THE USE AND MANAGEMENT OF THE OGALLALA AQUIFER FROM 1990-2015

by

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I. Introduction

Groundwater aquifer boundaries, like all common-use natural resources, do not follow political boundaries established by local, state, or federal authorities. The management of groundwater resources vary by the administrative structures that govern the aquifer within the confines of the specific political boundaries in which it is being utilized. Groundwater resources throughout the United States consist of different hydrological characteristics driven by the geology of the region that directly affect aquifer recharge rates, and the boundaries of an aquifer can exist within single a state that spans multiple counties, such as the Edwards Aquifer located in central Texas, or throughout interstate boundaries such as the Ogallala Aquifer.

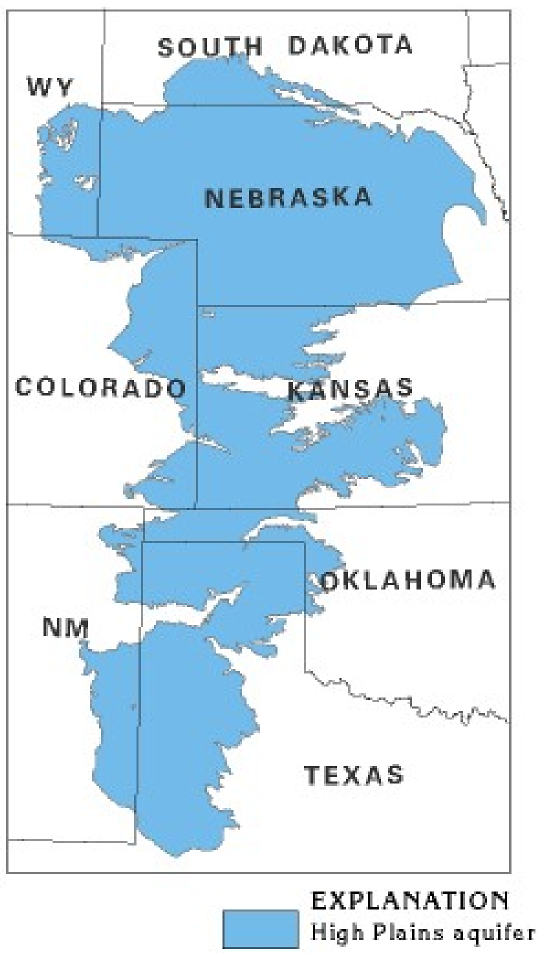

Figure 1. Ogallala Aquifer Boundary (Adapted from U.S. Geological Survey Office of Groundwater 2016)

Groundwater aquifers are used as a resource for different industries such as irrigation for agriculture and livestock operations, municipal water supply, oil and gas mining operations and various other industries throughout the United States. Agriculture within the High Plains region of the U.S., consisting of Wyoming, South Dakota, Colorado, Nebraska, Kansas, Oklahoma, New Mexico, and Texas, account for about 10 percent of the U.S. agriculture market share (Dennehy et al. 2002). Within the High Plains region over 90 percent of the irrigation for agriculture is supplied by the Ogallala Aquifer (Maupin and Barber 2005). Because of intensive agriculture use and irrigation demands, the Ogallala Aquifer has experienced an exponential decline of water resources since the 1950s (Haacker et al. 2016). Since the Ogallala Aquifer spans across multiple state boundaries, each state independently manages the groundwater. The fragmented management of the aquifer creates uneven regulation and use of the common pool resource in which eight states share the use of its groundwater (Figure 1).

The purpose of my research will be to compare and contrast the management and use of the Ogallala Aquifer throughout its extent beneath South Dakota, Wyoming, Colorado, Nebraska, Kansas, Oklahoma, New Mexico and Texas. The objective of this study is to conduct an analysis and evaluate the use of pumping groundwater from the Ogallala Aquifer from 1990 to 2015 and the management of the Ogallala Aquifer at the state level. My research will consist of two topics that characterize the use and management of the Ogallala Aquifer from 1990 to 2015. To analyze the use of the Ogallala Aquifer I will quantify the amount of groundwater level change in the Ogallala Aquifer due to agriculture irrigation throughout the entire aquifer by collecting groundwater pumping and groundwater change data from 1990, when ethanol was mandated to be included into gasoline, to 2015. Secondly, my intent is to compare and contrast the groundwater management governance of the eight states by examining the groundwater laws and management practices as it pertains to the pumping of the Ogallala Aquifer.

To evaluate the use of the Ogallala Aquifer I obtained groundwater data from public sources such as the United States Geological Survey (USGS) and individual state water planning and regulatory agencies. To evaluate the amount of water pumped from the Ogallala Aquifer I will collect data for the volume of groundwater pumped, measured in acre-ft pumped, for each state at the county level from the United States Department of Agriculture, Natural Resources Conservation Service (USDA NRCS) and respective state agencies. To evaluate the water level of the Ogallala Aquifer I utilized public descriptive data of the water table level from federal and state agencies measured by water level of feet below the land surface from 1990 to 2015. Lastly, in each state the precipitation data from 1990 to 2015 for the months of January through August to compare the amount of water pumped and Ogallala Aquifer water levels with the amount of precipitation in each state. Using a single linear regression, I expect to find a proportional relationship between precipitation, the dependent variable, and the amount of groundwater used for irrigation, the independent variable. The amount of groundwater irrigation use will be dependent upon the amount of precipitation for the specified year. I will not focus on the crop type grown throughout the region, only the number of acres irrigated for agriculture production.

To evaluate the management of the Ogallala Aquifer throughout its extent, I will compare and contrast the groundwater management doctrines for each state. A matrix will be developed to illustrate a comparison of laws governing the multistate aquifer. I expect the matrix to exhibit a variety of public vs private use doctrines that result in a fragmented management scheme of the Ogallala Aquifer.

II. Literature Review

Background

The Ogallala Aquifer is one of the largest groundwater resources in North America and was formed from streams flowing to the east and depositing sediment from the Rocky Mountains during the late Tertiary Period (Hornbeck and Keskin 2014). Prior to World War II, agriculture in the high plains was limited by the amount of rainfall available due to the lack of technology to pump large amounts of groundwater for irrigation (Hornbeck and Keskin 2014). After World War II many new irrigation innovations began to revolutionize the agricultural industry in the high plains and eventually agriculture turned into the main source of income for many of the residents who were living and farming there.

Irrigation changed the landscape of the high plains from livestock grazing and wheat production to become primarily an irrigation agricultural economy dependent upon the Ogallala Aquifer. Currently, the Ogallala Aquifer supports agriculture that generates over $35 billion in crops every year (Basso et al. 2013). For descriptive reasons, the Ogallala Aquifer is split into three regions based largely on differences in climate, hydrology, and crops: the northern high plains (NHP), central high plains (CHP) and southern high plains (SHP).

Agriculture

The land over the Ogallala Aquifer encompasses about 174,000 square miles. (Hornbeck and Keskin 2015). The Homestead Act of 1862 was a catalyst for people moving west to establish new settlements throughout the high plains which established the agricultural economy (Gutentag et al. 1984). Irrigation was very limited due to the general inability to drill very deep into the ground. However, new irrigation innovations were created in post-World War II to pump

Ogallala Aquifer water to irrigate agriculture. Throughout the years since the 1950s, many farmers have been forced to integrate new water-efficient crops and irrigation methods with the Ogallala Aquifer, but the main crops grown in the high plains region remain to be relatively water intensive such as corn, sorghum, and cotton. Due to the new ability to irrigate land in the high plains land values within counties that existed over the newly irrigated agriculture from Ogallala Aquifer groundwater increased relative to non-Ogallala irrigated land in the 1960s (Hornbeck and Keskin 2014).

In the 1970s corn accounted for about 2 million acres of irrigated crop land over the Ogallala, but by the mid-1990s corn production increased to account for over 7.5 million acres of irrigated crops (Smidt et al. 2016). There are six major commodities that dominate the landscape and require irrigation: corn, soybeans, winter wheat, alfalfa, cotton, and sorghum (Smidt et al. 2016). Cropland and rangeland is estimated to take up 94 percent of the area over the Ogallala Aquifer. Currently corn is the dominant crop in the northern high plains consisting of over 50 percent of all irrigated agriculture. The dominant crop in the southern high plains is cotton. Both corn and cotton are very water intensive crops (Smidt et al. 2016).

Groundwater Policy

Throughout the Ogallala Aquifer region, there are eight different management structures, one for each state, with four predominant management doctrines governing them. The four doctrines are the Rule of Capture, American Reasonable Use, Correlative Rights, and Prior Appropriation (Baxtresser 2010).

Normally when commerce crosses state lines the federal government has authority to regulate such commerce. Unlike surface water, however, the Interstate Commerce Clause

(Article I, Section 8, Clause 3, US Constitution) doesn't apply to groundwater. If groundwater crossed state boundaries for irrigation, such as the Republican River Compact, groundwater could be governed by the Interstate Commerce Clause. Surface water allocation is governed at the state level and groundwater is either considered private property or public property. For example, in Texas groundwater is property of the landowner, and the Rule of Capture applies, but over time, by applying the states' police powers, the state legislature has established groundwater law through legislation, administration action, and case-made law (Johnson et al. 2009). Originally in Texas, groundwater law was created by common law through a state supreme court decision, common law, then with the addition of the conservation amendment to the Texas Constitution in 1916 placed the responsibility of developing groundwater law to the state legislature through administrative law (Johnson et al. 2009). Though absolute ownership does not create a pumping limit, absolute ownership predominately does not protect against adjacent landowner over-withdrawals potentially causing an injury.

The doctrine of American Reasonable Use was adopted by Oklahoma which constitutes groundwater is appropriated by either the courts or a state/local regulatory agency. To receive a groundwater use permit under American Reasonable Use, the permit must specify how the groundwater will be used "reasonably." What makes the doctrine unique is how its prohibitive of water transfers, also called "off-tract" use (Johnson et al. 2009).

The Prior Appropriation doctrine is a common law doctrine that was originally developed strictly for surface water management but has been adapted by states to be used as groundwater policy. Prior Appropriation used with groundwater can have multiple interpretations for how groundwater is allocated for junior and senior rights in any designated area. The rights to groundwater is defined by obtaining a right to put the water to beneficial use, have a specified point of diversion and are quantified as to amount, can be revoked for non-use of rights, and can be rights can be transferred if other water rights holders are not impacted (Baxtresser 2010). Colorado and Kansas both operate under prior appropriation doctrine, but they have different levels of governmental oversight that monitor and regulate their groundwater law (White and Kromm 1995). Colorado's groundwater law is managed at the state level and Kansas has developed local authorities that have been delegated the responsibility for granting permits to private landowners (White and Kromm 1995).

Finally, the doctrine of Correlative Rights applied to groundwater is similar to oil and gas law in that groundwater is a shared common resource for reasonable share based upon the amount of land owned (Baxtresser 2010. The rights of all landowners over a common aquifer are equal (correlative), and a landowner cannot extract more than the amount of groundwater allotted to them. Unlike American Reasonable Use, Correlative Rights permits off-tract use of groundwater and by setting a limit on the allotment of groundwater to the landowner. The groundwater allotted to the landowner is considered private property to the landowner. However, off-tract use is prohibited unless annual recharge aquifer exceeds the permitted withdrawals (Baxtresser 2010). However, Nebraska is the only state among those that use the Ogallala Aquifer that has adopted a modified version of the doctrine of Correlative Rights and American Reasonable Use where governance is controlled by a local management authority with state oversight to determine groundwater allotment and off-tract use (McGuire 2003).

Corn Ethanol Production

The Clean Air Act in 1990 created a mandate for oxygenates in gasoline to address air quality problems and replace methyl tertiary butyl ether (MTBE) (Hoekman, Broch, and Liu 2017). The Energy Independence and Security Act of 2007 mandates an increase in biofuel production that will cause an increase in corn production to develop corn-based ethanol for biofuels (Huffaker 2010). With the steady increase of biofuel production beginning in the 1990s and mandated to increase by at least 5-fold from 2007 to 2022, growing crops, primarily corn, to produce ethanol will likely continue rise in our agricultural industry. Thus, 1990 serves as an important start date from which change in groundwater pumping can be studied.

III. Methods

For this study I will follow the same boundary/study area as defined by the USDA Ogallala Aquifer Initiative (OAI).

The OAI explains that the Ogallala Aquifer exists within a total of 237 counties throughout the eight states and I will focus on 215 of the counties due to the source of groundwater in the 215 counties comes directly from the Ogallala Aquifer (Gollehon and Windston 2013). Nebraska consists of 78 counties over the Ogallala Aquifer, 51 counties in Kansas, 46 counties in Texas, 13 counties in Colorado, 8 counties in Oklahoma, 6 counties in New Mexico, and 5 counties in Wyoming (Table 1).

Table 1. Counties that are coincident with the Ogallala Aquifer.

Nebraska (78)			Kansas (52)		Texas (46)		Colorado (13)	Oklahoma (8)	South Dakota (7)	New Mexico (6)	Wyoming (5)
Adams	Fillmore	Madison	Barber	Marion	Andrews	Hemphill	Kit Carson	Beaver	Bennett	Curry	Converse
Antelope	Franklin	McPherson	Barton	McPherson	Armstrong	Hockley	Baca	Beckham	Gregory	Harding	Goshen
Aurther	Frontier	Merrick	Cheyenne	Meade	Bailey	Howard	Cheyenne	Cimarron	Jackson	Lea	Laramie
Banner	Furnas	Morill	Clark	Morton	Borden	Hutchinson	Kiowa	Ellis	Mellette	Quay	Niobrara
Blaine	Garden	Nance	Comanche	Ness	Briscoe	Lamb	Las Animas	Harper	Shannon	Roosevelt	Platt
Boone	Garfield	Nuckolls	Decatur	Norton	Carson	Lipscomb	Lincoln	Roger Mills	Todd	Union	
Box Butte	Gosper	Perkins	Edwards	Pawnee	Castro	Lubbock	Logan	Texas	Tripp		
Boyd	Grant	Phelps	Ellis	Phillips	Cochran	Lynn	Phillips	Woodward			
Brown	Greeley	Pierce	Ellsworth	Pratt	Crosby	Martin	Prowers				
Buffalo	Hall	Platt	Finney	Rawlins	Dallam	Midland	Sedgwick				
Burt	Hamilton	Polk	Ford	Reno	Dawson	Moore	Washington				
Butler	Harlan	Red Willow	Gove	Rice	Deaf Smith	Motley	Weld				
Cedar	Hayes	Rock	Graham	Rooks	Dickens	Ochiltree	Yuma				
Chase	Hitchcock	Saline	Grant	Rush	Donley	Oldham					
Cherry	Holt	Scotts Bluff	Gray	Scott	Ector	Parmer					
Cheyenne	Hooker	Seward	Greely	Sedgwick	Floyd	Potter					
Clay	Howard	Sheridan	Hamilton	Seward	Gains	Randall					
Colfax	Jefferson	Sherman	Harper	Sheridan	Garza	Roberts					
Cuming	Kearney	Sioux	Harvey	Sherman	Glasscock	Sherman					
Custer	Keya Paha	Stanton	Haskell	Stafford	Gray	Swisher					
Dawes	Kieth	Thayer	Hodgeman	Stanton	Hale	Terry					
Dawson	Kimball	Thomas	Kearny	Stevens	Hansford	Wheeler					
Deuel	Knox	Valley	Kingman	Thomas	Hartley	Yoakum					
Dodge	Lincoln	Wayne	Kiowa	Trego							
Douglas	Logan	Webste	Lane	Wallace							
Dundy	Loup	Wheeler	Logan	Wichita							
		York									

Within the confines of the 215 counties identified I will extract the water use and management data for comparison and contrast (Figure 2).

