Natural Resources Conservation Service
U.S. DEPARTMENT OF AGRICULTURE

Impacts to the Ogallala Aquifer: How Changes in Long-term Weather Patterns and Shifts in Climate Regions Affect the Aquifer – An Overview of Selected Papers

Fumiko Yamazaki, Ph.D., and Julie A. Suhr Pierce, Ph.D.

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December 2024

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Introduction

The Ogallala Aquifer is a natural subterranean reservoir that lies underneath a 111-million-acre region of the Great Plains that includes parts of Wyoming, South Dakota, Nebraska, Kansas, Colorado, Oklahoma, Texas, and New Mexico. Around 1.9 million people depend on the aquifer for their municipal and industrial water supply, and the Ogallala was key to the establishment of a thriving agricultural economy within the region. Beyond human uses, the aquifer is also crucial to the ecological health of the Great Plains. During times of low precipitation and drought, groundwater from the aquifer feeds creeks and streams that can't be sustained by surface water. It is anticipated that over time the many complicated aspects of managing the Ogallala will only become more difficult as increasingly hot summers lead to increased demand for water from the aquifer; demand that already exceeds its recharge rate. The expected result will be an ongoing drawdown of the aquifer into the future (USGS, 2018).

The aquifer has supported large-scale agriculture in the Great Plains since the period following World War II. Prior to that time, going back as far as 1911, withdrawals from the aquifer were minimal (Lennon, 2020). Since that time, as drilling and withdrawals increased, the balance between aquifer recharge and drawdown has tipped to the point where long-term dependence on irrigation from the aquifer will not be sustainable unless major changes in irrigation habits are made. Overlying this setting are looming changes in temperature and precipitation patterns due to climate change. If predicted changes and impacts are realized, agricultural production in the region will run into binding resource constraints that will affect regional physical output and economic outcomes for Great Plains producers and their supply chains; the economies of the region, the U.S., and the global agricultural sector; and consumers worldwide.

Despite the critical importance of the aquifer, however, there is no overarching policy in place at the present time to protect the Ogallala from depletion. As will be discussed below, the policies that regulate the use of the aquifer are not the same from one state to another. Another complicating factor is the degree of variation in laws regarding ownership of the water supplied by the aquifer. In some parts of the region dependent on the Ogallala, the state owns groundwater as a public resource; in other parts of the area served by the aquifer, groundwater is private property. Because of these

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differences and due to similar variations in rules that govern the use of various irrigation technologies throughout the region, it is not likely that any one policy or set of policies will slow or reverse the drawdown and rapid depletion of the Ogallala; it will require an array of policies and changes in behaviors to successfully address these critical resource issues.

In this slice-in-time overview of a cross-section of published papers, we will take a look at the subject of the Ogallala Aquifer and will connect the aquifer's history, its current status, and predictions about its future both to climate change and to how increased uncertainty about precipitation patterns and temperatures, and the dissonance between current and future demands on the aquifer, stand in contrast to the geological realities of the water the aquifer contains and its recharge rate. This is not intended to serve as an encyclopedic literature review. This survey includes a variety of sources including peer reviewed papers and popular press articles as well as historical non-fiction books. Many more research papers and online sources of data are available, and we recommend that interested readers pursue additional information. With the publications selected for this paper, we illustrate issues and some of the proposed strategies for responding to the challenges posed by aquifer depletion in combination with climate change. Over the years to come, people are going to have to change how they use the aquifer. It is uncertain whether that change will occur soon enough to sustain the food supply it supports into the future.

