	139

Table 4. Water sources reported for well stimulation in California from 1/1/14 to 12/10/14. All but two were for operations in Kern County. Source: modified from Stringfellow, et al., 2015.

2015). The difference between estimated water use and actual usage in 2014 may be due to the third year of a severe drought affecting California at the time, or it may indicate the choices operators made to reduce expenses during an oil price downturn, as will be discussed below. Water amounts are shown in AF from the original report.

Usually a well is only stimulated once by fracking or other stimulation technique. After the initial fracking injection, the next phase of oil production involves flooding the well with water or steam to increase the flow of oil (Long et al., 2015a). This is known as enhanced oil recovery (EOR), and is used to continue to produce oil from the well as long as it is active (Long et al., 2015a). Enhanced oil recovery uses more water annually than fracking, but most of it is sourced from so-called “produced water,” which is the water produced from the well along with oil (Long et al., 2015a). Water amounts for enhanced oil recovery were not available by county; the study by Long and others (2015) analyzed statewide data from the California Department of Conservation, Division of Oil, Gas and Geothermal Resources (DOGGR). The data from DOGGR included reported water sources that were vague, so a category of “possibly freshwater” (**Table 5**) is included along with amounts of fresh water given for EOR (Stringfellow, et al., 2015).

Type of Water	Enhanced Oil Recovery in California (Mm ³)	Enhanced Oil Recovery in California (acre-feet)
Produced water	288	233,486
Salt water	94	76,207
Possibly freshwater	45	36,482
Freshwater	15	12,161
Totals		358,336

Table 5. Enhanced Oil Recovery water amounts for California based on amounts reported in 2013. Source: Modified from Stringfellow et al., 2015. The category “Possibly freshwater” includes amounts reported for water combined with chemicals such as polymers, not reported, and another kind of water.

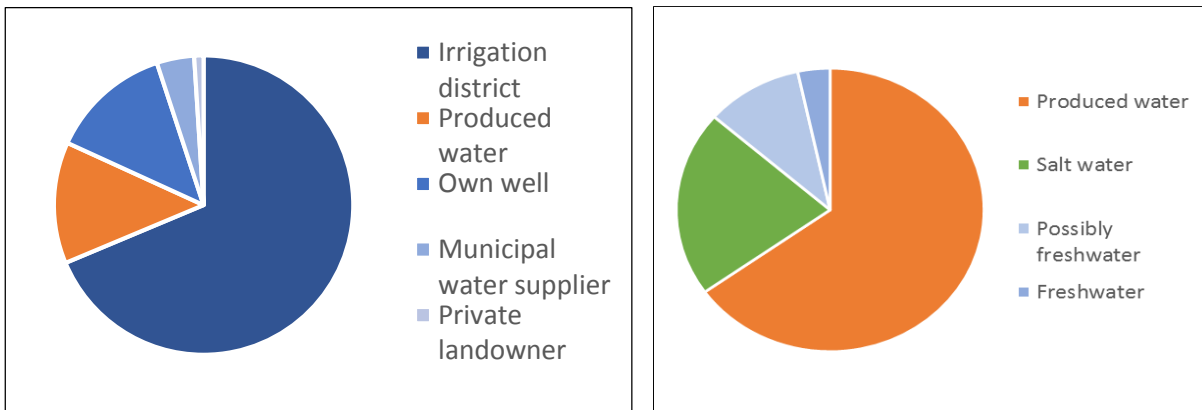


Figure 12. Water sources for fracking and other well stimulation in CA from Jan. 1- Dec. 10, 2014. (Left). Water sources for enhanced oil recovery (EOR) (Right). Data source: Stringfellow et al., 2015.

The majority of water used for enhanced oil recovery (65 percent in 2013, from reported data), and a smaller percentage of water for well stimulation, is produced water (**Figure 12**). After being stimulated, the oil will flow to the surface for several months, and with it flows water. The first water to emerge from the well is called “flowback” and this contains the highest concentrations of chemicals from the fracking solution, as well as elements derived from the oil itself, or elements that may be present in the rocks (Long et al., 2015a). This wastewater must be disposed of, and local methods of disposal include unlined evaporation/percolation pits, or deep injection, both of which pose problems, which will be discussed below (Stringfellow, et al., 2015). As oil continues to flow out of the well, it is mixed with water. The water volume which eventually flows out of a stimulated well is much higher than the amount of water initially injected because water is produced from the rock as well as oil. This water is called “produced water” and generally contains less concentrated amounts of stimulation chemicals than flowback, but may contain other elements, including radioactive elements, present in the source rock (Long et al., 2015a). The ratio of produced water to produced oil can be as high as 13:1 by volume (**Table 6**). The ratio of produced water volume to produced oil volume increases over time as a well ages (Long et al., 2015a). Given that fact, it is interesting to note that the average ratio of water to oil production increased in Kern County in 2015. This might be because fewer wells were brought

into production to replace wells that were retired, which is what the numbers might indicate—the number of active wells dropped in 2015.