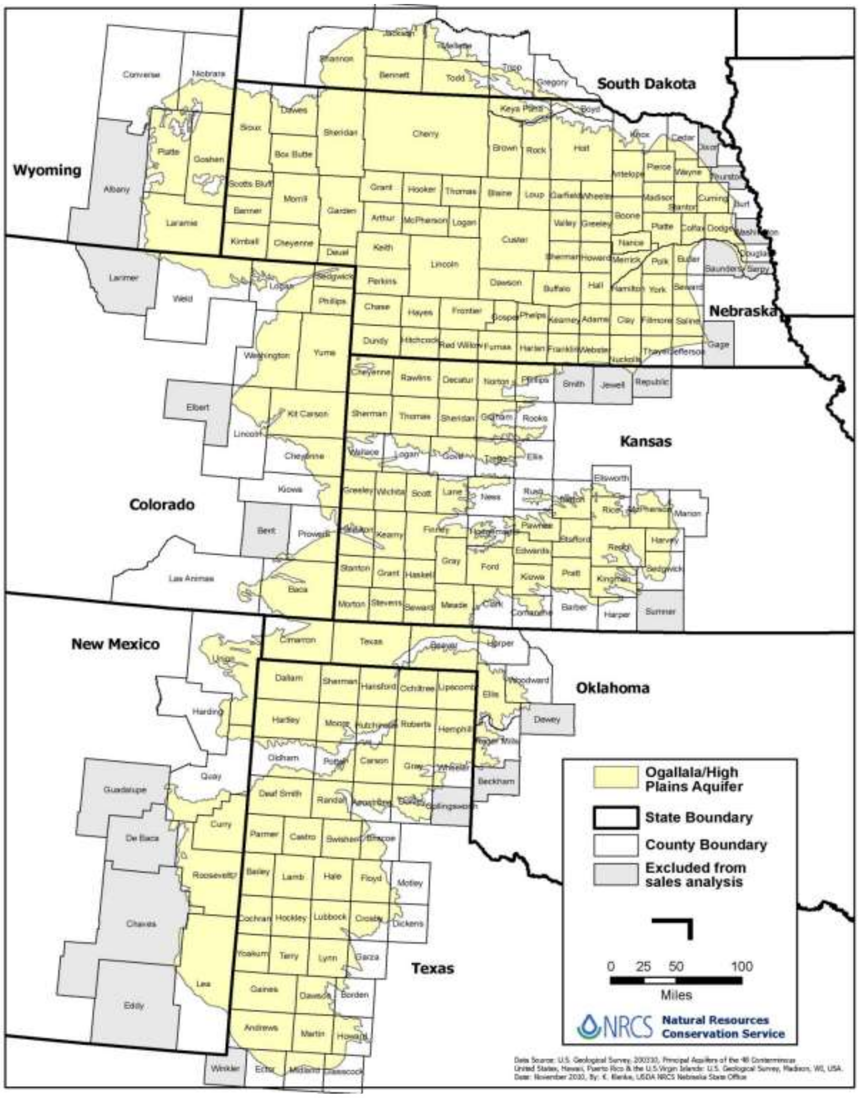

Figure 2. The Ogallala Aquifer showing the counties included in this study (Adapted from Gollehon and Windston 2013)

A. Groundwater Use of the Ogallala Aquifer

To measure the use of groundwater from the Ogallala Aquifer I will access federal databases provided by the USGS and USDA NRCS. Three data points will be gathered to analyze the use of the Ogallala Aquifer:

1) From January 1, 1990 – December 31, 2010: Volume of water, measured in acre-feet, pumped from the Aquifer at the county level from the USGS database at 5-year intervals from 1990 to 2010. Each year presents one year of estimated total water use from USGS.

2) From January 1, 1990 – December 31, 2015: Volume of water, measured in decline of feet from land surface to the top of the water table, at the county level in each state collected from the USGS groundwater database; and

3) Precipitation data summarized by year collected from the National Climatic Data Center-National Oceanic and Atmospheric Administrations (NCDC-NOAA), at eight locations (Table 2), one in each state in a location directly over the Ogallala Aquifer from 1990-2015 consisting of the months January through August.

Table 2. Precipitation monitoring locations

Location	NCDC NOAA I.D.
Arapahoe, CO	GHCND:USC00050304
Alexander, KS	GHCND:USC00140135
Arthur, NE	GHCND:USC00250365
Clovis, NM	GHCND:USC00291963
Beaver, OK	GHCND:USC00340593
Oelrich, SD	GHCND:USC00396212
Amarillo, TX	GHCND:USW00023047
Albin, WY	GHCND:USC00480080

County level data will be collected for only the counties in each state that overly the Ogallala Aquifer using the USDA OAI model (Figure 2 and Table 1). These data will be analyzed and graphed at 5-year intervals from 1990 to 2010.

Annual precipitation data will be collected at five-year intervals of 1990, 1995, 2000, 2005, and 2010 and compared to the corresponding year of inches groundwater irrigated per acre. Inches of irrigation per acre will be determined by using the total amount of estimated irrigated acres per state divided by the total estimated groundwater irrigation. I will use a simple linear regression with precipitation as the dependent variable and estimated irrigation groundwater withdrawals as the independent variable to determine if there is a proportional relationship between the two variables.

B. Groundwater Management of the Ogallala Aquifer

Groundwater management throughout the Ogallala Aquifer region is controlled by the individual states' laws and regulations. I will develop a table comparing the management structure, laws, and policies governing groundwater management in each of the 8 states according to the following factors:

-Doctrine: Rule of Capture, American Reasonable Use, Correlative Rights, Prior Appropriation
-Level of Management: State/Local/Private
-Governing Authority: State/Local/Private
-Funding Source: Taxes/Fees/Both
-Groundwater Metering Requirement: Yes/No; If Yes, Mandated or Self-Reporting
-Inter-Basin Transfer: Y/N
-Well Permit Required: Y/N
-Allocation for Pumping: Y/N

Each category will consist of a description and extrapolated information when further explanation of the management authority is required. The key objective to the groundwater management table is to provide descriptive information to explain how groundwater laws and policies govern the use of the groundwater within each state. My intent is to provide an explanatory description of how each state currently operates.

IV. Method of Analysis

I will use descriptive statistics to measure the annual mean and median to evaluate the trend from 1990 to 2015 of the change of the aquifer level. The data of the aquifer change will be analyzed by the change in depth from 1990 to 2015 to characterize the change of the Ogallala Aquifer in each state. I will conduct a simple linear regression analysis on the relationship between precipitation (independent variable) and irrigation water used (dependent variable) to determine the extent to which variability in the latter can be explained by the former between 1990 and 2010 at five-year intervals.

Beginning in 1990, key milestones of legislation were implemented requiring increased ethanol blending with gasoline and in 2007, the Energy and Securities Act required greater amounts of ethanol production. I will explore for change in water demand due to Ogallala Aquifer dependent agriculture and identify any trends for all three factors should any emerge.

The number of estimated acres of irrigated land from the USGS database will be used to determine whether agriculture has increased in the region of each state over the Ogallala Aquifer derived from the county level from 1990 to 2010.

The groundwater management table will feature key elements of the states' management structures and ideally provide insight to how each state manages the Ogallala Aquifer within their political jurisdiction. Understanding the management structures within and across the eight states will help with understanding the fragmentation or cohesiveness of groundwater management across this important aquifer.

V. Discussion and Results

A. Groundwater Use of the Ogallala Aquifer

Groundwater use from the Ogallala Aquifer is presented in alphabetical order of the states, and presents the quantitative data of groundwater use, acres irrigated, and precipitation.

I. Colorado

Colorado's groundwater usage for irrigation in the study area had an overall decrease in volume of 50 percent and a decrease in overall total groundwater usage of 49 percent from 1990 to 2010. Colorado had a decrease in acres irrigated of 2 percent (Table 3).

Table 3. Change in Water Use and Total Acres Irrigated: 1990-2010

Colorado - Water Use Change 1990-2010	Acre-Ft Change (1990-2010)	% Change
Groundwater Irrigation Use	-791400	-50%
Surface Water Irrigation Use	-785400	-48%
Total Groundwater	-806200	-49%
Total Surface Water	-78200	-47%
Total Water (GW+SW)	-1587400	-48%
Acres Irrigated: Total Acre Change 1990 to 2010	-34490	-2%

Table 4. Proportion of Water Usage from 1990-2010

Colorado - Proportion of Water Usage						
	1990	**1995**	**2000**	**2005**	**2010**	**1990-2010**
% GW Irrigation Usage from GW Total	96%	95%	98%	97%	94%	**-2%**
% SW Irrigation Usage from SW Total	97%	98%	97%	98%	94%	**-3%**
% GW Irrigation Usage from Total Water Usage	48%	39%	41%	44%	46%	**-2%**
% SW Irrigation Usage from Total Water Usage	49%	57%	56%	53%	48%	**-1%**

Irrigation accounted for over 90 percent of total groundwater use in Colorado with a two percent reduction from 1990 to 2010 (Table 4).

Table 5. Precipitation and Groundwater Irrigation Use/Acre

Colorado				
Year	**Precipitation (in)**	**GW Irrigation Use (Acre-Ft)**	**Acres Irrigated**	**GW Irrigation Use/Acre (in)**
1990	14.52	1579900	1387980	13.66
1995	15.35	1385000	1311280	12.67
2000	10.87	1358000	1360480	11.98
2005	14.36	1394100	1082120	15.46
2010	15.38	788500	1353490	6.99
Mean	13.99	1301100	1299070	12.15
Driest Year	2000 (10.87)			
Wettest Year	2010 (15.38)			

From 1990 to 2015 the Ogallala Aquifer had a median aquifer level decline of 13.6 feet, Logan County had an increase of 12 feet, and maximum decline in Cheyenne County of 64 feet. Colorado had a mean precipitation of 13.99 inches with a minimum average of 10.87 inches of precipitation in 2000 and maximum average of 15.38 inches of precipitation in 2010. The trend of irrigated inches per acre decreased from 1990 to 2010. Using a simple linear regression where the amount of precipitation is used to predict the volume of groundwater used for irrigation, an

r^2 value of seven percent is obtained. This coefficient of determination, however, is not statistically significant with a p-value of 0.23 tested at 0.05 significance (Table 5 and Figure 4).

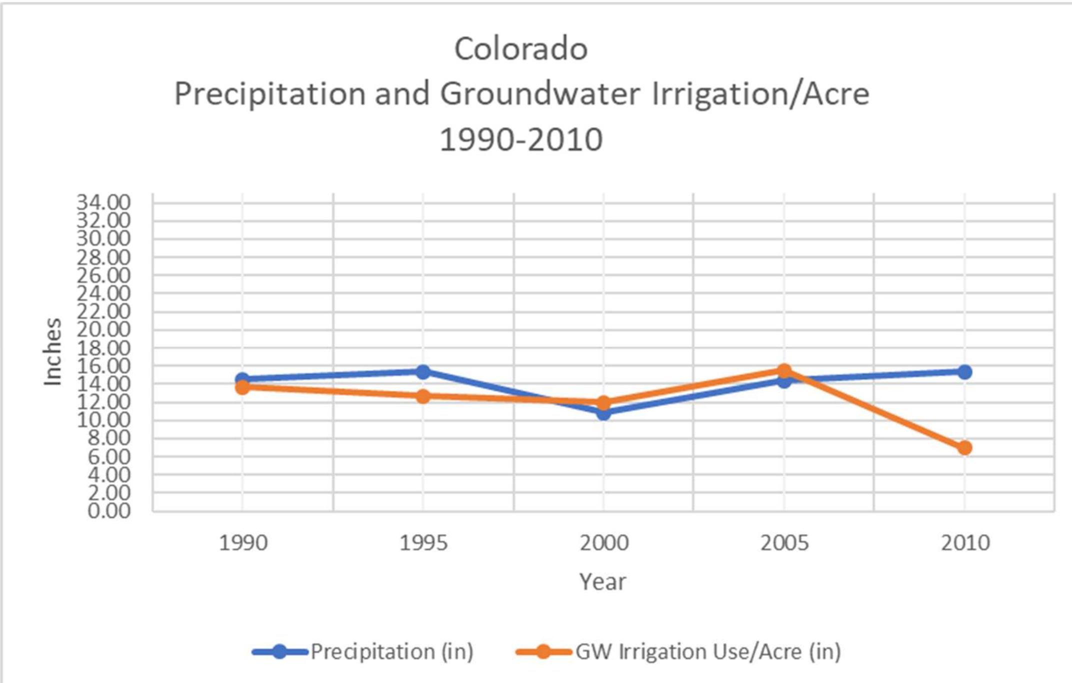

Figure 3. Precipitation and Groundwater Irrigation/Acre (inches) 1990-2010

The overall trend of groundwater use per acre irrigated from 1990 to 2015 is downward (Figure 3).

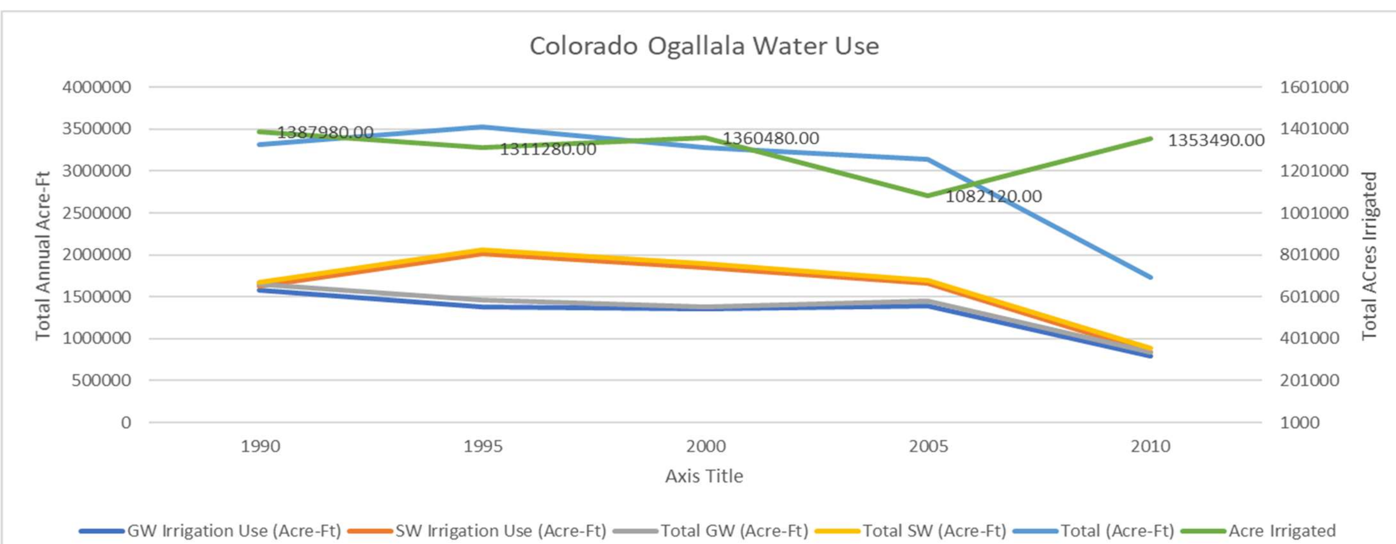

Figure 4 Colorado Ogallala Aquifer Use and Acres Irrigated 1990-2010

II. Kansas

Kansas's groundwater usage for irrigation in the study area had an overall decrease in volume of 28 percent and a decrease in overall total groundwater usage of 27 percent from 1990 to 2010. Kansas had a decrease in acres irrigated of 3 percent (Table 6).