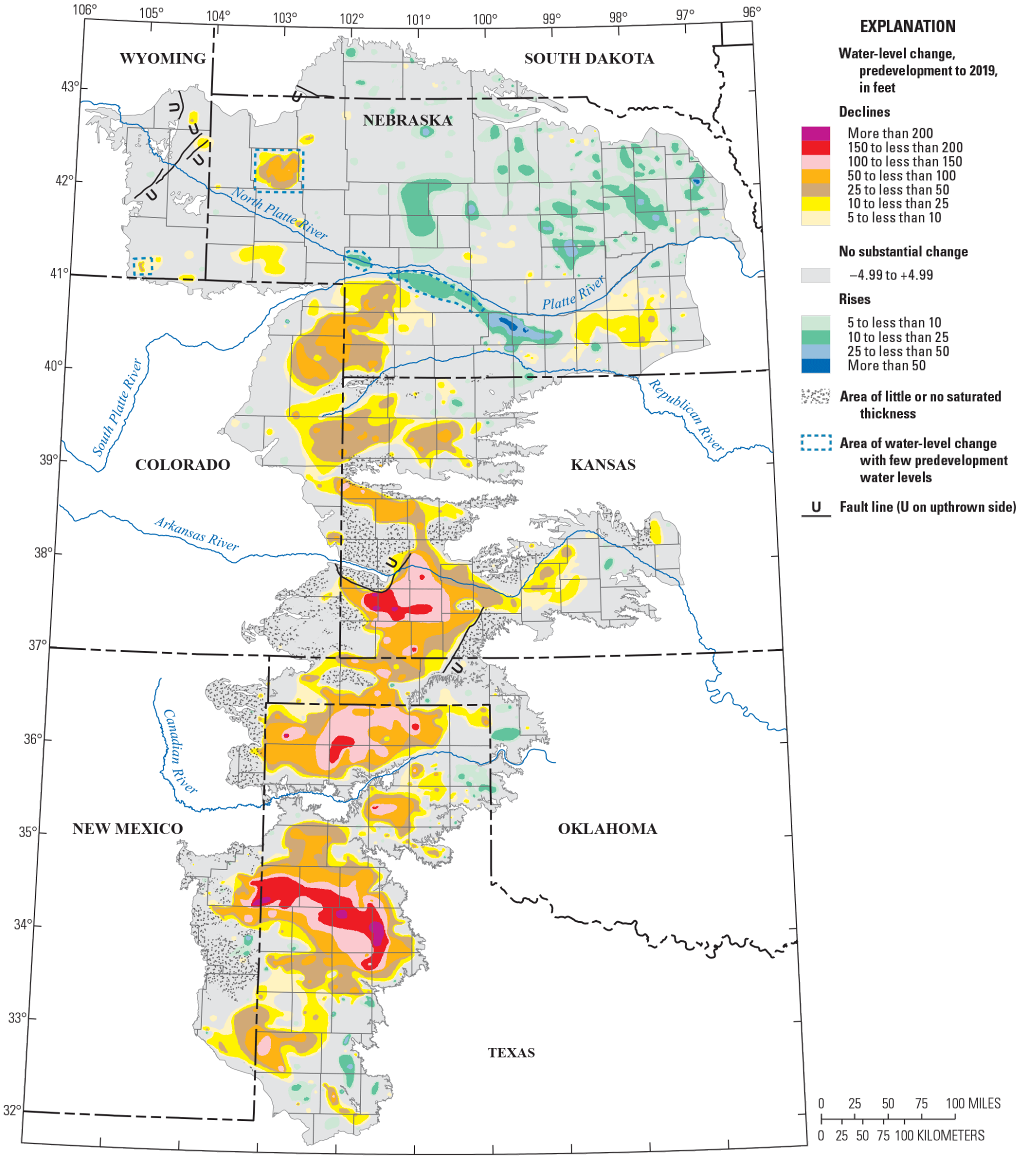
Background

According to the Fourth National Climate Assessment (NCA4), producers who depend on the Ogallala Aquifer for irrigating their crops, such as wheat, corn, and cotton—both for human consumption and livestock feed—are extracting water faster than the aquifer can recharge. The resulting imbalance in the aquifer's water budget means that parts of the Ogallala Aquifer have essentially become a nonrenewable resource (Gowda et al., 2018). The Fifth National Climate Assessment (NCA5) goes on to add that, "Groundwater levels have already been declining in many major aquifers due to lack of management, overpumping, and decreased recharge; increased pumping could accelerate long-term storage losses, but those impacts will depend on the regional factors noted above. Groundwater declines caused by increased drought severity and duration in the future are a concern in many parts of the country." The regional economy of the Great Plains depends almost entirely on agriculture irrigated by Ogallala Aquifer (U.S. Global Change Research Program, 2018; U.S. Global Change Research Program, 2023).

Although in some regions of the aquifer groundwater levels have increased over time, especially in Nebraska, most of the aquifer is in decline. This declining region primarily includes the areas served by the aquifer from southwestern Nebraska and northeastern Colorado southward.