Another interesting number in **Table 6** is oil production for 2014, which increased despite the low incidence of well stimulation reported for that year (see **Table 4**). This might indicate that more oil was produced from wells already in production using enhanced oil recovery, and fewer wells were fracked. Fracking is energy intensive, and possibly more energy intensive than EOR. A Stanford study showed that the energy return on energy invested of oil production had declined over time in California because of the increasing use of energy-intensive technologies to extract oil since 1955 (Brandt, 2011). When the price of oil declined in 2014, operators may have chosen to use less energy (less fracking or other stimulation of new wells) but more water (increase EOR of existing wells) and as a cost saving measure to increase production.

Year	Active Wells	Inactive Wells	Oil production (bbl)	Water production (bbl)	Water: Oil	Water Production (AF)
2012	42,875	15,803	141,481,290	1,828,374,391	13	235,665
2013	43,568	15,863	141,585,620	1,789,002,860	13	230,590
2014	44,518	15,908	145,697,818	1,883,838,717	13	242,814
2015	44,284	16,643	144,472,957	1,991,303,876	14	256,666

Table 6. Oil Production statistics for Kern County 2012-2015. Source: California Department of Energy; California Department of Conservation, Division of Oil, Gas, and Geothermal Resources (DOGGR) annual reports.

Water Use in Agriculture

All crops grown in Kern Basin must be irrigated, since groundwater levels are tens to hundreds of feet below the surface in most areas (Faunt, 2009). Even though oil production may use millions of gallons of freshwater each year, irrigation use—over 2 million AF in an average year in Kern County—dwarfs this amount. Fracking uses much less fresh water than agriculture. **Figure 13** demonstrates the relative scale of freshwater use for irrigation, enhanced oil recovery, and well stimulation. Irrigation uses 4 orders of magnitude more fresh water than fracking. The numbers come from the estimate of

800 AF of water used annually for well stimulation in California, and the combination of freshwater and “possible freshwater” for EOR in California rounded to 49,000 AF from **Table 5**, above (Stringfellow et al., 2015). The amount of irrigation is taken from the Kern County Water Agency website, 2,294,000 AF, as an average for irrigation use. Actual amounts of freshwater used annually in Kern County for oil production are likely to be even less.

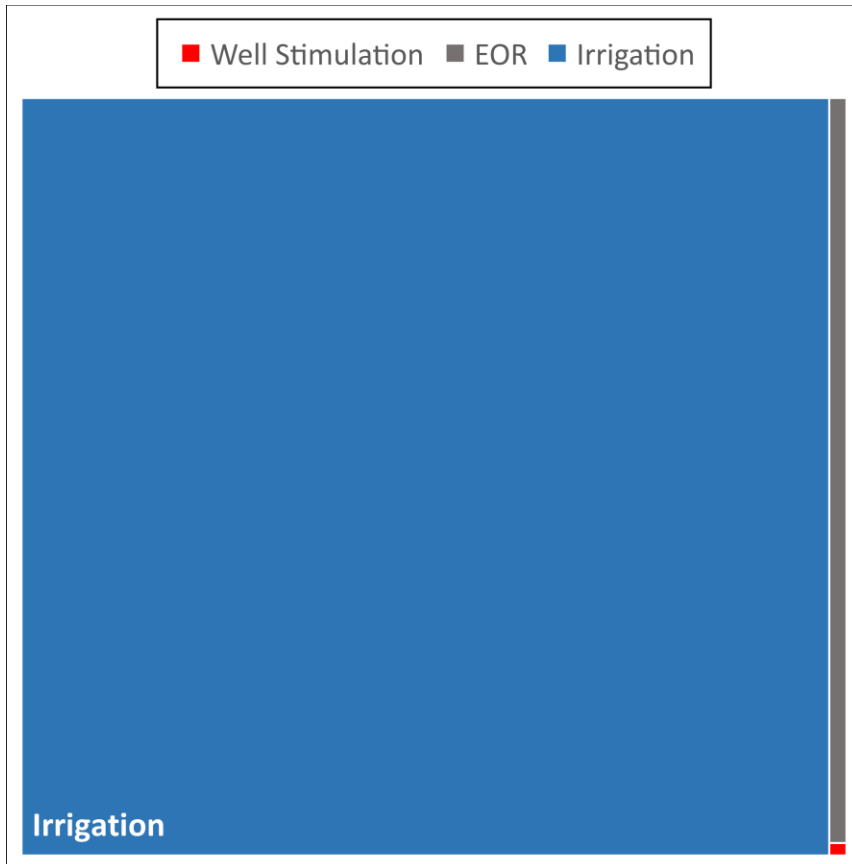


Figure 13. A comparison of water use amounts for irrigation and oil production. Well stimulation and EOR amounts are estimates of annual use in all of California. Irrigation amount is an estimate of annual use in Kern County (Kern Basin). Sources: Stringfellow et al., 2015; Water Association of Kern County, 2016a.