Table 6.Change in Water Use and Total Acres Irrigated: 1990-2010

Kansas - Water Use Change 1990-2010	Acre-Ft Change (1990-2010)	% Change
Groundwater Irrigation Use	-1209700	-28%
Surface Water Irrigation Use	9500	12%
Total Groundwater	-1239700	-27%
Total Surface Water	24600	22%
Total Water (GW+SW)	-1215100	-25%
Acres Irrigated: Total Acre Change 1990 to 2010	-93860	-3%

The amount of groundwater irrigation usage from the total amount of groundwater used remained relatively the same throughout the study period and decreased only by 1 percent from 1990 to 2010 (Table 7).

Table 7. Proportion of Water Usage from 1990-2010

Kansas - Proportion of Water Usage						
	1990	**1995**	**2000**	**2005**	**2010**	**1990-2010**
% GW Irrigation Usage from GW Total	94%	93%	93%	92%	93%	**-1%**
% SW Irrigation Usage from SW Total	70%	80%	80%	59%	64%	**-6%**
% GW Irrigation Usage from Total Water Usage	92%	88%	88%	89%	89%	**-3%**
% SW Irrigation Usage from Total Water Usage	2%	4%	4%	2%	2%	**1%**

From 1990 to 2015 the Ogallala Aquifer had a median drawdown of 8 feet, Hamilton County had an increase of aquifer level of 6 feet, and maximum drawdown in Grant County of 101 feet.

Kansas had a mean precipitation of 19.42 inches with a minimum of 14.72 inches of precipitation in 2010 and maximum average of 21.98 inches of precipitation in 1990. The trend of irrigated inches per acre decreased from 1990 to 2010. Using a simple linear regression where the amount of precipitation is used to predict the volume of groundwater used for irrigation, an r^2 value of 11 percent is obtained. This coefficient of determination, however, is not statistically significant with a p-value of 0.37 tested at 0.05 significance (Table 8 and Figure 6).

Table 8. Precipitation and Groundwater Irrigation Use/Acre (inches) 1990-2010

Kansas				
Year	**Precipitation (in)**	**GW Irrigation Use (Acre-Ft)**	**Acres Irrigated**	**GW Irrigation Use/Acre (in)**
1990	21.98	4367600	2906060	18.04
1995	20.19	3443300	2867920	14.41
2000	19.22	3714700	3051540	14.61
2005	21.68	2843100	2873710	11.87
2010	14.72	3157900	2812200	13.48
Mean	19.56	3505320	2902286	14.48
Driest Year	2010 (14.72)			
Wettest Year	1990 (21.98)			

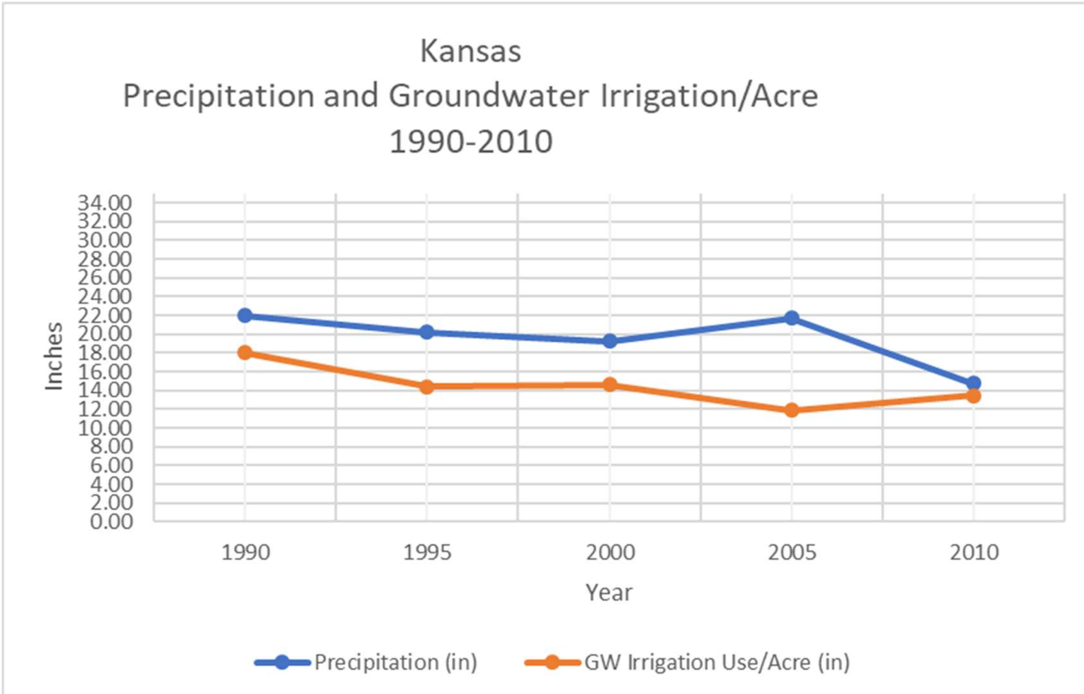

Figure 5. Precipitation and groundwater Irrigation/Acre (inches) 1990-2010

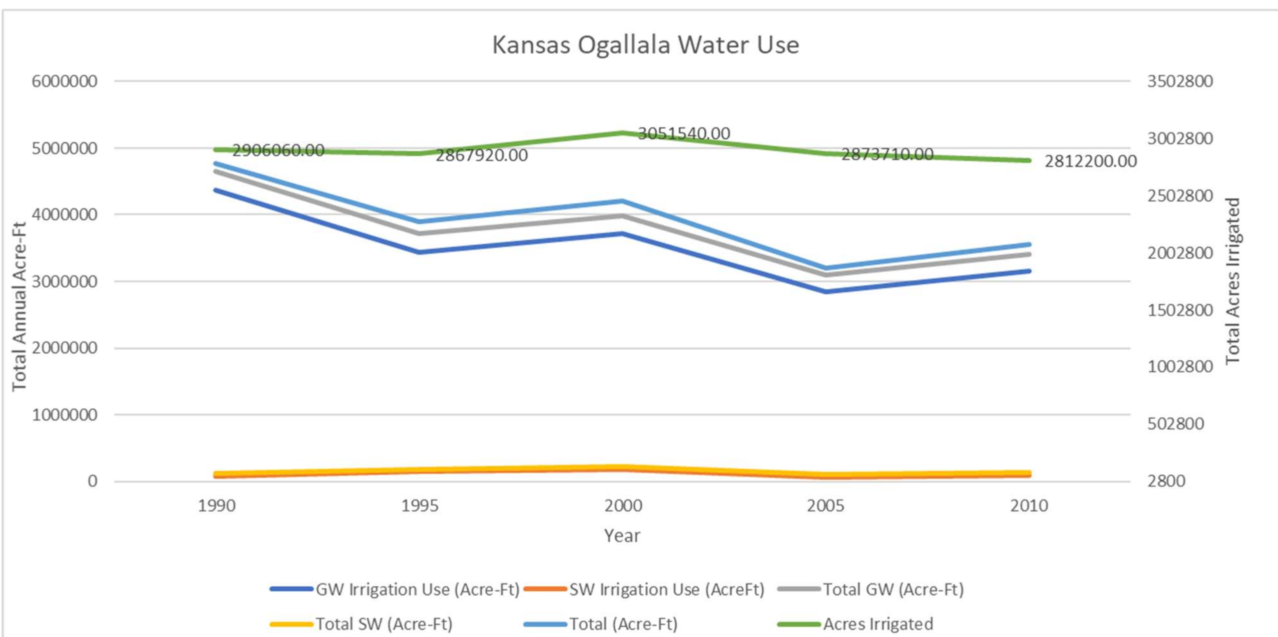

Figure 6. Kansas Ogallala Aquifer Use and Acres Irrigated 1990-2010

Throughout 1990 to 2015 the trend of groundwater usage and acres irrigated decreased (Figure 5).

III. Nebraska

Nebraska's groundwater usage for irrigation in the study area had an overall decrease in volume of 2 percent and a decrease in overall total groundwater usage of 2 percent from 1990 to 2010. Nebraska had an increase in acres irrigated of 26 percent (Table 9).

Table 9. Change in Water Use and Total Acres Irrigated: 1990-2010

Nebraska - Water Use Change 1990-2010	Acre-Ft Change (1990-2010)	% Change
Groundwater Irrigation Use	-80800	-2%
Surface Water Irrigation Use	-409500	-21%
Total Groundwater	-92000	-2%
Total Surface Water	-1073700	-34%
Total Water (GW+SW)	-1165600	-14%
Acres Irrigated: Total Acre Change 1990 to 2010	1743390	26%

The amount of groundwater irrigation usage from the total amount of water used increased by 8 percent (Table 10). Groundwater became the predominant water sourced used in for irrigation in Nebraska.

Table 10. Proportion of Water Usage from 1990-2010

Nebraska - Proportion of Water Usage						
	1990	**1995**	**2000**	**2005**	**2010**	**1990-2010**
% GW Irrigation Usage from GW Total	94%	95%	96%	96%	94%	**0%**
% SW Irrigation Usage from SW Total	62%	60%	51%	42%	74%	**12%**
% GW Irrigation Usage from Total Water Usage	58%	64%	71%	71%	66%	**8%**
% SW Irrigation Usage from Total Water Usage	24%	20%	13%	11%	22%	**-2%**

From 1990 to 2015 the Ogallala Aquifer had a median drawdown of .022 feet, Valley County had an increase of aquifer level of 22 feet, and maximum drawdown in Banner County of 51 feet.

Nebraska had a mean precipitation of 16.86 inches with a minimum average of 9.44 inches of precipitation in 2000 and maximum average of 22.57 inches of precipitation in 2010. The trend of irrigated inches per acre decreased from 1990 to 2010. Using a simple linear regression analysis, the amount of precipitation accounts for about half of the variation of the amount of groundwater used for irrigation with an r^2 value of 48 percent. The value is also statistically significant with a p-value of 0.02 tested at 0.05 significance (Table 11 and Figure 7).

Table 11. Precipitation and Groundwater Irrigation Use/Acre 1990-2010

Nebraska				
Year	**Precipitation (in)**	**GW Irrigation Use (Acre-Ft)**	**Acres Irrigated**	**GW Irrigation Use/Acre (in)**
1990	17.20	4762600	6613300	8.64
1995	17.30	6266600	7185650	10.47
2000	9.44	8049500	7533010	12.82
2005	17.80	7921700	8029490	11.84
2010	22.57	4681800	8356690	6.72
Mean	16.86	6336440	7543628	10.10
Driest Year	2000 (9.44)			
Wettest Year	2010 (22.57)			

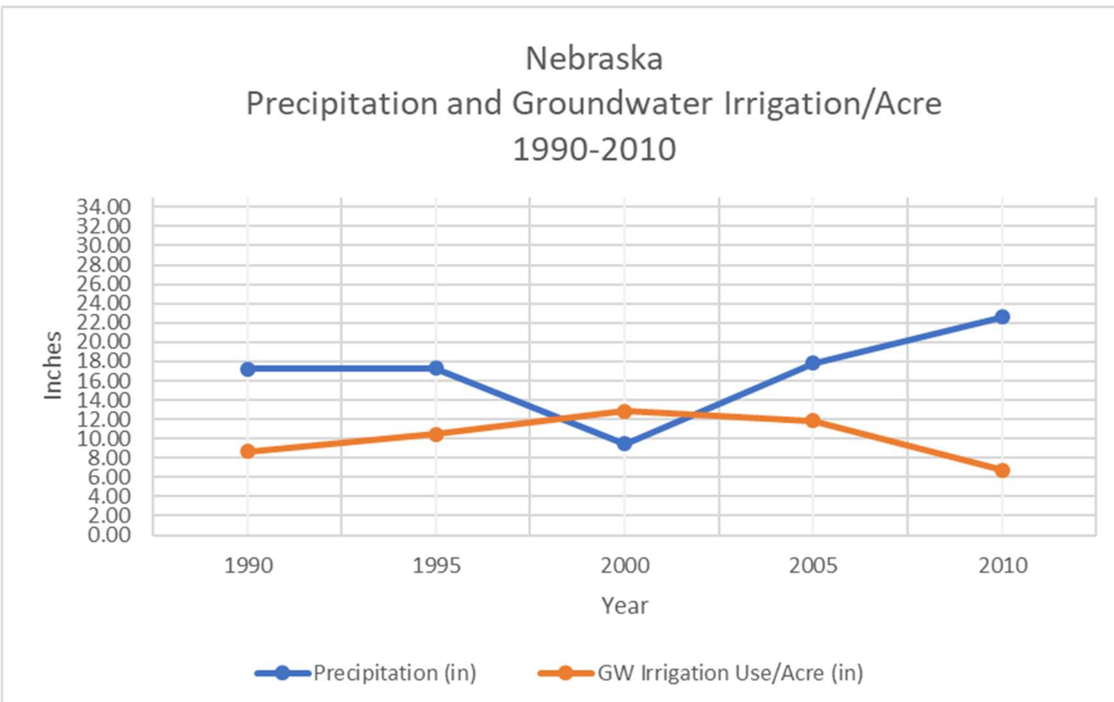

Figure 7. Precipitation and Groundwater Irrigation/Acre (inches) 1990-2010

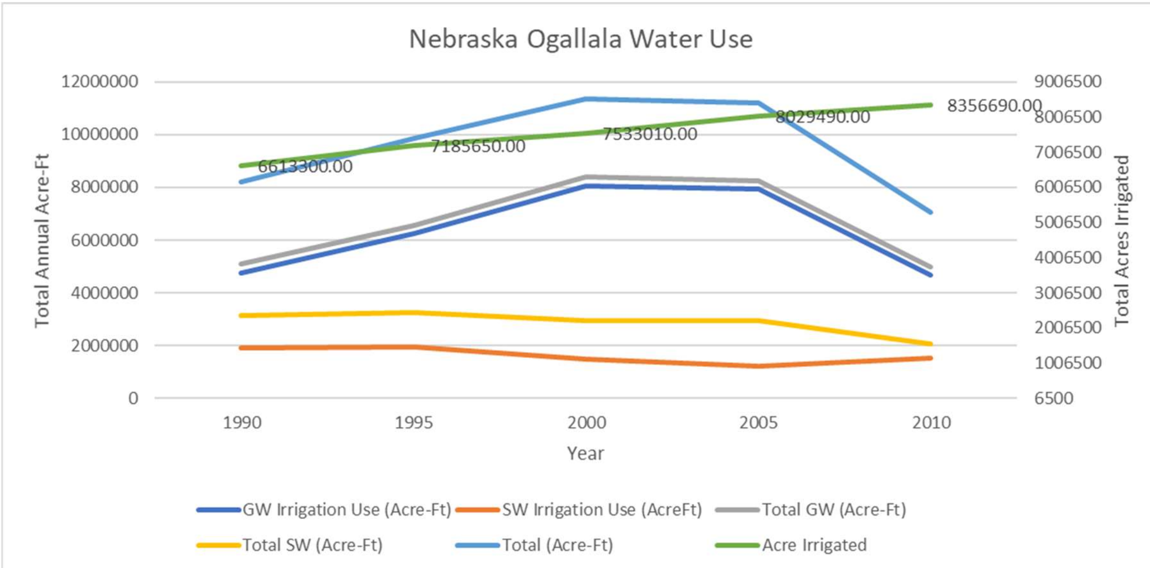

Figure 8. Nebraska Ogallala Aquifer Use and Acres Irrigated 1990-2010

Throughout 1990 to 2015 the trend of acres irrigated increased and the trend of groundwater used for irrigation decreased (Figure 8).

IV. New Mexico

New Mexico's groundwater usage for irrigation in the study area had an overall decrease in volume of 18 percent and a decrease in overall total groundwater usage of 18 percent from 1990 to 2010. New Mexico had a decrease in acres irrigated of 14 percent (Table 12).