Beginning in the early 1900s, farmers converted large stretches of the Great Plains over time from native perennial prairies to cropland. New farmers who came from Europe without an understanding of basic agriculture—many of them having come from non-farming backgrounds—fell prey to folk tales about "rain follows the plow," and broke out increasing acres of sod into cultivated cropland. As total yields increased, farm commodity prices fell. For those farmers who had borrowed money to fund land or equipment and inputs, this was disastrous. In response, more acres were ploughed into crops, total yields increased accordingly, prices fell further, and a vicious cycle ensued, leading to financial fragility and a natural resource base that was vulnerable to collapse (Egan, 2006).

Drought tipped this unsteady system into collapse during the Dust Bowl of the 1930s. In response, better soil conservation, improved crop cultivation practices, and modernized irrigation techniques—introduced by the U.S. Department of Agriculture and spread by county extension agents—helped to restore the regional economy. A danger posed by climate change is a potential return to these Dust Bowl storm events. The NCA4 points out that global warming, changes in precipitation (such as prolonged drought), along with continued declines in aquifer levels, will lead to agricultural damages that will threaten the food security of millions of people. Furthermore, the economic impacts will be dire: In the early 2000s, the total market value from agricultural production in the region was estimated at a value of approximately $35 billion (U.S. Global Change Research Program, 2018).



Base from U.S. Geological Survey digital data, 1:2,000,000, 2001
Albers Equal-Area projection, standard parallels 29° 30' and 45° 30' N.,
central meridian −101° W.
North American Datum of 1983

Aquifer boundary from Qi (2010); areas of little or no saturated thickness and faults from Gutentag and others (1984) and Cederstrand and Becker (1999a, 1999b); areas of water-level change with few predevelopment water levels from Lowry and others (1967), Luckey and others (1981), Cederstrand and Becker (1999c), and Young and others (2019)

Image: Water-level changes, High Plains aquifer, predevelopment (about 1950) to 2019. Source: https://pubs.usgs.gov/publication/sir20235143/full

The NCA4 addresses these threats to agriculture and the connected economy, and it outlines the range of identified risks and potential opportunities for establishing better resilience within the regions. Those who depend on the Ogallala for irrigation water as well as culinary and municipal water supplies are drawing down the level of the aquifer faster than it can recharge. Some examples of technologies that could help to lessen the impacts from aquifer drawdown include precision irrigation, improvements in telemetry to sense weather conditions and automate irrigation systems accordingly, and plant materials and crop varieties developed to adapt to drought conditions. All of this, however, will not offset the impacts of aquifer depletion if improved technologies are used to increase yields rather than decreasing water demand (Review by Gowda, Paper by Scott, 2019).

Status of the aquifer in the Oklahoma Panhandle

In "The Ogallala Aquifer," Taghvaeian et al., 2017, describe the current status of the aquifer and discuss how the drawdown of the Ogallala Aquifer could potentially affect the people who use it to support agricultural operations. In one subregion that depends on the aquifer, consisting of 14 percent of the total aquifer area, the Ogallala supplies 25 percent of all water demand for agricultural production on irrigated cropland, with a market value of as much as $7 billion. USGS estimates that the level of the entire Ogallala fell by an average of about 15 feet in recent years. In some portions of the area that depends on the aquifer to one degree or another, however, primarily in Nebraska, the level of the aquifer increased. At the same time, there were significant decreases in the level of the aquifer in the southern High Plains. Because the aquifer's recharge rate is very slow, and because alternate sources of water in the region are minimal, to be successful, efforts to extend the lifespan of this valuable resource will have to emphasize demand management. This will require a high degree of coordination between producers, state and federal agencies, and universities. Interest groups in the region have been actively involved in pumped water demand management. One example of their work is the establishment of the Panhandle Regional Water Plan, which was developed in cooperation with other local groups with an interest in protecting the aquifer from excessive use (Taghvaeian et al., 2017).