Even though agriculture clearly uses more freshwater than oil production, water consumption in the two sectors differs in important ways. Because oil producers may be able to pay more than irrigators, competition for surface water, especially in dry years, may be a driver of groundwater use

locally (Stringfellow et al., 2015). In any case, agriculture is by far the greater user of fresh water, including groundwater.

Irrigation water for agriculture is sourced from conjunctive use between groundwater and surface water in Kern Basin, as elsewhere in California (Johnson and Cody, 2015). Surface water in Kern Basin, as elsewhere in rural California, is complicated. There are at least 16 water districts in Kern Basin which supply water from the State Water Project (12 member units), the Kern River (7 districts), and the Central Valley Project (5 districts); the numbers add up to more than 16 because several districts obtain water from more than one source (Water Association of Kern County, 2016b). Many of these districts also pump groundwater to supplement, or in dry years possibly to supplant, surface water deliveries (Cawelo Water District, 2014). Groundwater banking is a common practice among water districts; Kern Water Bank is the largest of the water banks, located near the center of Kern Basin. Water districts use water banking to store excess water in wet years for sale to users in dry years (Water Association of Kern County, 2016a). Surface water supplies vary in cost depending on the fees charged by each district, the water year, and the source of the water; water from the State Water Project is generally ten times the cost of water from the federal Central Valley Project (St. Marie and Zafar, CPUC, 2016).

In an average year, groundwater use may supply 30-40 percent of the water for irrigation in Kern Basin (Water Association of Kern County, 2016a), but it's unclear how much is used since none of the wells are metered and most are not even mapped (Long et al., 2015c; DWR 2013). In dry years when surface water deliveries are reduced, groundwater pumping for irrigation increases (Heberger and Donnelly, 2015). This is known mostly through measuring the effects of overdraft—high rates of subsidence in some parts of San Joaquin Valley in the most recent drought, for example—and remotely sensed data showing widespread areas of groundwater depletion (Sneed et al., 2013; Famiglietti et al., 2011).

California is subject to periodic dry periods. In times past, farmers have responded by fallowing acreage to get through times of less water availability, but changes from annual crops to permanent tree plantings is changing this relationship to water (Heberger and Donnelly, 2015). **Figure 14** illustrates the change in crop acreage in Kern Basin since 1958. While fruit and nut trees slowly increased in acreage, cotton dominated the agricultural landscape until as recently as the late 1990's. As cotton acreage plummeted in the 2000's, almond and pistachio acreage soared. Unlike annual crops such as cotton, almonds and other tree crops are a long-term investment: almond trees produce their first crop after five years of irrigation, pistachios produce after seven years (Heberger and Donnelly, 2015). Trees must