Table 12. Change in Water Use and Total Acres Irrigated: 1990-2010

New Mexico - Water Use Change 1990-2010	Acre-Ft Change (1990-2010)	% Change
Groundwater Irrigation Use	-136200	-18%
Surface Water Irrigation Use	-47400	-56%
Total Groundwater	-148900	-18%
Total Surface Water	-47400	-55%
Total Water (GW+SW)	-196300	-22%
Acres Irrigated: Total Acre Change 1990 to 2010	52040	-14%

Groundwater irrigation usage from the total amount of water use in New Mexico increased by 4 percent and surface water usage for irrigation decreased from 1990 to 2010 (Table 13).

Table 13. Proportion of Water Usage

New Mexico - Proportion of Water Usage						
	1990	1995	2000	2005	2010	1990-2010
% GW Irrigation Usage from GW Total	92%	90%	93%	86%	92%	0%
% SW Irrigation Usage from SW Total	99%	99%	100%	98%	98%	-1%
% GW Irrigation Usage from Total Water Usage	83%	77%	78%	81%	87%	4%
% SW Irrigation Usage from Total Water Usage	10%	15%	16%	6%	5%	-4%

From 1990 to 2015 the Ogallala Aquifer had a median drawdown of 10 feet, Quay County had an increase of aquifer level of 2 feet, and maximum drawdown in Union County of 41 feet.

New Mexico had a mean precipitation of 13.17 inches with a minimum of 7.95 inches of precipitation in 1990 and maximum of 20.92 inches of precipitation in 2010. The trend of irrigated inches per acre decreased from 1990 to 2010. Using a simple linear regression analysis, the amount of precipitation can account for about a quarter of the variation of the amount of groundwater used for irrigation with an r^2 value of 27 percent. The value is also statistically significant with a p-value of 0.008 tested at 0.05 significance (Table 14 and Figure 9)

Table 14. Precipitation and Groundwater Irrigation Use/Acre 1990-2010

New Mexico				
Year	**Precipitation (in)**	**GW Irrigation Use (Acre-Ft)**	**Acres Irrigated**	**GW Irrigation Use/Acre (in)**
1990	7.95	742000	369230	24.12
1995	9.08	641000	374440	20.54
2000	14.53	561900	386710	17.44
2005	13.37	513600	293700	20.98
2010	20.92	605900	317190	22.92
Mean	13.17	612880	348254	21.20
Driest Year	1990 (7.95)			
Wettest Year	2010 (20.92)			

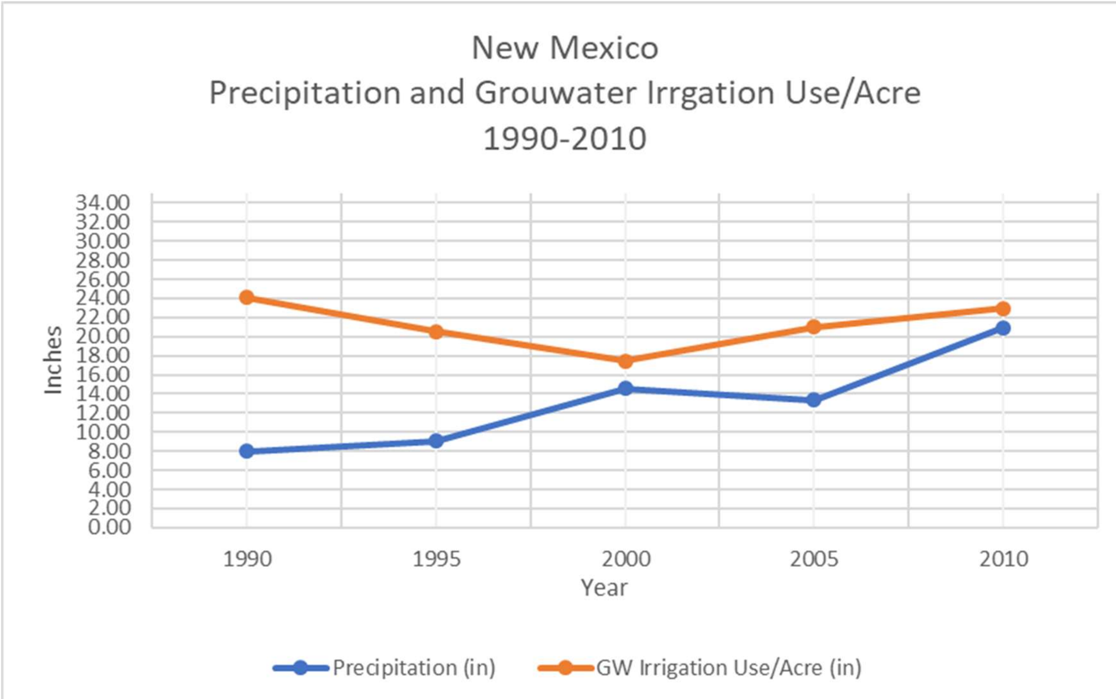

Figure 9. Precipitation and Groundwater Irrigation/Acre (inches) 1990-2010

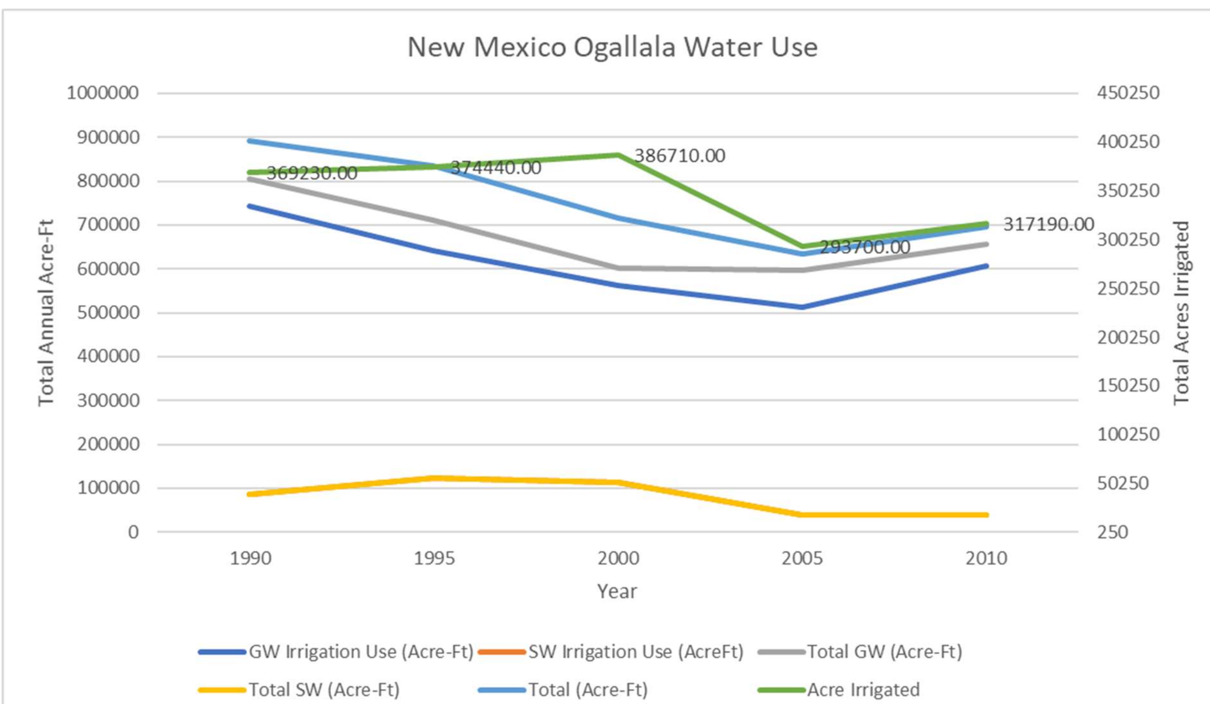

Figure 10. New Mexico Ogallala Aquifer Use and Acres Irrigated 1990-2010

Throughout 1990 to 2015 the trend of acres irrigated and groundwater use for irrigation decreased (Figure 10).

V. Oklahoma

Oklahoma's groundwater usage for irrigation in the study area had an overall decrease in volume of 17 percent and an in overall total groundwater usage of 9 percent from 1990 to 2010. Oklahoma had an increase in acres irrigated of 12 percent (Table 15).

Table 15. Change in Water Use and Total Acres Irrigated: 1990-2010

Oklahoma - Water Use Change 1990-2010	Acre-Ft Change (1990-2010)	% Change
Groundwater Irrigation Use	-71600	-17%
Surface Water Irrigation Use	-4800	-38%
Total Groundwater	43500	9%
Total Surface Water	5700	-36%
Total Water (GW+SW)	37700	8%
Acres Irrigated: Total Acre Change 1990 to 2010	28620	12%

Although total groundwater usage increased throughout the study period, the amount of groundwater used for irrigation from the total amount of groundwater used decreased by 21 percent (Table 16). Oklahoma must have experienced an increase of groundwater usage by a different usage group throughout the study period.

Table 16. Proportion of Water Usage from 1990-2010

Oklahoma - Proportion of Water Usage						
	1990	**1995**	**2000**	**2005**	**2010**	**1990-2010**
% GW Irrigation Usage from GW Total	88%	91%	88%	80%	67%	**-21%**
% SW Irrigation Usage from SW Total	80%	72%	80%	79%	78%	**-2%**
% GW Irrigation Usage from Total Water Usage	85%	89%	85%	77%	65%	**-19%**
% SW Irrigation Usage from Total Water Usage	3%	1%	2%	3%	1%	**-1%**

From 1990 to 2015 the Ogallala Aquifer had a median drawdown of 6 feet, Roger Mills County had an increase of aquifer level of 14 feet, and maximum drawdown in Texas County of 55 feet.

Oklahoma had a mean precipitation of 16.30 inches with a minimum of 12.29 inches of precipitation in 2000 and maximum of 16.68 inches of precipitation in 2010. The trend of irrigated inches per acre decreased from 1990 to 2010. Using a simple linear regression analysis, the amount of precipitation can account for very little variation of the amount of groundwater

Table 17. Precipitation and Groundwater Irrigation Use/Acre 1990-2010

Oklahoma				
Year	**Precipitation (in)**	**GW Irrigation Use (Acre-Ft)**	**Acres Irrigated**	**GW Irrigation Use/Acre (in)**
1990	14.09	420000	239540	21.04
1995	16.33	737400	276760	31.97
2000	12.29	479200	263380	21.83
2005	22.10	275200	218320	15.13
2010	16.68	348400	268160	15.59
Mean	16.30	452040	253232	21.11
Driest Year	2000 (12.29)			
Wettest Year	2010 (16.68)			

used for irrigation with an r^2 value of 17 percent. The value is not statistically significant with a p-value of 0.15 tested at 0.05 significance (Table 17 and Figure 11)

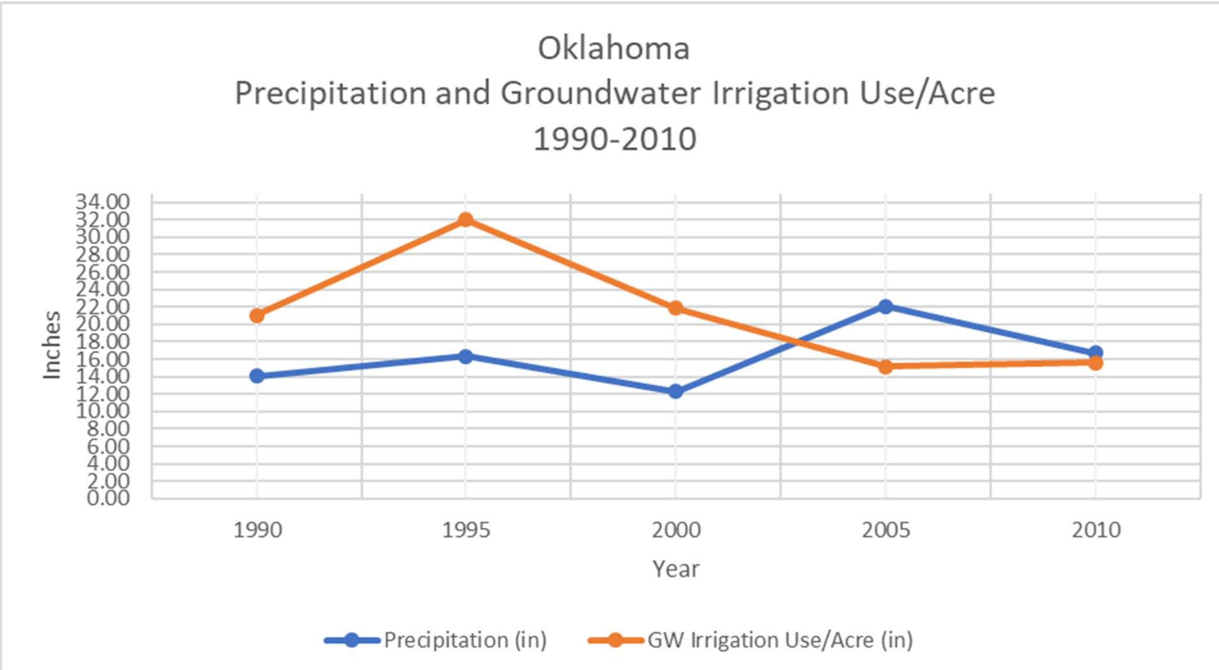

Figure 11. Precipitation and Groundwater Irrigation/Acre (inches) 1990-2010

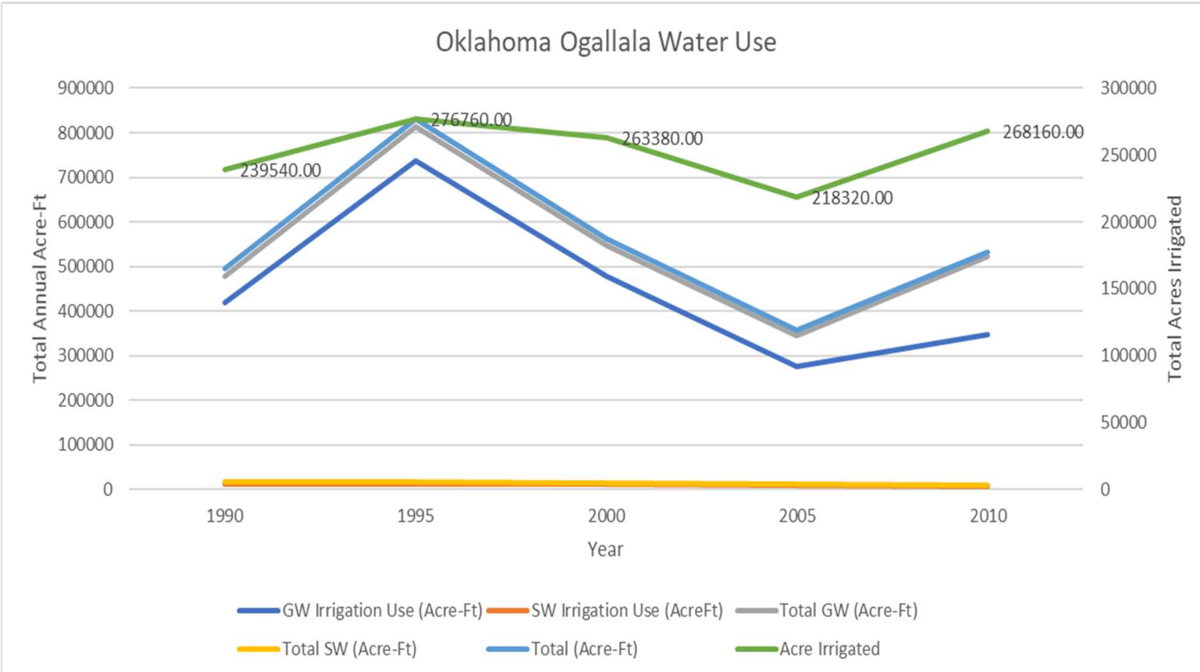

Figure 12. Oklahoma Ogallala Aquifer Use and Acres Irrigated 1990-2010

Throughout 1990 to 2015 the trend of acres irrigated increased however, from 1995 to 2010 the trend of groundwater used for irrigation decreased (Figure 12).