Taghvaeian et al. (2017), continue on to describe the geology and importance of the Ogallala Aquifer in the region around the Panhandle of Oklahoma. The aquifer is one of the primary sources of groundwater in the area in and surrounding the Panhandle. In some places, the Ogallala is located above consolidated layers of sediment that are 250 million or more years old. In some parts of western Texas, there is a younger geological formation called the Dockum group, which is made up of sedimentary rock. In portions of Panhandle region, there are segments of Dakota sandstone and Morrison Formation. This region has a semi-arid climate with average rainfall of around 20 inches per year. It is not unusual for the region to experience droughts. Because of these dry conditions, the Ogallala Aquifer is particularly important in the area, supplying nearly 100 percent of the region's water supply. Alternate sources of ground and surface water only provide around two percent of the water used in the Panhandle region, and there is only a minimal amount of alternate groundwater flowing in subsurface alluvium, feeding artesian water sources. Furthermore, surface flows in streams and rivers often fall to zero, making surface water an undependable source of water for the area.

Irrigation is the largest use of water in the Panhandle. Based on 2007 crop mix data, there are approximately 230,000 acres of irrigated land in Cimarron, Texas, and Beaver counties, requiring more than 290,000 acre-feet of water per year. This is about 85 percent of the total water demand in the region. Due to increased agricultural production and additional well-drilling, it is expected that demand for irrigation will increase to about 306,000 acre-feet by 2060. The major irrigated crops are corn for grain and wheat, accounting for about three-fourths of the total irrigated area. According to the USDA National Agricultural Statistics Service, the total harvested areas of irrigated corn and wheat in 2012 were more than 106,000 and 65,000 acres, respectively. Grain sorghum ranked lower, with a total irrigated area of about 20,000 acres (Taghvaeian et al., 2017).

The expansion of irrigated agriculture in Oklahoma Panhandle has been a major driving force for economic development and prosperity of this region. However, this growth has come at the cost of declining non-renewable water resources. Since the predevelopment period (prior to 1950), about 3,000 irrigation wells have been drilled into the Ogallala aquifer. The largest number of drilled wells (more than half) were in Texas County, followed by Cimarron, Beaver, and Ellis counties. Hence, it is not surprising that the largest decline in groundwater has been experienced in Texas County. According to the Oklahoma Water Resources Board, water levels in the Ogallala aquifer have declined more than 70 feet in Texas County and more than 50 feet in Cimarron County since predevelopment. These large declines can be attributed to the high density of irrigation wells. The highest rate of adding new wells occurred during the 1960s, with about 107 new wells being drilled every year in three counties of the Panhandle area. The period from 2010 to 2015 was characterized by a major drought in the region. During this five-year period, 226, 95 and 31 new irrigation wells were drilled in Texas, Cimarron, and Beaver counties, respectively. Declines in the level of water in the aquifer were more than 13 feet in Texas County, nine feet in Cimarron County, and four feet in Beaver County over the same period (Taghvaeian et al., 2017).

Irrigation

A primary question that underlays all discussion of irrigation that depends on the Ogallala is the degree to which changes in water-saving irrigation technologies actually lead to reductions in overall water demand. In their study, "Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence," Pfeiffer and Lin (2014) conclude that installation of higher-efficiency irrigation systems does not, in fact, result in decreases in demand for water. They reason that one cause of this outcome is shifts in crop patterns rather than reductions in withdrawals from the Ogallala. Their analysis is based on empirical observations in western Kansas. While a sensitive topic, it is important for planners and leaders to recognize that switching from conventional irrigation systems to high-efficiency systems will not automatically resolve the dilemmas posed by Ogallala Aquifer drawdown rates. This information should be kept in mind when reading any studies related to irrigation patterns and the Ogallala (Pfeiffer and Lin, 2014).

In a similar study that was based on modeling, as opposed to empirical observation, Upendram and Peterson (2007) looked at what the effect would be from upgrading conventional center-pivots to higher-efficiency center-pivots incorporating drop nozzles in terms of demand for pumped water from the High Plains aquifer. The authors created a model to simulate corn and sorghum cultivation with limited irrigation to see whether the upgrade in irrigation technology would result in a decrease in total demand for water. They found that the resulting savings in water demand was minimal and that the reduction in water use could be attributed to prevention of water losses due to reduced droplet evaporation. This study reaffirms the position that upgraded irrigation systems will not solve the groundwater depletion issue for farms and municipalities depending on the Ogallala to provide for their water supply needs.

Possible/Predicted Impacts from Climate Change

A crucial question to ask is, how will changes in climate affect the Ogallala Aquifer and, in turn, all of the socioeconomic systems that depend on water from the aquifer?