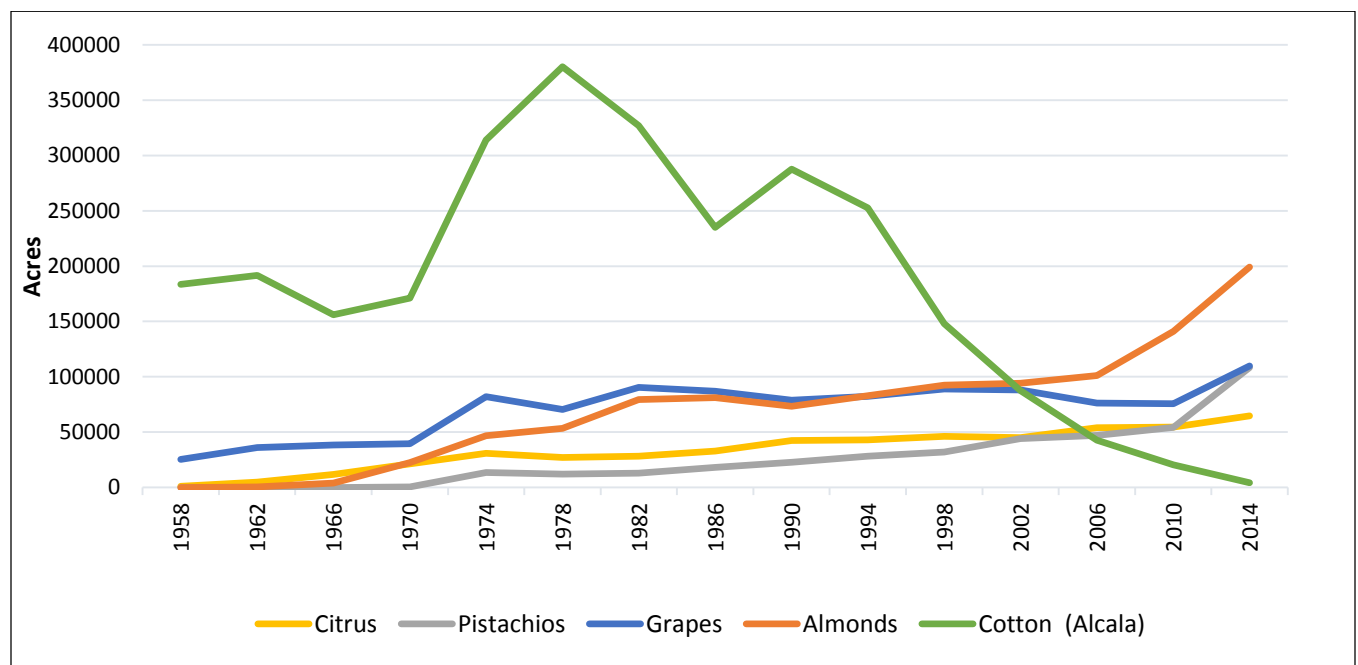


Figure 14. Selected crop acreage change over time in Kern Basin. Source: Kern County Department of Agriculture, Annual Crop Reports, 1958-2014.

be irrigated or they die. Unlike fallowing an annual crop, losing an orchard of nut trees means losing the investment of several years of irrigation. Almonds and other permanent crops are thus said to create a “hardened demand” for water (Heberger and Donnelly, 2015).

To determine where the change in agricultural crop acreage took place in Kern Basin, and whether crops were replaced or whether new acreage came into production, crop acreage in the years

2000 and 2015 were mapped and compared. Over 150 crop types were recategorized into 12 categories, based on economic importance and logical groupings. Uncultivated agriculture was included as a category by itself, in case it showed an increase in fallowed acreage between the two years. **Figure 15** shows the resulting maps that were created. Almond acreage clearly increased in the north and