VI. South Dakota

South Dakota's groundwater usage for irrigation in the study area had an overall increase in volume of 245 percent and an increase overall total groundwater usage of 195 percent from 1990 to 2010. South Dakota had a decrease in acres irrigated of 25 percent (Table 18).

Table 18. Change in Water Use and Total Acres Irrigated: 1990-2010

South Dakota - Water Use Change 1990-2010	Acre-Ft Change (1990-2010)	% Change
Groundwater Irrigation Use	52500	245%
Surface Water Irrigation Use	3800	42%
Total Groundwater	52200	195%
Total Surface Water	7300	62%
Total Water (GW+SW)	59500	154%
Acres Irrigated: Total Acre Change 1990 to 2010	-7130	-25%

As the total amount of groundwater use increased from 1990 to 2010, the dependence of groundwater use for irrigation increased more than surface water use for irrigation (Table 19).

Table 19. Proportion of Water Usage from 1990-2010

South Dakota - Proportion of Water Usage						
	1990	1995	2000	2005	2010	1990-2010
% GW Irrigation Usage from GW Total	80%	71%	73%	82%	94%	14%
% SW Irrigation Usage from SW Total	75%	57%	56%	56%	66%	-9%
% GW Irrigation Usage from Total Water Usage	55%	53%	57%	69%	75%	20%
% SW Irrigation Usage from Total Water Usage	23%	15%	12%	9%	13%	-10%

From 1990 to 2015 the Ogallala Aquifer had a median increase of aquifer level of 2 feet, Jackson County had an increase of aquifer level of 7 feet, and maximum drawdown in Gregory County of 1 foot.

South Dakota had a mean precipitation of 14.65 inches with a minimum of 12.07 inches of precipitation in 1990 and maximum of 17.65 inches of precipitation in 2005. The trend of irrigated inches per acre increased from 1990 to 2010. Using a simple linear regression analysis, the amount of precipitation can account for about half of the variation for groundwater used for irrigation with an r^2 value of 48 percent. The value is not statistically significant with a p-value of 0.34 tested at 0.05 significance (Table 20 and Figure 13).

Table 20. Precipitation and Groundwater Irrigation Use/Acre 1990-2010

South Dakota				
Year	**Precipitation (in)**	**GW Irrigation Use (Acre-Ft)**	**Acres Irrigated**	**GW Irrigation Use/Acre (in)**
1990	12.07	21400	28450	9.03
1995	14.03	15900	24360	7.83
2000	13.28	18900	23160	9.79
2005	17.65	42300	42880	11.84
2010	16.21	74000	21320	41.65
Mean	14.65	34500	28034	16.03
Driest Year	1990 (12.07)			
Wettest Year	2005 (17.65)			

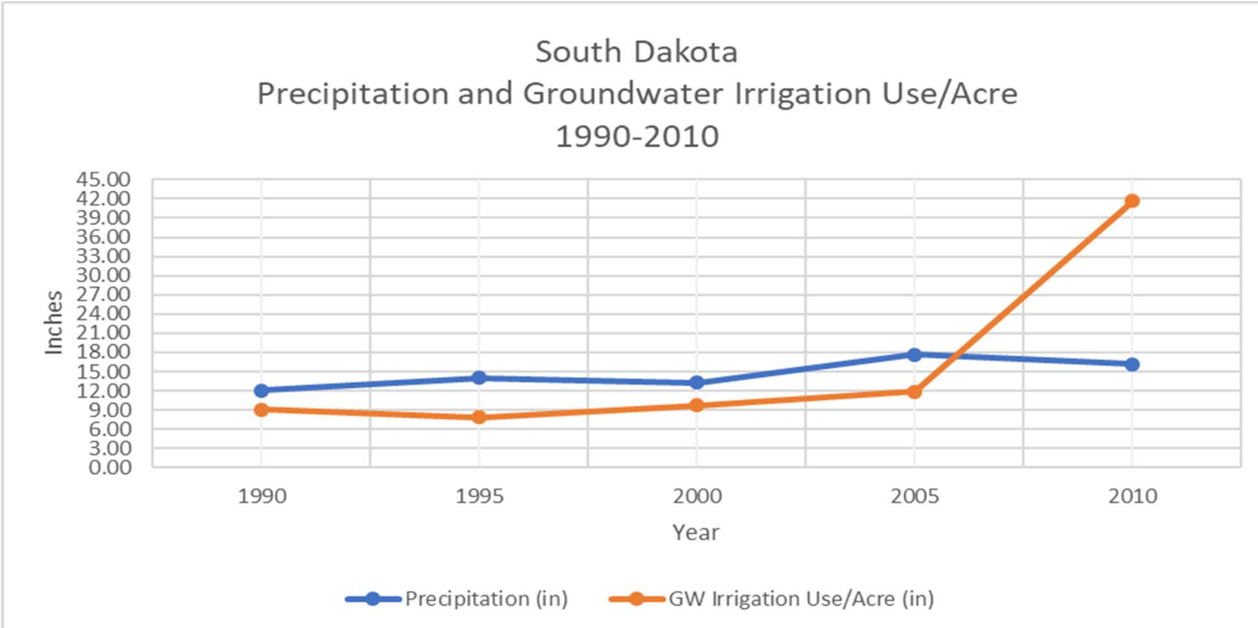

Figure 13. Precipitation and Groundwater Irrigation/Acre (inches) 1990-2010

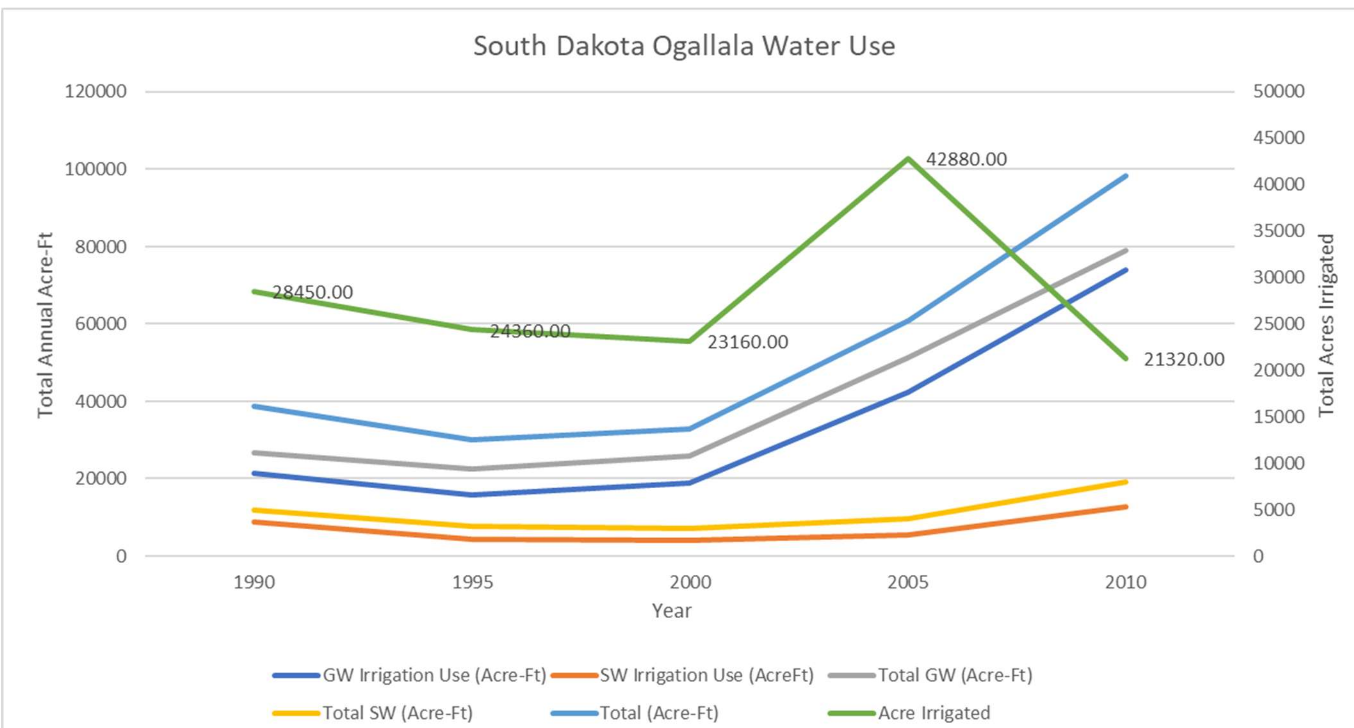

Figure 14. South Dakota Ogallala Aquifer Use and Acres Irrigated 1990-2010

Throughout 1990 to 2010 there was a trend in increased amount of total and irrigated groundwater usage and a decrease of acres irrigated (Figure 14).

VII. Texas

Texas groundwater usage for irrigation in the study area had an overall decrease in volume of 8 percent and a decrease overall of total groundwater usage of 3 percent from 1990 to 2010. Texas had an increase of acres irrigated of 10 percent (Table 22).

Table 21. Change in Water Use and Total Acres Irrigated: 1990-2010

Texas - Water Use Change 1990-2010	Acre-Ft Change (1990-2010)	% Change
Groundwater Irrigation Use	-367900	-8%
Surface Water Irrigation Use	4300	14%
Total Groundwater	-155800	-3%
Total Surface Water	-35600	-27%
Total Water (GW+SW)	-191300	-4%
Acres Irrigated: Total Acre Change 1990 to 2010	387970	10%

As the use of groundwater for irrigation decreased from 1990 to 2010, the dependence upon groundwater remained as the principal source for irrigation. However, surface water use for irrigation increased by 13 percent from 1990-2010 (Table 21). From 1990 to 2015 the Ogallala

Table 22. Proportion of Water Usage from 1990-2010

Texas - Proportion of Water Usage						
	1990	1995	2000	2005	2010	1990-2010
% GW Irrigation Usage from GW Total	92%	92%	0%	92%	88%	-5%
% SW Irrigation Usage from SW Total	24%	20%	0%	11%	38%	13%
% GW Irrigation Usage from Total Water Usage	90%	90%	0%	90%	86%	-4%
% SW Irrigation Usage from Total Water Usage	1%	1%	0%	0%	1%	0%

Aquifer had a median decrease of aquifer level of 19 feet, Andrews County had an increase of aquifer level of 9 feet, and maximum drawdown in Castro County of 82 feet.

Texas had a mean precipitation of 16.08 inches with a minimum of 12.27 inches of precipitation in 2000 and maximum of 22.70 inches of precipitation in 2010. The trend of irrigated inches per acre decreased from 1990 to 2010. Using a simple linear regression analysis, the amount of precipitation can account for about half of the variation for groundwater used for irrigation with an r^2 value of 52 percent. The value is also statistically significant with a p-value of 0.007 tested at 0.05 significance (Table 23 and Figure 15)

Table 23. Precipitation and Groundwater Irrigation Use/Acre 1990-2010

Texas				
Year	**Precipitation (in)**	**GW Irrigation Use (Acre-Ft)**	**Acres Irrigated**	**GW Irrigation Use/Acre (in)**
1990	14.48	4690500	3978840	14.15
1995	15.09	5815700	4227840	16.51
2000	12.27	5763700	4716400	14.66
2005	15.84	5597100	4688400	14.33
2010	22.70	4322500	4366810	11.88
Mean	16.08	5237900	4395658	14.30
Driest Year	2000 (12.27)			
Wettest Year	2010 (22.70)			

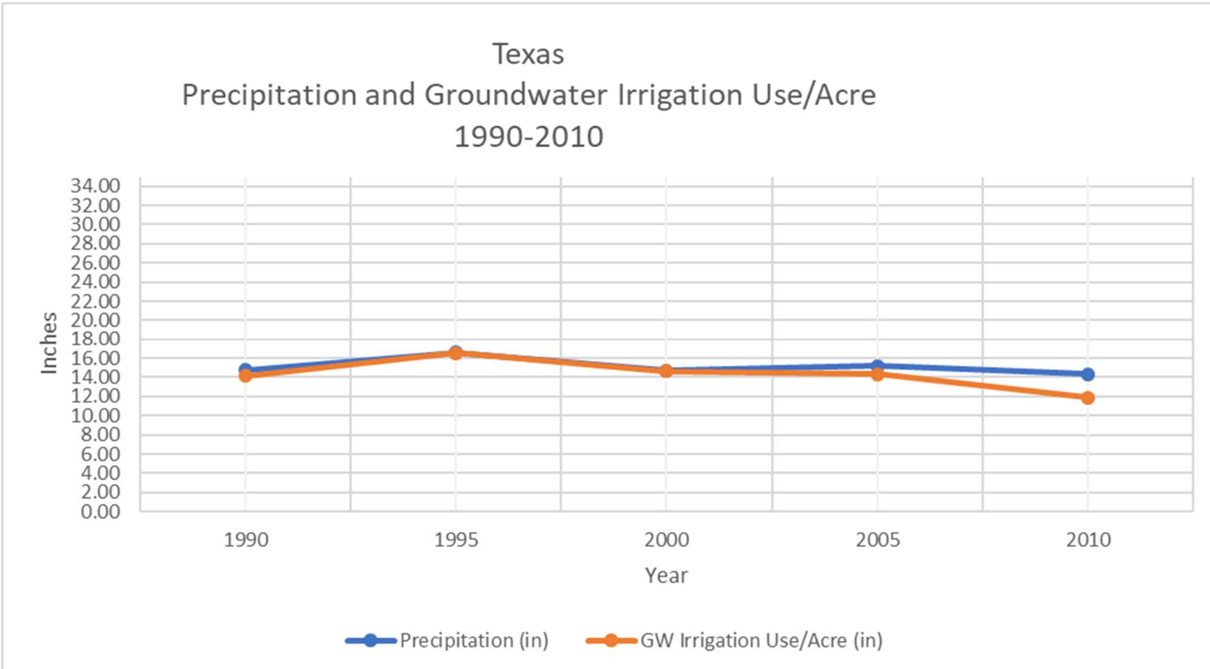

Figure 15. Precipitation and Groundwater Irrigation/Acre (inches) 1990-2010

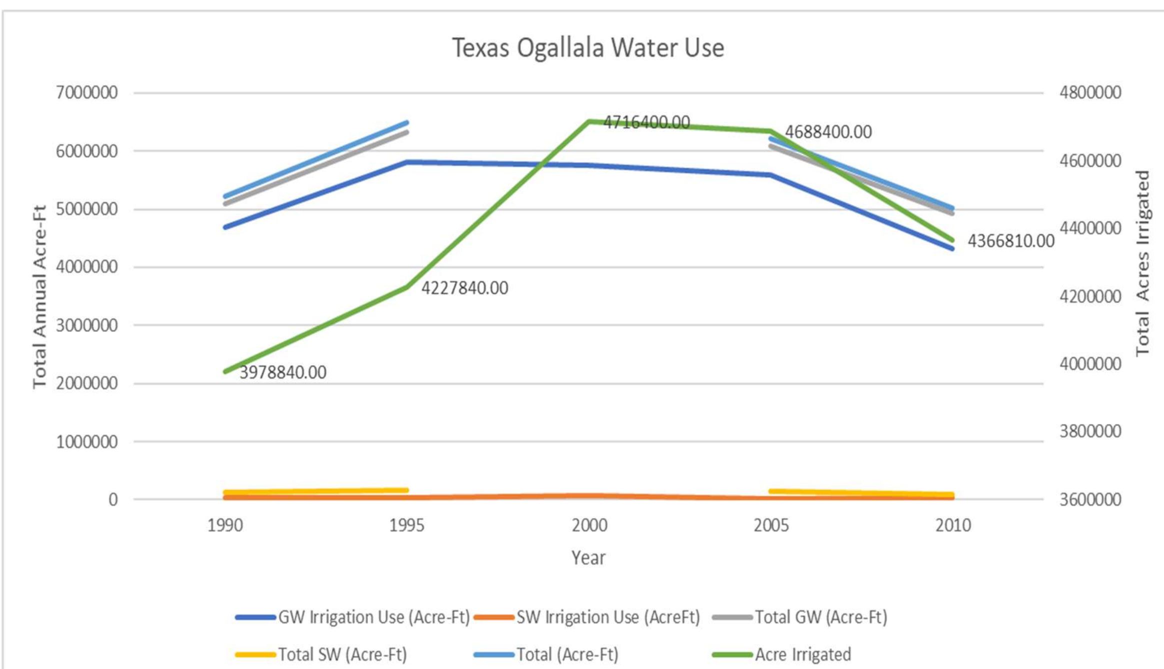

Figure 16. Texas Ogallala Aquifer Use and Acres Irrigated 1990-2010

Throughout 1990 to 2015 there was a trend of increased acres irrigated and decreased use of groundwater for irrigation (Figure 16).