In "The Effects of Irrigation and Climate on the High Plains Aquifer: A County-Level Econometric Analysis," Silva et al. (2019) address the impacts of irrigation on Ogallala Aquifer depletion. They point out that the region supplied by the aquifer produced 9% or more of U.S. crop sales as of 2019, and those crops depend on the Ogallala for irrigation. Because withdrawals from the aquifer have reduced the underground reservoir, it follows that impacts will likely be felt at a local level, not just a national level. To evaluate potential impacts, the authors examined aggregated county-level effects on the High Plains Aquifer from groundwater withdrawal for irrigation. They also address related effects from changes in climate and from fluctuations in energy prices. The authors applied economic principles to hydrology to develop mathematical functions that describe the behavior of farmers who irrigate using water from the aquifer as well as to construct a water balance equation for the aquifer. Based on this modeling—in combination with observed values for depletion and recharge rates, 1.24 feet and 0.76 feet, respectively—groundwater depletion would increase by 50 percent if precipitation were to decrease by 25 percent combined with a doubling of days when the temperature is above 36° C (Silva et al., 2019).

According to Dan Lennon (2020) in "Climate Change and the Ogallala Aquifer," while 80 percent of residents and industry in the region served by the Ogallala Aquifer depend on it for their culinary, municipal, and industrial needs, an estimated 94 percent of the water extracted from the aquifer is used for agriculture. Agriculture occupies 80 percent of the land area in this region and as of 2012 was worth an estimated $92 billion in market value. This amount combines sales of both livestock and crop outputs, in nearly equal proportions. In the High Plains subset of the region, grain production—key to the U.S. food and energy supplies—is said to be 100 percent dependent on irrigation water from the Ogallala Aquifer. Without this source of irrigation, existing socioeconomic structures in the area would be significantly altered. According to the USDA's Economic Research Service, approximately 40 percent of corn production in the U.S. goes to feeding livestock, and another 45 percent supplies the ethanol industry (ERS, 2024).

Lennon (2020) goes on to say that the Great Plains region served by the aquifer has already experienced warming effects from global climate change. He states that the average temperature in North Dakota, for example, has gone up faster than in any other of the lower 48 states in the contiguous United States. Specific impacts from climate change are expected to be different from one plant hardiness zone to another, due to differences in their respective latitudes. By the year 2050, it is anticipated that the number of days exceeding temperatures over 100°F in the Northern Plains will be twice their current number. Accordingly, a major threat from climate change is the potential for severe reductions in agricultural yields. Because the region served by the aquifer is a critical source of food for both the U.S. and nations around the world, if predicted effects from climate change are realized—increased speed of depletion of the aquifer in particular—they will impact food markets and basic food supply on a global scale.

In the article, "As the Climate Warms, Could the U.S. Face Another Dust Bowl?" Nathaniel Scharping (2021) points out that the Fourth National Climate Assessment, released in 2018 warns that average temperatures in the southern portion of the Great Plains are expected to increase by as much as 5.1 ^{o}F and, potentially, by 8.4 ^{o}F by 2100, in comparison to the average temperature from 1976 to 2005. Even without reaching these extreme increases in temperature, stresses on the Ogallala Aquifer—which provides irrigation water to an estimated 30 to 40 percent of all irrigated lands within the region—will result in a possible depletion of 70 percent by around the year 2070. Based on these modeled outcomes, a continuation of past trends in aquifer drawdown would be expected to result in water shortages that would have widespread impacts on food production (Scharping, 2021).

In "Possible Impacts of Global Warming on the Hydrology of the Ogallala Aquifer Region," Rosenberg et al. (1999) state that, "the Ogallala or High Plains aquifer provides water for about 20% of the irrigated land in the United States." Because there has been no compensation for irrigation withdrawals from the aquifer since the explosive growth of agricultural production in the region during the post-WWII era, the authors of this paper draw parallels between the drawdown of the aquifer and overall climate change itself. Specifically, temperature and precipitation trajectories in many climate models indicate that the region served by the aquifer will experience warmer and drier conditions at a rate that increases at the same time as the level of the aquifer decreases. The authors apply multiple general circulation models to a subregion comprising the Missouri and Arkansas-White-Red water resource regions to project the possible effects of climate change on the level of the Ogallala Aquifer and on socioeconomic activities in the region. These impacts are expected to occur because of net aquifer recharge, which is predicted to be negative over coming decades due to lower precipitation, higher demand, and insufficient ground water recharge. The authors included effects from expected changes in atmospheric CO_2 concentrations to predict possible effects from CO_2 on plant growth and plant water demand. In some subregions, precipitation is expected to decrease, and in those regions, aquifer drawdown is expected to increase accordingly. In other subregions, precipitation is expected to increase, and, as a result, aquifer drawdown in those subregions is projected to be slower overall. Higher CO_2 levels have a beneficial effect on plant growth—all else being equal—so in places where overall conditions are favorable for crop production, marginally higher crop yields from increased CO_2 concentrations would be predicted to occur. Furthermore, benefits from increased CO_2 concentrations would be expected to increase the rate of recharge in the aquifer if there were no climate change occurring. When predicted impacts to temperature and precipitation are added to the model, however, net withdrawals from the aquifer increase in each of the three models examined by the researchers (Rosenberg et al., 1999).