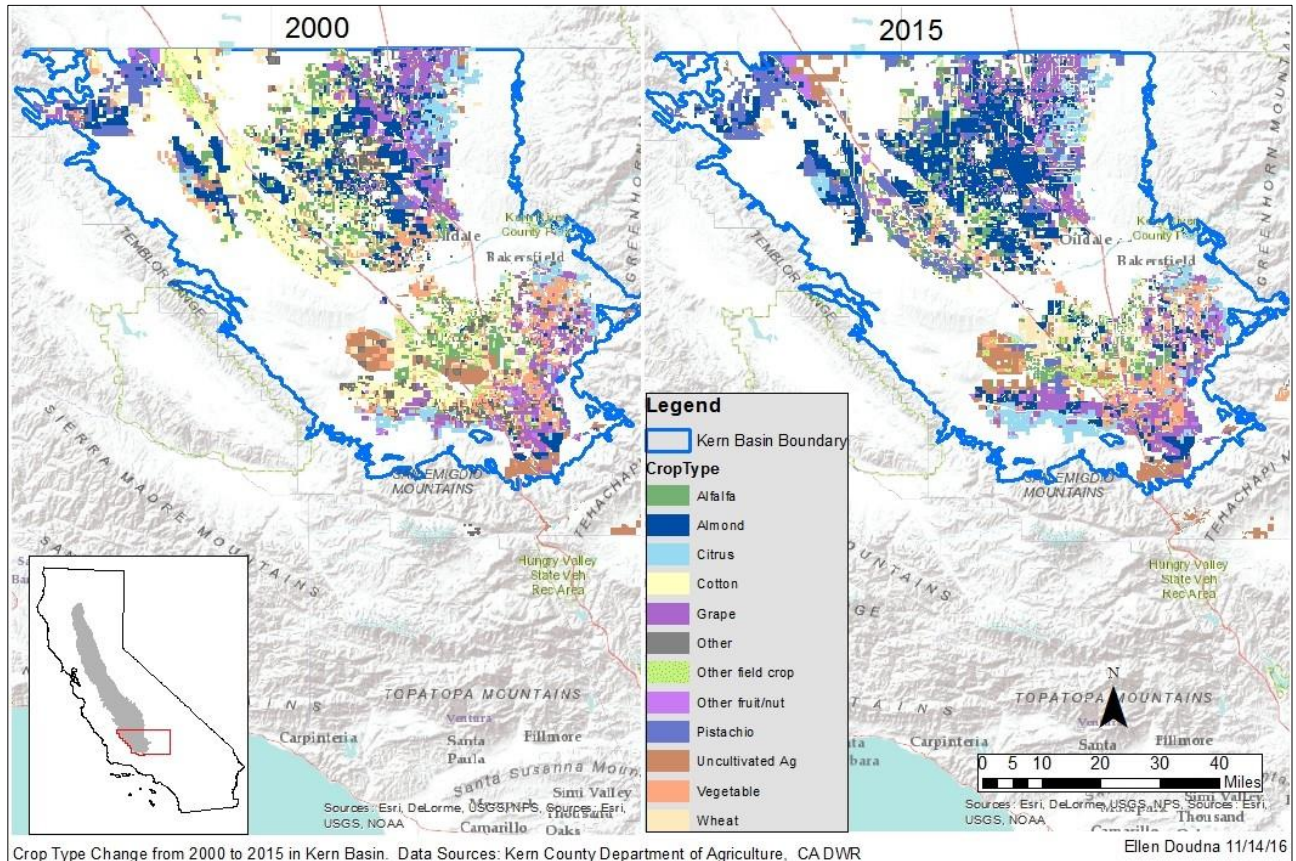


Figure 15. Crop Type Change from 2000 to 2015 in Kern Basin. Data Sources: US Census 2014; US Census 2015; Kern County Dept. of Ag, 2016; DWR 2016a.

central regions of the Kern Basin in 2015, while pistachio and fruit tree acreage increased in the northwest. Acreage devoted to cotton in 2000 appears to be where most of the increase in nut orchards took place by 2015, during the four driest continuous water years in California’s recorded history, 2011-2014 (NOAA, 2016).

Several reasons explain the decline of cotton acreage. Competition from overseas growers brought prices down, persistent pests resistant to pesticides hurt yields, clothing manufacturers

switched to other fibers, and the cost of water increased in the drought as a sharp decline in surface water deliveries increased reliance on expensive groundwater (Tabuchi, 2015). Kern Basin's hot dry climate is well suited for almonds, and there is little competition from growers elsewhere. Lower labor costs and high wholesale prices due to growing demand both domestically and in Asia has made almonds a highly profitable crop (Sumner et al., 2015). Switching from low value to high value crops is considered a better use of precious water by water policy makers and economists (Hanak et al., 2011). However, since the increase in almond acreage may be due in part to the increasing costs of groundwater pumping, almond acreage may be a response to groundwater depletion as well as a driver of future groundwater depletion. Indeed, Mexican farmers are switching to higher value fruit and nut crops in response to higher costs of groundwater pumping (Scott, 2011).

Cawelo Water District is the locus of the third driver of vulnerability considered in this paper, irrigation with produced water. Cawelo Water District is located in the northeast region of Kern Basin; 82 percent of the district is planted in permanent tree crops (Cawelo Water District, 2015). The CWD receives surface water deliveries from the Kern River, and from the State Water Project through Kern County Water Agency (**Figure 16**) (Water Association of Kern County, 2016a).