VIII. Wyoming

Wyoming groundwater usage for irrigation in the study area had an overall increase in volume of 124 percent and an increase of overall of total groundwater usage of 106 percent from 1990 to 2010. Wyoming had a decrease of acres irrigated of 17 percent (Table 25).

Table 24. Change in Water Use and Total Acres Irrigated: 1990-2010

Wyoming - Water Use Change 1990-2010	Acre-Ft Change (1990-2010)	% Change
Groundwater Irrigation Use	229100	124%
Surface Water Irrigation Use	267500	45%
Total Groundwater	226600	106%
Total Surface Water	120400	15%
Total Water (GW+SW)	347000	35%
Acres Irrigated: Total Acre Change 1990 to 2010	-54670	-17%

The dependence upon groundwater for irrigation increased by 7 percent from 1990 to 2010 and the amount of irrigation use of surface water increased by 19 percent from 1990 to 2010 (Table 24).

Table 25. Proportion of Water Usage from 1990-2010

Wyoming - Proportion of Water Usage						
	1990	**1995**	**2000**	**2005**	**2010**	**1990-2010**
% GW Irrigation Usage from GW Total	87%	85%	91%	94%	94%	**7%**
% SW Irrigation Usage from SW Total	76%	69%	78%	75%	95%	**19%**
% GW Irrigation Usage from Total Water Usage	18%	18%	25%	30%	31%	**12%**
% SW Irrigation Usage from Total Water Usage	60%	55%	56%	51%	64%	**4%**

From 1990 to 2015 the Ogallala Aquifer had a median increase of aquifer level of 1 foot, Platt County had an increase of aquifer level of 3 feet, and maximum drawdown in Laramie County of 3 feet.

Wyoming had a mean precipitation of 14.26 inches with a minimum of 9.26 inches of precipitation in 2000 and maximum average of 17.62 inches of precipitation in 2005. The trend of irrigated inches per acre increased from 1990 to 2010. Using a simple linear regression analysis, the amount of precipitation can account for very little variation of the amount of

Table 26. Precipitation and Groundwater Irrigation/Acre 1990-2010

Wyoming				
Year	**Precipitation (in)**	**GW Irrigation Use (Acre-Ft)**	**Acres Irrigated**	**GW Irrigation Use/Acre (in)**
1990	15.93	184400	322800	6.86
1995	16.56	173500	366740	5.68
2000	9.26	381200	270590	16.91
2005	17.62	411200	233210	21.16
2010	11.91	413500	268130	18.51
Mean	14.26	312760	292294	13.82
Driest Year	2000 (9.26)			
Wettest Year	2005 (17.62)			

groundwater used for irrigation with an r^2 value of 20 percent. The value is not statistically significant with a p-value of 0.13 tested at 0.05 significance (Table 26 and Figure 17).

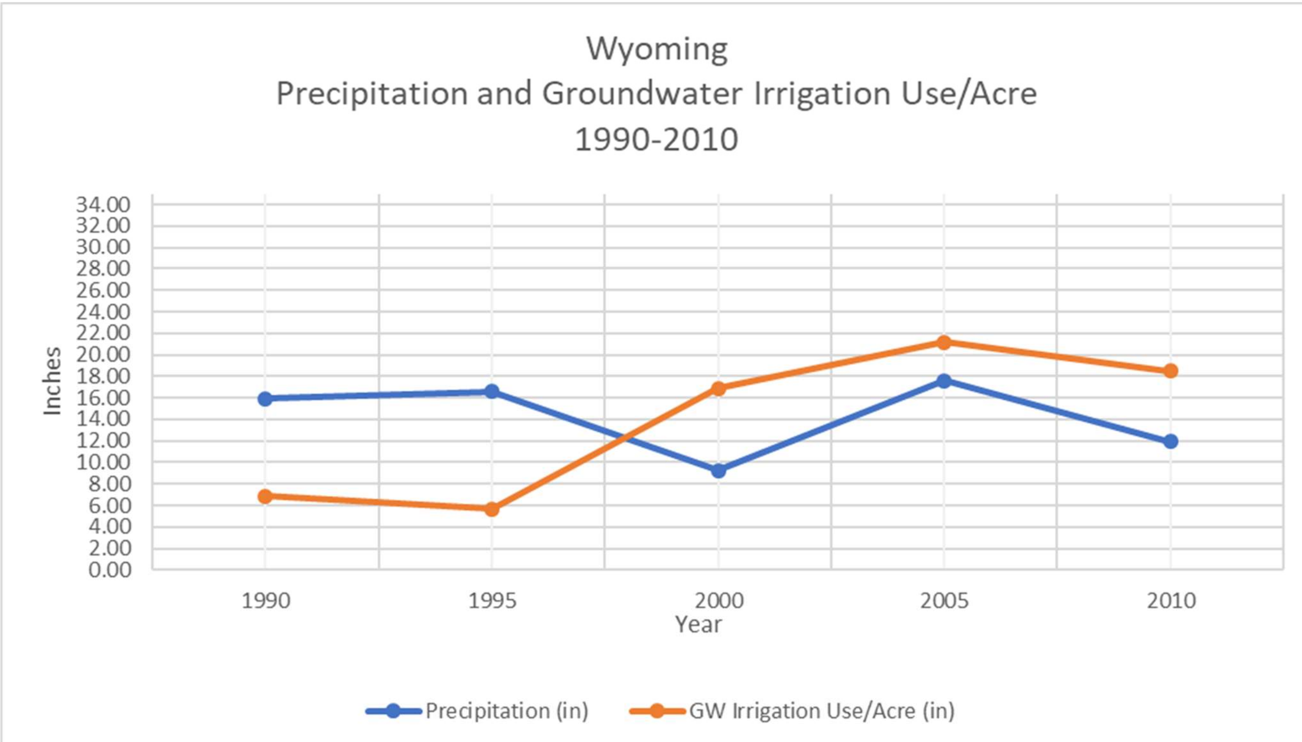

Figure 17. Precipitation and Groundwater Irrigation Use/Acre 1990-2010

Throughout 1990 to 2015 the trend of acres irrigated decreased and groundwater usage increased (Figure 18).

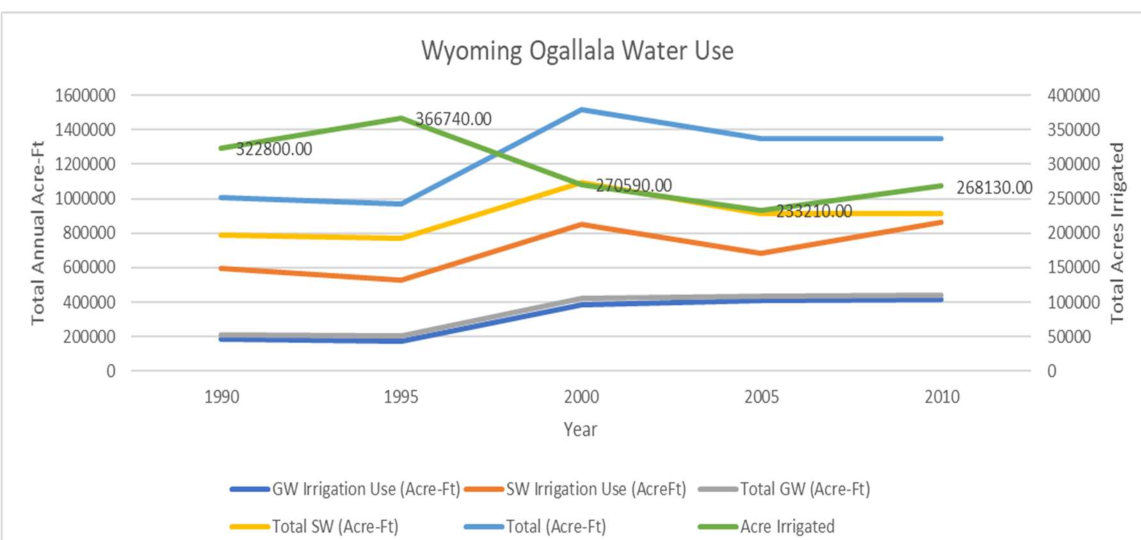

Figure 18. Wyoming Ogallala Aquifer Use and Acres Irrigated from 1990-2010

B. Groundwater Management of the Ogallala Aquifer

I. Colorado

Colorado's groundwater management laws are set as a modified prior appropriation state where the groundwater is owned by the state and the authority to appropriate groundwater can be delegated down to local authorities. Groundwater allocated to the landowner is based upon the usage. Within Colorado, there are 13 counties that lie directly over the Ogallala Aquifer which is used this study (Table 1), 11 of which exist within a local planning and regulatory authority. The regional structure for groundwater management consist of the Northern High Plains Designated Groundwater Basin and the Southern High Plains Groundwater Basin (Figure 19).

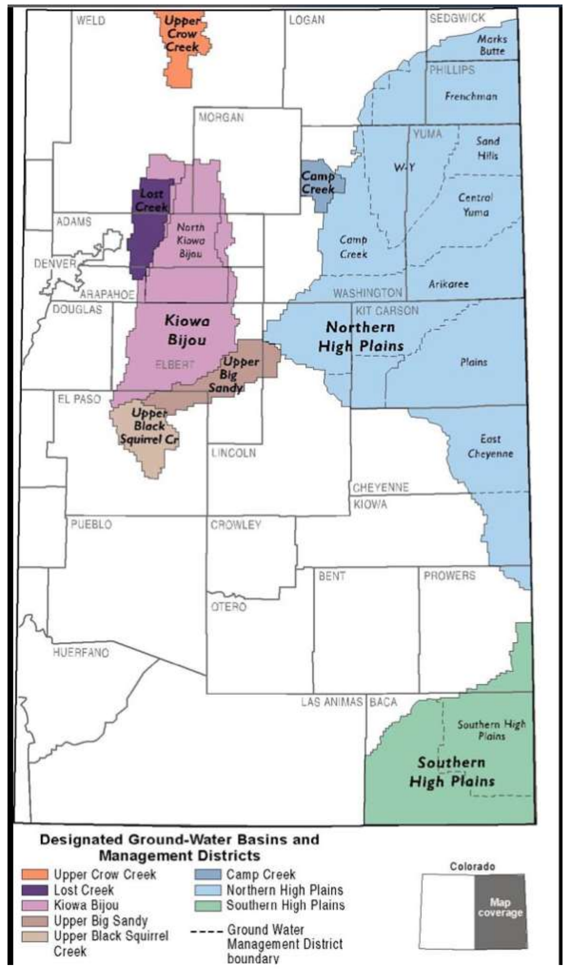

Figure 19. Colorado Designated Groundwater Basins (Adapted from Topper et al 2003)

Each individual groundwater basin is governed at the state level by the Colorado Groundwater Commission administered by the state engineer. Each individual basin consists of different rules and regulations that govern the local Groundwater Management Districts (GMD). The Northern High Plains consists of six GMDs each of which contain partial boundaries of 10 counties. Within the boundaries of each county, a board of directors is elected from the constituency within the political boundaries of the GMD. The board of directors within each GMD act as an advisory committee to the state engineer for developing and implementing rules and regulations for groundwater permitting. Funding to the GMD's is assessed by fees based upon the annual usage of permitted, non-exempt, wells in the GMD. Within the entirety of the Northern High Plains Designated Groundwater Basin there are no new large capacity wells allowed (wells that pump more than 2.5 acre-ft/day) however, there can be smaller wells permitted that pump less than an annual appropriation of 25 acre-ft. Within the Southern High Plains Designated Groundwater Basin, large capacity wells can still be appropriated with local approval and the same for the two counties (Las Animas and Weld) that do not fall into a Designated Groundwater Basin or GMD. In the absence of a GMD the State Engineer is the regulatory authority that appropriates groundwater based upon usage. Table of specific groundwater management characteristics in Appendix A.

II. Kansas

Kansas' groundwater laws are set by the doctrine of prior appropriation. Kansas is regulated through state and local control through the state's Chief Engineer at the Division of Water Resources, and local control through five Groundwater Management Districts (GMD). Private property owners are required to obtain a permit for using groundwater for anything other than domestic uses. The five GMDs are delegated the authority to provide groundwater permits through the

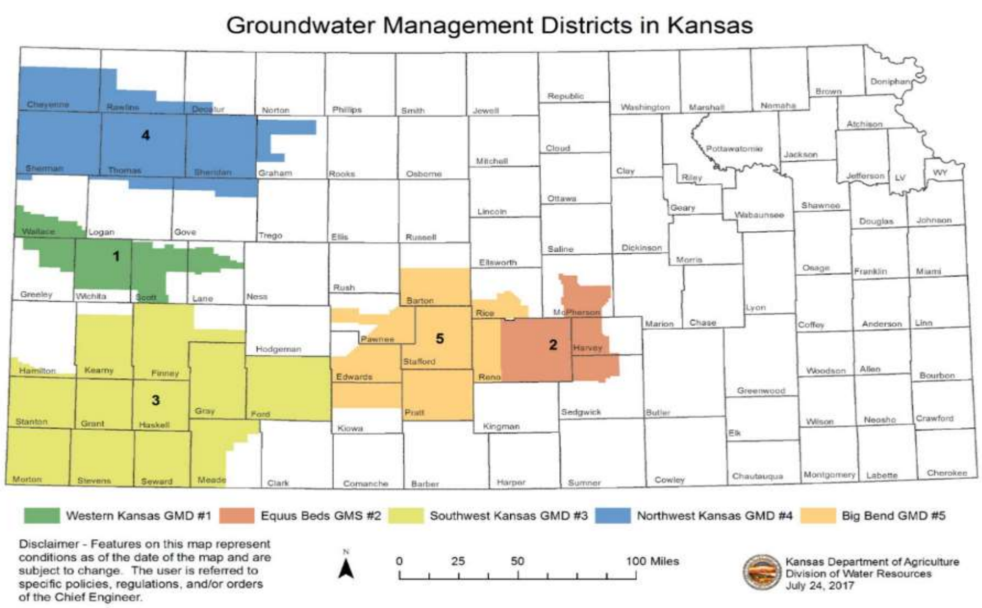

Figure 20. Kansas Groundwater Management Districts (GMD) (Adapted from Kansas Department of Agriculture 2016)

current state regulations and can propose new regulations to the state engineer based upon local demand. The GMD authorities consist of a board of directors ranging from three to 15 members. Each board member is elected by the constituency within the GMD if they're considered *eligible voters* which means individuals owning 40 contiguous acres of land or more. The local GMDs are funded through taxes based upon annual water usage assessments. Permits are issued to landowners based upon the beneficial use of the groundwater that it will be used for its intended purpose and not impair existing water rights or the public interest (Figure 20). Table of specific groundwater management characteristics in Appendix B.