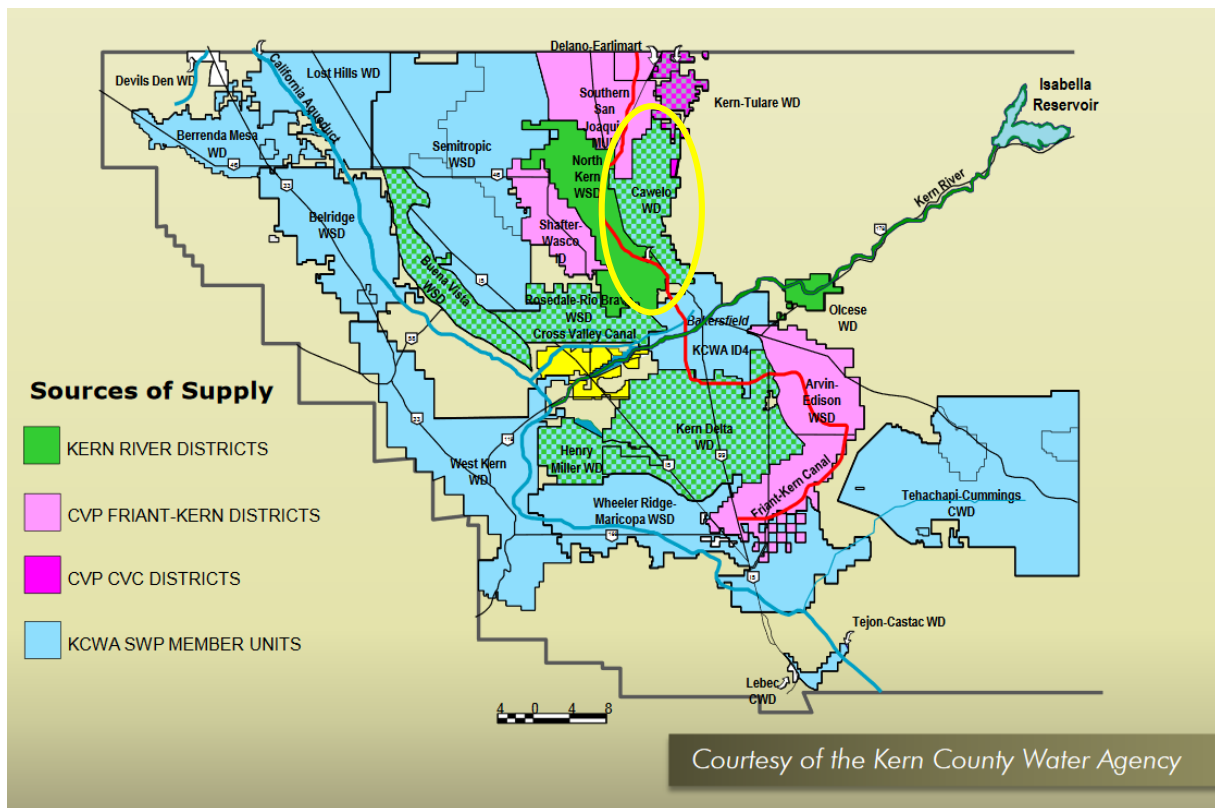


Figure 16. Map of water districts in Kern County, showing surface water sources. Map Source: Water Association of Kern County, 2016b.

Cawelo Water District receives surface water from both Kern River Project and the State Water Project (SWP) (Water Association of Kern County, 2016b). Water deliveries from the SWP ranges in price from \$30-\$60 per AF, in a year of average rainfall (Onishi, 2014). Surface water is delivered according to a system of water rights seniority which dates back to the gold rush; those with junior water rights purchase water through water markets which involve within- or between-basin water transfers (SWRCB, 2016). The spot price for water varies by water year and is higher on average during dry years; in 2013 the median spot price of water in California was \$190 (\$/AF/YR), with a price range of \$50 - \$305 (\$/AF/YR) (West Water Research, LLC, 2014). The Cawelo Water District pumps groundwater to supplement surface water deliveries, and more water is pumped in dry years (Cawelo Water District, 2015).

Year	Total Surface Water (AF)	Total GW (AF)	Total Water Supply (AF)
2008	69,792	10,175	79,967
2009	73,980	1,825	75,805
2010	94,190	1,030	95,220
2011	95,554	109	95,663
2012	72,697	4,865	77,562
2013	59,741	24,500	84,241
2014	51,650	25,294	76,944
2015	38,034	29,870	67,904

Table 7. Water supply sources for Cawelo Water District. Data Source: Cawelo Water District, 2015.

In the years of California’s recent drought, surface water deliveries decreased by over 57,000 AF; in the same time period groundwater pumping increased as a percent of total water supply from less than 1 percent in 2011 to 44 percent in 2015 (**Table 7**) (Cawelo Water District, 2015). Groundwater depth to

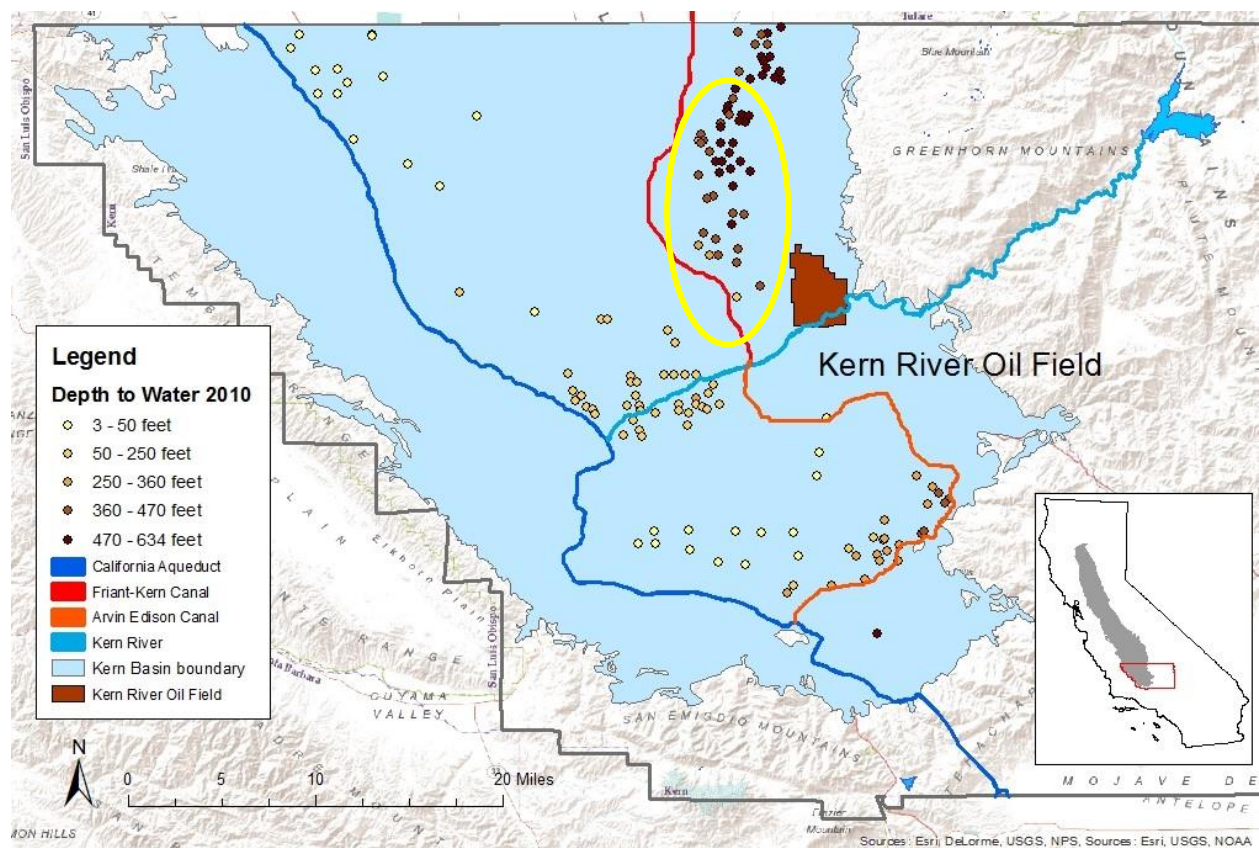


Figure 17. Depth to water in Kern Basin in 2010, and location of Kern River Oil Field. Yellow circle indicates approximate location of Cawelo Water District. Sources: US Census 2014; US Census 2015; DWR 2016a; DWR 2016e; Kern County ESPS 2016; CDOC 2016a.

water in Cawelo Water District can exceed 600 feet, one of the deepest levels in Kern Basin (**Figure 17**) (DWR 2013). Increasing costs to pump groundwater, permanent crops, and relatively expensive, or unavailable, surface water during droughts form a powerful combined incentive for Cawelo Water District to buy oilfield produced water.

Chevron USA, Inc. (Chevron) produces oil from Kern River Oil Field, just east of the Cawelo Water District. Kern River Oil Field produces about 760,000 barrels of water a day, compared with 70,000 barrels of oil (Long et al., 2015c). The Kern River Oil Field injected between 1.89 million and 5.66 million barrels of saline produced water into injection wells in 2013 (Long et al., 2015c), a small fraction of the estimated 186 million barrels of water produced that year. Chevron has had a contract to sell produced water to Cawelo Water District for irrigation since 1996 (Long et al., 2015c; Cawelo Water District, 2015). Chevron sells about 300,000 barrels a day to the Cawelo Water District, for less per unit of water than the State Water Project (Onishi, 2014). Produced water is significant to Cawelo Water District; since 2012 it has comprised more than half of total surface water supplies (Cawelo Water District, 2015) (**Table 7**). Even though the amount of oilfield produced water declined from 2012 to 2015, it increased as a percent of surface water supplies over the same time period. In 2015, oilfield produced water comprised 82 percent of surface water supplies, and nearly half of total water supplies

Year	Oilfield Produced Water (AF)	Percent of Surface Water Supply	Percent of Total Water Supply
2008	28,422	41%	36%
2009	31,700	43%	42%
2010	33,139	35%	35%
2011	27,359	29%	29%
2012	37,107	51%	48%
2013	34,031	57%	40%
2014	32,089	62%	42%
2015	31,010	82%	46%

Table 7. Produced water used in Cawelo Water District irrigation supply. Source: Modified from Cawelo Water District, 2015.

(Cawelo Water District, 2015). Even though produced water has been used as part of the irrigation supply for Cawelo Water District for 20 years, questions remain about the safety of this practice (Long, et al., 2015c;), or how this may impact crops and potentially human health (Heberger and Donnelly, 2015). Irrigation with oilfield produced water is a vulnerability within the WEF Nexus in Kern County, driven by trends in agricultural land use, groundwater pumping, oilfield production, and climate change.