III. Nebraska

Nebraska's groundwater management is based upon a modified version of reasonable use doctrine and correlative rights. Every landowner is entitled to reasonable use of the groundwater underlying the landowners land and considered correlative in times of shortage. Groundwater rights authority is delegated from the state to the 23 Natural Resource Districts (NRD) which possess the mission of managing the natural resources of the state within the respective political

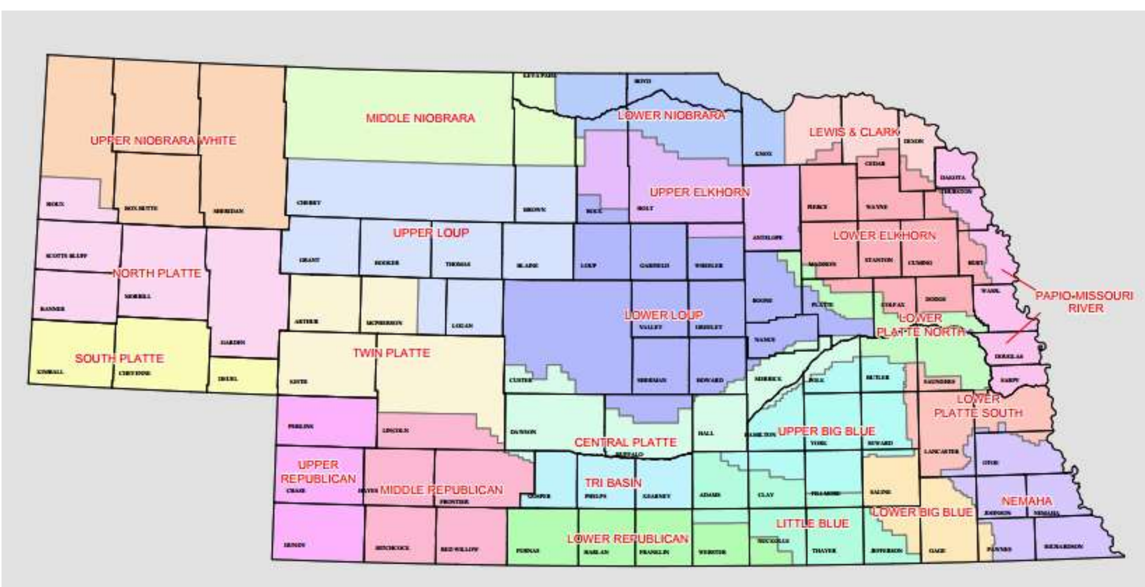

Figure 21. Natural Resource Districts in Nebraska (Adapted from Boundaries & PLSS Data 2002)

boundaries. The Ogallala exists within 19 of the 23 NRDs. The NRDs maintain the responsibility of providing groundwater rights based upon the size of the tract of land in which the landowner wants to irrigate/use. Nebraska NRDs regulate the allotment of groundwater in conjunction with surface water demands. NRDs possess full autonomy to create regulations as required by the district. Generally, groundwater permits are not required for withdrawal, however permits are required in control areas set which are set by NRDs. All funding for NRDs is provided by taxes within the district. Board members are elected from the constituency to govern the NRD (Figure 21). Table of specific groundwater management characteristics in Appendix C.

IV. New Mexico

New Mexico's groundwater is a public resource governed by the state through the prior appropriation doctrine, however groundwater is only regulated when an area is placed into a Declared Groundwater Basin. Five counties on the eastern edge of New Mexico are located

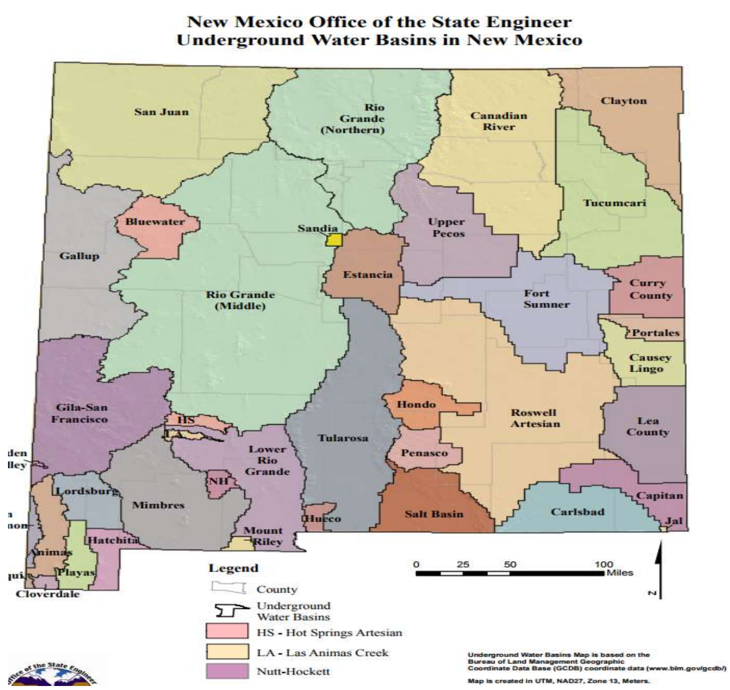

Figure 22. New Mexico Underground Water Basins (Adapted from Rules and Regulations Governing the Appropriation and Use of Groundwater in New Mexico, Article 7 Declared Underground Water Basins. 2006)

within five Declared Groundwater Basins where each are required to meter their groundwater usage. The state develops recommended drawdown levels based upon the modeled estimated saturated thickness. Groundwater pumping permits are issued individually by the state through the prior appropriation system and groundwater can be pumped if it does not impair surface water. Inter-basin transfer of groundwater is allowed in New Mexico but requires a permit from the State Engineer. The Curry County, Portales, and Lea County declared groundwater basins are not allowing new groundwater appropriations after 2009 (Figure 22). Table of specific groundwater management characteristics in Appendix D.

V. Oklahoma

Oklahoma groundwater is considered a public resource owned by the state and groundwater rights are issued to private landowners through the reasonable use doctrine based upon the acreage of land. Within the Ogallala region there two regional classifications that determine the amount of acre-ft allotted per acre owned by the private landowner. In the *Ogallala-Panhandle* region each landowner is allotted 2 acre-ft/year for every acre which consists of three counties and 1.4 acre-ft/year in the *Ogallala-Northwest* region consisting of four counties. Reporting of metered wells is required for permanent and temporary wells, but voluntary for any other classification of exempt wells. The Oklahoma Water Resources Board reviews all permit applications to ensure a 40-year yield of groundwater is available prior to approving any well (Figure 23). Table of specific groundwater management characteristics in

Appendix E.

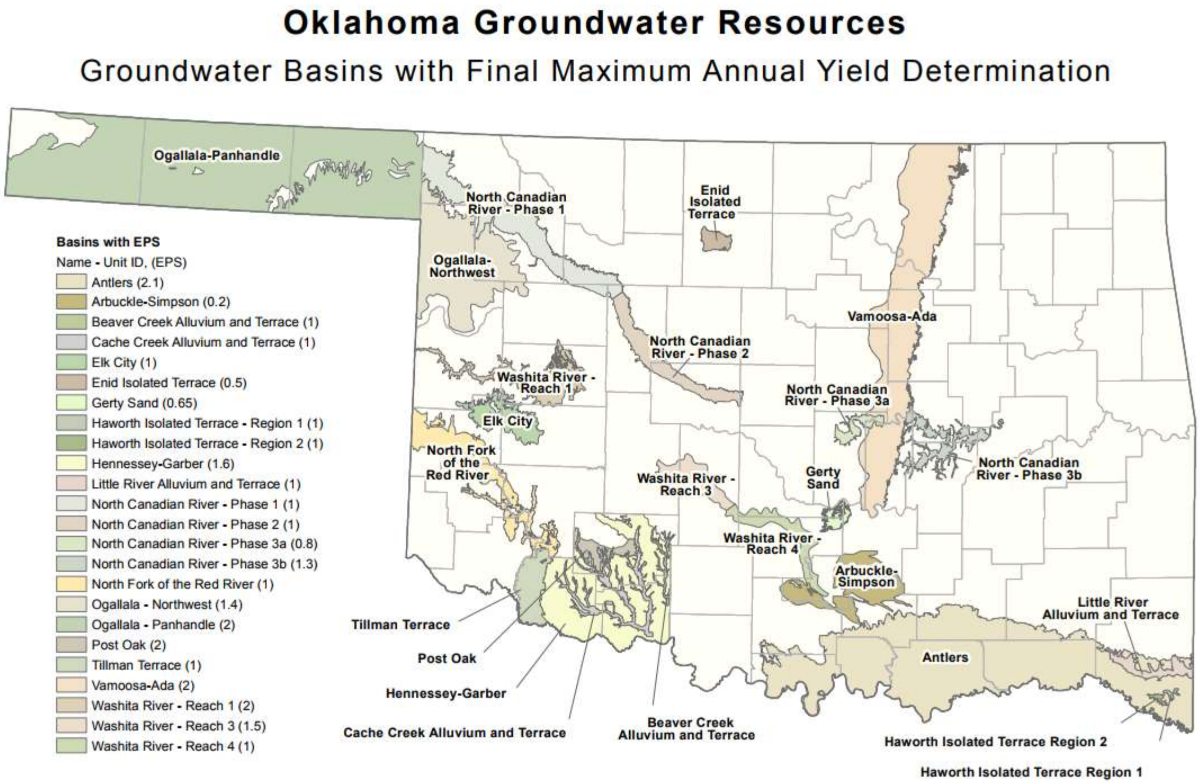

Figure 23. Oklahoma Groundwater Boundaries (adapted from Oklahoma Groundwater Resources 2017)

VI. South Dakota

South Dakota groundwater is managed by the state as a public resource through the prior appropriation system set by the state and the individual Indian reservations. Groundwater on the Indian reservations are governed by the respective tribe. The state requires permits for all wells excluding domestic use. South Dakota possesses a “no-mining law” that state groundwater cannot be extracted at a faster rate than it can recharge. Use of the groundwater determines priority under the prior appropriation system. Highest to lowest priority in South Dakota: Domestic use, municipal, agricultural, mining (not exceeding recharge), recreational, and other beneficial. Inter-basin transfers are permitted in South Dakota. The Ogallala Aquifer exists over four counties owned by the state and three counties owned by the local Indian tribe. Table of specific groundwater management characteristics in Appendix F.

VII. Texas

Groundwater is treated as private property in Texas through the rule of capture doctrine. Texas created the regional authority of Groundwater Management Areas (GMA) which typically follow along the boundaries of the major aquifers within Texas. Within the GMAs, local constituencies can create Groundwater Conservation Districts (GCD) which serve to regulate the groundwater usage throughout the designated region (typically county, but can consist of multiple counties). The Ogallala Aquifer is managed by four GMAs, 12 GCDs, and four counties that do not possess any management structure. The GMAs develop a Desired Future Condition (DFC) for the desired level of the aquifer in 50 years. Each of the 4 GMAs that overly the Ogallala Aquifer consist of four different DFC levels to manage the aquifer level. Within each of the 12 GCDs, they possess different funding structures consisting of taxes assessed based upon water use, fees based upon water use, initial fees for permitting, or no funding source. In the case of no GCD, there isn’t a regulatory authority to control groundwater usage. The board of directors that preside over the GCDs are either elected or appointed and develop individual rules that apply to that specific GCD for administering, monitoring, and reporting groundwater pumping regulations. The state agency, Texas Water Development Board (TWDB), serves as the planning authority for groundwater, and where a GCD exists, the GCD and GMA act as the local planning authority with oversight form the TWDB (Figure 24 & 25). Table of specific groundwater management characteristics in Appendix G.

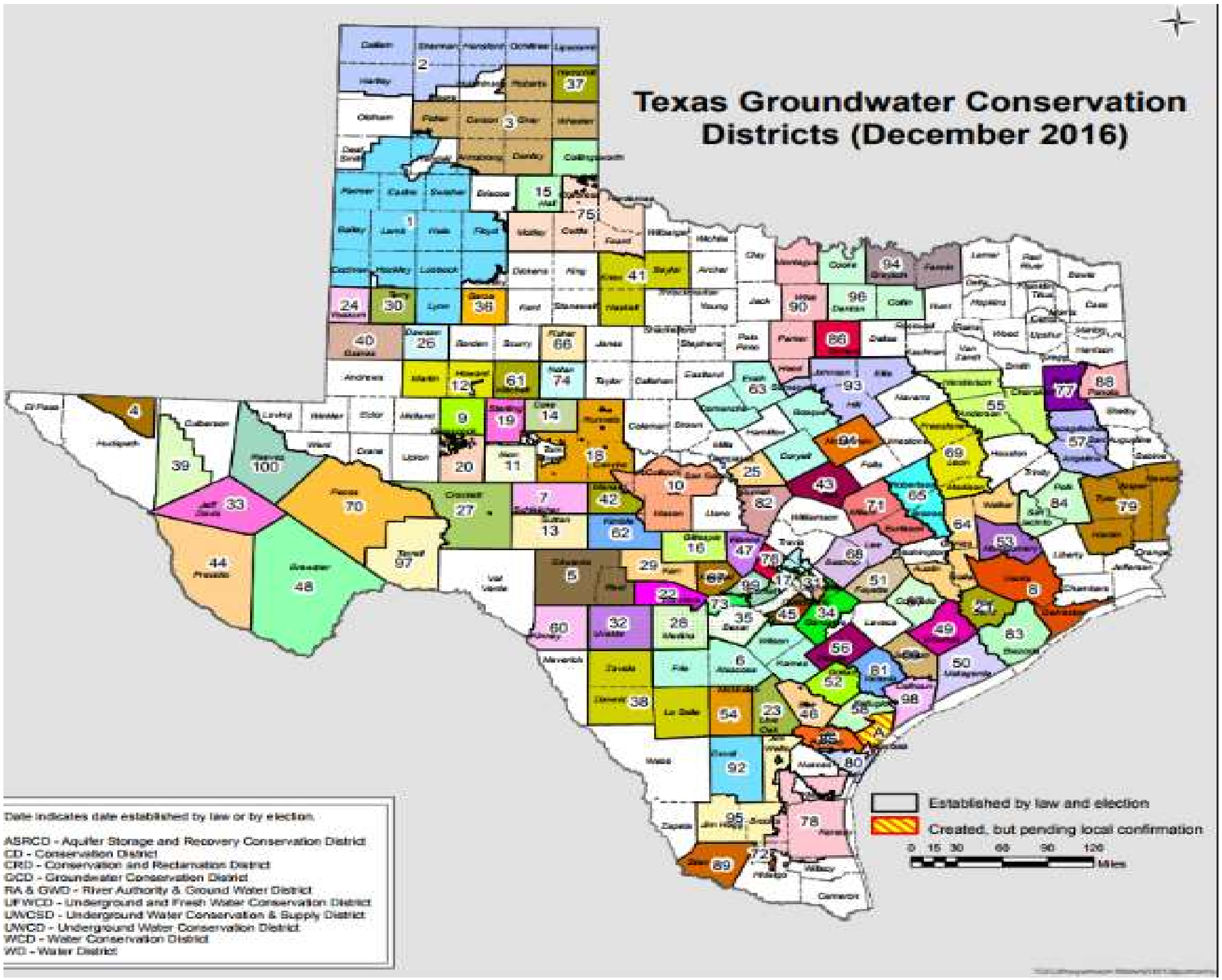

Figure 24. Texas Groundwater Conservation District Map – Local level (Adapted from TWDB Maps, Groundwater Conservation Districts 2016)

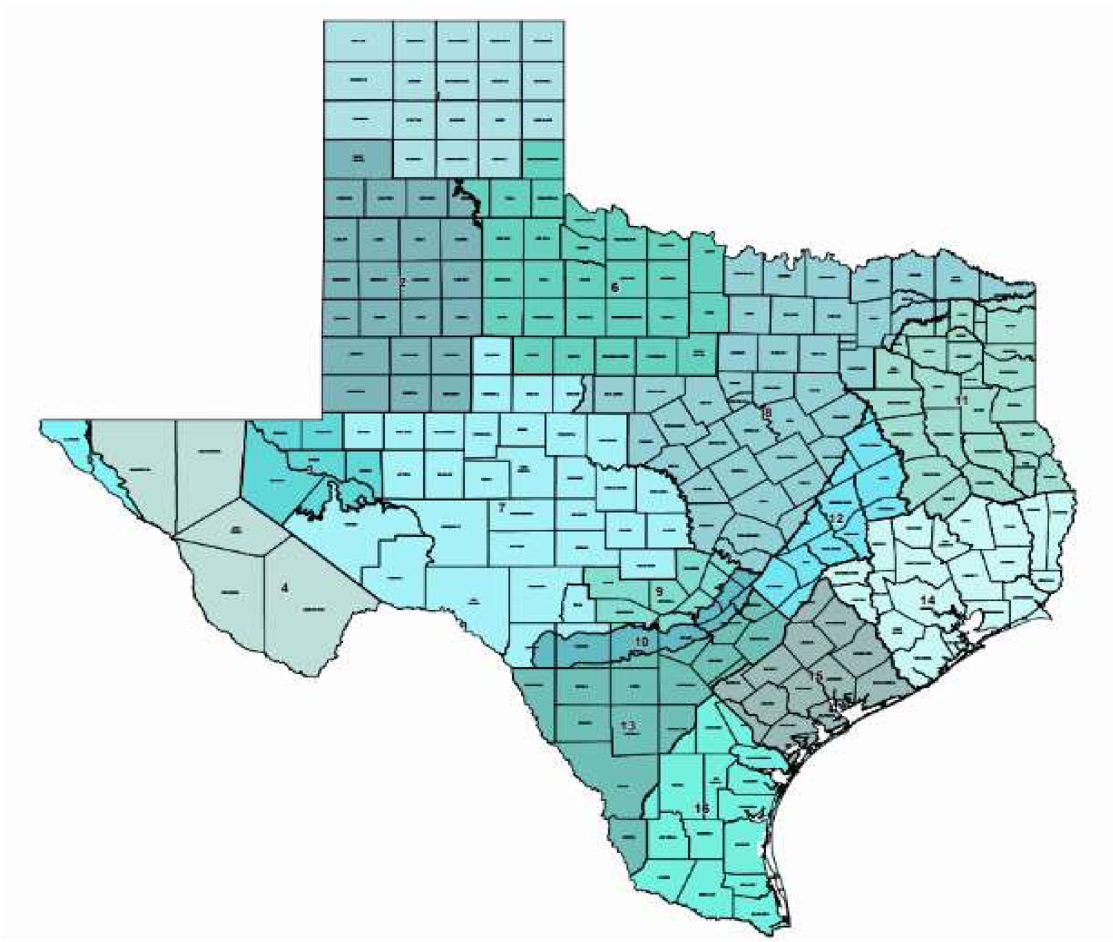

Figure 25. Texas Groundwater Management Areas – Regional Management (Adapted from TWDB Maps, Groundwater Management Areas 2015)

IX.   Wyoming

Wyoming's groundwater resources are governed by the prior appropriation doctrine and administered by the Wyoming Water Development Commission (WWDC). The State Engineer located at the WWDC provides permits for allocating groundwater resources based upon beneficial use. Beneficial use is described in the permit application to the State Engineer through describing the location and declared use, then the State Engineer determines whether there is available groundwater to be permitted. There isn't any limit for allocation of groundwater resources as determine by the State Engineer. Local advisory boards called Groundwater Control

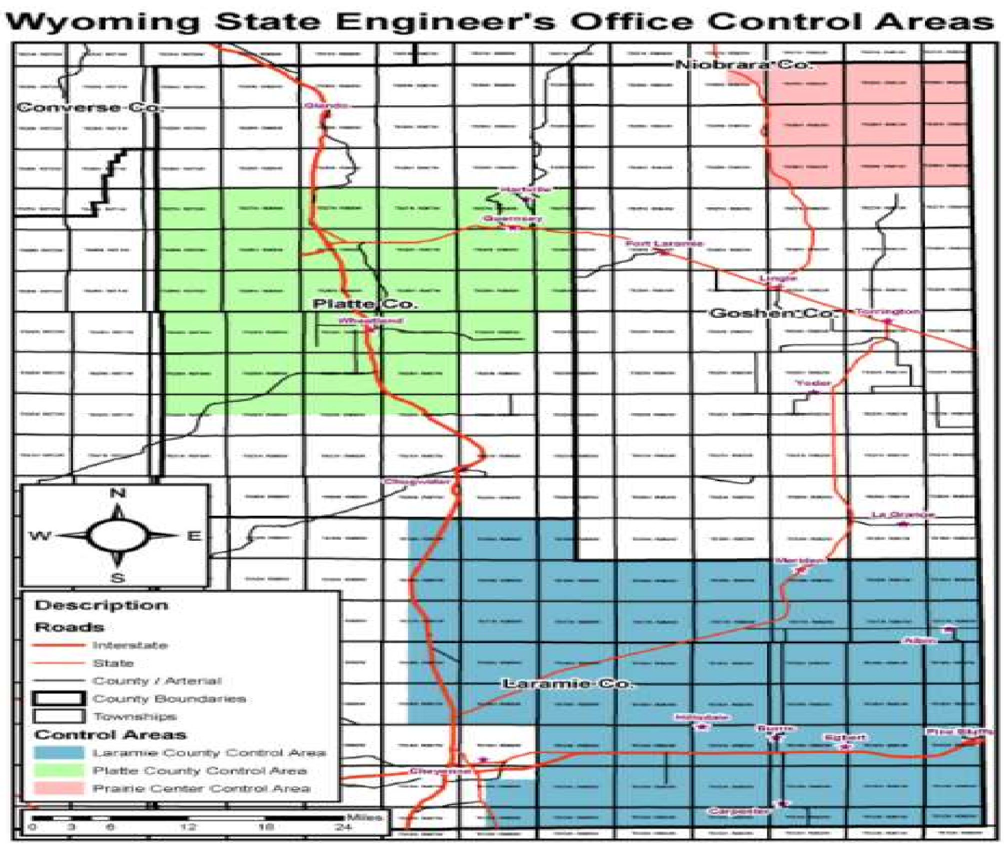

Figure 26. Wyoming Groundwater Control Areas (Adapted from Groundwater Control Areas and Advisory Boards)

Areas (GCA) serve in an advisory role to the State Engineer for appropriating groundwater rights. Highest preference is given to domestic use then following is municipal, agricultural, industrial, mining, and other recreational uses. Inter-basin transfer is allowed through obtaining a permit from the State Engineer. The advisory board for the GCAs are elected consisting of 5 board members (Figure 26). Table of specific groundwater management characteristics in Appendix H.

VI. Analysis

Table 27. Summary of Groundwater Legal and Management Factors Across the Eight States Using Ogallala Aquifer Water

Doctrine	Level of Management (State/Local/Private)	Governing Authority	Funding Source	Groundwater Metering Requirement (Y/N)	Inter-Basin Transfer (Y/N)	Well Permit Required (Y/N)	Allocation for Pumping
Modified Prior Appropriation	State and Local	State: Colorado Groundwater Commission Regional: Designated Grounwater Basins Local: Groundwater management Districts	Fees based upon pumping allocation	Yes	Yes (with permit)	Yes - with exemptions	Yes - Provided through appropriations
Prior Appropriation	State and Local	State: Division of Water Resources Local: Groundwater Management Districts	Taxes thorugh usage assessments	GMD-Yes; State-No	Yes	Yes - with exemptions	Yes - Determined by GMD
Modified Reasonable Use & Correlative Rights	Local	Natural Resource Districts	Taxes	Determined by NRD	Yes	Yes - with exemptions	As determined by NRD
Prior Appropriation	State	New Mexico Office of the State Engineer	Initial Permit Fees	Yes	Yes	Yes - with exemptions	Yes - Provided through appropriations
Reasonable Use	State	Oklahoma Water Resources Board	Initial Permit Fees	Yes	Yes	Yes	Yes - Determined by Basin

Table 28. Ogallala Aquifer Summary of Change 1990-2010

State	Groundwater Irrigation	Total Groundwater Use	Acres Irrigated	Irrigation/Acre	Aquifer Level Change (ft)	Precipitation & Irrigation/Acre Significance (Y/N)
Colorado	-50%	-49%	-2%	-49%	-13.6	N
Kansas	-28%	-27%	-3%	-25%	-7.95	N
Nebraska	-2%	-2%	26%	-22%	-0.22	Y
New Mexico	-18%	-18%	-14%	-5%	-9.40	Y
Oklahoma	-17%	9%	12%	-26%	-6.21	N
South Dakota	245%	195%	-25%	361%	2.10	N
Texas	-8%	-3%	10%	-16%	-18.9	Y
Wyoming	124%	106%	-17%	170%	1.22	N

Each state possesses one of the four, or modified versions, of groundwater law that has supported the states intent to manage the drawdown of groundwater in the Ogallala Aquifer and, uses of the Ogallala Aquifer vary among each state (Table 27 & 28).

Colorado uses a modified prior appropriation system that allocates groundwater rights to permittees through using Groundwater Management Districts (GMD). The GMDs serve in an advisory role to the state to facilitate groundwater rights permitting and metering. In 2007 the Norther High Plains Designated Groundwater Basin (DGB) restricted any new permitting for "large-capacity wells." From 2005 to 2010 the number of acres irrigated dropped from about 3.1 million acres irrigated to about 1.7 million acres irrigated which accounted for the largest reduction throughout the 1990 to 2010 period for Colorado. With the decreased number of irrigated acres and groundwater irrigation pumping decreased by about 50 percent, the restriction of "large-capacity wells" could have caused the decreased amount of groundwater pumping throughout the time-period. As a prior appropriation state, the state has the ultimate authority to restrict groundwater pumping through limiting groundwater allocations.

Similar to Colorado, Kansas is a prior appropriation state with local groundwater management authorities that determine the appropriation of groundwater rights. Colorado and Kansas are the only two states that experienced a reduction for groundwater irrigation use, total groundwater use, acres irrigated, aquifer level decline, and over 25 percent reduction of inches irrigated per acre. The difference between the two states management structure is the source of funding provided to the local groundwater management authorities. Colorado receives funds from groundwater pumping fees and Kansas from taxes however, both funding schemes are based off an assessment of groundwater usage. Both states pumping limits are determined through appropriations from the local management authority.

Texas and Nebraska compared similar groundwater usage trends but, contrast for management doctrines. However, both states possess similar frameworks for their management structure. Both states had similar trends for decreasing use for groundwater irrigation, total groundwater use, increasing numbers of irrigated acres, decreasing inches irrigated per acre and a reduction of aquifer level. Aquifer level varied the largest among all of the quantitative factors with Nebraska's Ogallala Aquifer level reduction resulting in less than one inch and Texas at about 20 inches. However, with both states experienced an increase in acres irrigated and an overall reduction of inches irrigated per acre without precipitation being a significant factor or irrigation rates, this suggests agriculture is adapting to more water conservation-oriented irrigation. Although Nebraska uses a blend of reasonable use and correlative rights doctrines, and Texas uses the rule of capture doctrine, they both utilize groundwater management authority based upon autonomous local governance. Throughout Nebraska, the NRDs possess the authority to decide whether to manage groundwater through pumping allocations and Texas utilizes the regional GMA structure to establish groundwater pumping limits. Both states are similar in philosophy of allowing autonomous local authority to develop pumping regulation but enforce regulations through different doctrines.

Similar to four of the eight other states, New Mexico is a state that operates under the doctrine of prior appropriation but, possess different results for the use of the Ogallala Aquifer. Unlike any other state, New Mexico had a reduction in groundwater irrigation use, total groundwater use, acres irrigated, inches irrigated per acre, and decline in Ogallala Aquifer level. Precipitation was found to not affect the amount of groundwater usage for irrigation. However, similar to Colorado, New Mexico has stopped all new groundwater allocations for groundwater pumping from three of the groundwater basins after 2009 (Appendix D).

Oklahoma is the only state that experienced an increase of total groundwater use, a decrease of groundwater irrigation, and increase of acres irrigated. Oklahoma is also the only state that uses the doctrine of reasonable use. With an increase of total groundwater use and decrease of groundwater irrigation, this suggests there has been an increase of another groundwater usage in the Ogallala region of Oklahoma. Since the proportion of groundwater used for irrigation within the total amount of groundwater used decreased, this suggests there has been a change in irrigation technology over the Ogallala region and/or a potential for a change of crop selection for drought-resist crops requiring less water.

South Dakota and Wyoming are the two most similar states for groundwater management structure and use of the Ogallala Aquifer compared to the six other states. Both states use the prior appropriation doctrine and have had a substantial increase of groundwater use for irrigation, total groundwater use, inches irrigated per acre, and an increase of the Ogallala Aquifer level.

Both state have also had a reduction of acres irrigated in both states. Since both states had a decrease in irrigated acres and substantial increase of irrigation, this suggests that both states are irrigating water-intensive crops.

The states that possess a groundwater management structure consisting of a local autonomous management authority, such as Colorado, Kansas, Nebraska, and Texas, experienced similar trends with the reduction of total groundwater usage and groundwater used for irrigation. Oklahoma is the only state that experienced an increase in acres irrigated but an overall reduction of groundwater irrigation which could be attributed to drought-resistant crop selection and/or increased efficiency with irrigation technology. Oklahoma's reasonable use doctrine could provide an explanation to the state-controlled groundwater regulation that allows for a broader interpretation of reasonable use rather than appropriating groundwater for a specified use. The prior appropriation doctrine tends to have more stringent pumping regulations for uses and areas that are restricted from pumping which could account for the overall reduction of groundwater usage in the majority of the prior appropriation states.

VII. Conclusion

The states overlying the Ogallala Aquifer possess different groundwater management structures that create a fragmented framework for groundwater regulation and have achieved different effects for managing the resource. However, although irregular, many similarities among management structures exist throughout the Ogallala Aquifer region. Local authorities for groundwater are developed throughout multiple doctrines and appear to achieve desired results for reduction of groundwater resources. Nebraska and Texas possess two different doctrines but use local management authorities to reduce groundwater usage and appear to implement water conservation agricultural practices. Colorado, a prior appropriation state, uses local groundwater management districts to serve in an advisory role to the state to recommend management regulations to reduce the amount of groundwater pumped. The common theme among states that reduced the most amount of groundwater usage implemented a form of local management with either regulatory authority or, to serve in an advisory role to conserve groundwater usage. Oklahoma appeared to result in increased groundwater usage that is non-agricultural related.

Groundwater usage, apart from Wyoming, South Dakota, and Oklahoma, declined in most states during this study period. Wyoming and South Dakota increased groundwater usage for agriculture and every other state decreased the amount of irrigated acreage. Based upon the result of the overall reduction of acres irrigated and amount of groundwater used for irrigation, it suggests there is a trend of increased water efficiency for irrigation methods and potential for better technology for drought-resistant crops being grown in the Ogallala Aquifer region.

Of the simple linear regression analyses conducted for the eight states in this study, only Nebraska, New Mexico, and Texas exhibited statistically significant coefficients of determination. Precipitation by itself, however, explained only 27 percent of the variability in irrigation-groundwater use in New Mexico and about half of the variability in Nebraska (48 percent) and Texas (52 percent). This finding is not particularly surprising given that other variables such as crop selection and irrigation technology are likely to be important too. A recommendation for future research, therefore, is to include data on these factors and others that are thought to influence water use to see if a more robust model can be developed.

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