Discussion and Conclusions

The Sustainable Groundwater Management Act is a good first step in bringing California's groundwater under sustainable management. It will improve understanding and modeling of groundwater in California's high- and medium-priority basins, and it will improve understanding of the relationship between surface water and groundwater interactions. In terms of managing the drivers of groundwater vulnerability identified and explored in this study, SGMA may not be the appropriate tool, since it has no jurisdiction over crop choices or the economics of produced water irrigation. SGMA implementation in Kern Basin is likely to be contentious and challenging. As of October (2016) there were eight applications to be GSA for partial or full basin management of Kern Basin (DWR, 2016h). Since SGMA allows a single basin to be managed by several GSAs coordinating either a single GSP or multiple coordinated GSPs, it is likely that Kern Basin will choose one of these options rather than a single GSA managing a single GSP. Each GSA is allowed to choose a different groundwater model to determine basin sustainable yield (DWR, 2016f). This could lead to conflicting models of sustainable yield. It seems likely, and appropriate, that SGMA implementation will be focused at least for the next few years on determining sustainable yield and creating a management plan under coordinated leadership. As SGMA evolves, it will generate much more data on irrigation wells, groundwater levels, spatial data, and other data useful for further studies.

Even though fracking uses much less water than agriculture, it consumes water permanently. Both agriculture and oil production are consumptive uses of water. However, in agriculture, water

consumed through evaporation may return for use again elsewhere as precipitation. Irrigation water may contribute to water supplies elsewhere through runoff, and is a significant source of groundwater recharge in the San Joaquin Valley (Faunt et al., 2009), although both runoff and recharged water are altered by nitrate pollution, which renders the groundwater unfit to drink and can create dead zones in the ocean (Nixon, 1995). Water used in fracking is removed from the water cycle. So far, water deeper than 3,000 feet in the Central Valley has been considered unfit for irrigation or drinking water, but a new study suggests that deep brackish groundwater, treated or desalinated, could become a future source of water for human use (Kang and Jackson, 2016). If so, fracking injections would need to end in order to protect those deep groundwater resources, and that could impact water quality at shallower depths if fracking operators increase pit percolation disposal methods.

Produced water may be usable for irrigation if properly tested and treated, but there are many unknowns. Cawelo Water District's website has been updated since 2015 with a page about produced water and links to studies citing its safety to soil and crops (Cawelo Water District, 2016). If the climate in California sustains longer periods of drought, produced water may become a larger percentage of total irrigation supply, however, and this may pose risks to human and environmental health. Until these risks are better understood, produced water should not be used as an irrigation source (Long et al., 2015c). Since multiple factors contribute to drive the use of produced water for irrigation, and the ratio of water production to oil production increases as oil fields age, strong policies will be necessary to curb its use; already the practice may be spreading beyond Cawelo Water District (Henry, 2016). Groundwater Sustainability Plans could include provisions to protect groundwater from infiltration of surface pollutants, not currently required under SGMA.

The biggest driver of groundwater vulnerability is groundwater pumping, and the sector responsible for the most pumping is agriculture. Therefore, the only way to save the basin from complete depletion is to pump less, which may mean to take acreage out of agricultural production.

This seems unlikely barring dire circumstances, and will disproportionately affect small farmers if done according to market forces. In California, 10 percent of farms received 86 percent of agricultural profits in 2012 (USDA, 2012). Tariffs on energy use to reduce groundwater pumping in Mexico (Scott, 2015) may not be as effective in Kern Basin due to farm income disparity. Drip irrigation might be part of the solution, but it is more energy intensive, and in several instances, has resulted in the increase of agricultural acreage, negating any water savings (St. Marie & Zafar, CPUC, 2016; Smidt et al., 2016; Scott, 2011). Metering and perhaps pricing groundwater could begin to curb groundwater use; SGMA requires better monitoring of groundwater basins, but does not require every well be metered.

Limitations of this study include the fact that many drivers of groundwater vulnerability within the WEF Nexus of Kern Basin were not considered, such as the incidence of shallow well fracking near potential irrigation or drinking water aquifers (discussed at length in Long et al, 2015c), or the pollution of aquifers from agricultural runoff or recharge. Other types of vulnerabilities exist in regards to fracking, including increased air pollution, potential increase of earthquakes, and other effects discussed at length in the independent study by Lawrence Berkeley National Laboratory and California Center for Science and Technology (Long et al., 2015b). The lack of available data to evaluate additional drivers was also an issue. For example, this study was limited by lack of available data on energy sources, groundwater withdrawals, and pricing for groundwater pumping. Each piece of the puzzle of any particular driver within the WEF Nexus could be expanded upon. This study unearths questions to be explored in greater depth in future studies.

Future studies could include a WEF Nexus study on smaller basin with perhaps more unified concern for groundwater management, which might reveal alternate options for solutions. SGMA only applies to high- and medium-priority basins, but many low-priority basins are poorly understood and may be more vulnerable. A pre-emptive WEF Nexus study of groundwater sustainability and vulnerability could be conducted on a low-priority basin to better understand it in advance of potential

overdraft. Economic drivers of groundwater depletion in Kern Basin could be considered in greater detail. A study of water pricing dynamics might reveal additional drivers, and spatial patterns, of groundwater use. A study of social vulnerability in Kern Basin could re-imagine its economy to be both more equitable and less water intensive.

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