Based on county-level data covering the period from 1960 to 2007, in "The Effects of Irrigation and Climate on the High Plains Aquifer: A County-Level Econometric Analysis Adaptation Response," Silva et al. (2019) estimated that irrigation contributes an average increase of 51 percent in total biomass yield across counties in the region served by the Ogallala Aquifer. Based on this estimate, the average gross annual marginal value of irrigation would be approximately $196 per acre in 2007 terms with an estimated total annual value of around $ 3 billion in marginal revenue within the region supported by water from the aquifer.

In "What Is the Use Value of Irrigation Water from the High Plains Aquifer?", Garcia Suarez et al. (2019) projected that crops exposed to a sustained temperature above 91.4 ^{0}F for as little as 24 hours would cause a 3 percent loss in biomass yield, which would be valued at around $10 per acre using a 2007 market value (Garcia Suarez et al., 2019).

Agricultural Sustainability

In "The Declining Ogallala Aquifer and the Future Role of Rangeland Science on the North American High Plains", Rhodes et al. (2023) address the need to for better management decisions in how the aquifer is used. For the Ogallala Aquifer to continue to provide water for food and other ecosystem services to the region, those who manage the aquifer region must develop a shared vision that integrates the expertise of many disciplines, including demographics and ecosystems services among others. For the aquifer to be managed in a sustainable way, it will be important for conservationists to make decisions within the context of interdisciplinary social-ecological frameworks (Rhodes et al., 2023).

In "Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas," projections to 2110, Steward et al. (2013) discuss the degree to which long-term aquifer depletion comprises a threat to sustainable agriculture and food production within one of the most critical food-growing regions of the U.S.

According to the authors of the paper, the Kansas subregion of the area that depends on the High Plains Aquifer for agricultural production produces the highest market value of any congressional district in the country. Because the aquifer provides 30% of the nation's total groundwater for irrigation, it's important to monitor the level of water remaining in the aquifer today and to project the future status of the aquifer. According to the authors of the study, so far, 30% of the groundwater in the High Plains Aquifer has already been pumped. They project that an additional 39% will be pumped over the next 50 years if present trends persist. The aquifer's recharge rate is currently 15 percent of pumping, and it would take something in the range of 500 to 1,300 years to refill the aquifer if it is allowed to be completely drained, assuming the rate of recharge doesn't change during that time period (Steward et al., 2013).

While decreases in pumping rates are predicted to occur in coming decades, there is also a possibility that increases in agricultural production could negate the benefits from reductions in pumping. If irrigation from the aquifer were to be reduced by an average of 20 percent today, agricultural output from the region would decline to the levels where they were around two decades ago. This would, however, extend the projected timeframe for peak agricultural output for the Kansas portion of the region served by the aquifer out to the 2070s. Potential agricultural production after that decade could be even greater than projected if the current depletion rate were to be reduced even more and if irrigation efficiency were to be increased today: water saved now means higher potential agricultural output in the future. According to the study, should steps toward a higher degree of conservation of the aquifer not be taken in the present day, the ultimate result would be a collapse of production in the long-term and a significant threat to the future sustainability of food supplies provided by this region. If pumping from the aquifer were reduced by 80 percent, the net withdrawal from the water body would come close to mirroring the natural rate of recharge. Leaving more water in the aquifer today would result in increased agricultural output in the future because it is anticipated that increases in irrigation efficiency and, potentially, lower water demand by crops could make future crop production much less water dependent. To make this better future feasible, reductions in the drawdown of the aquifer need to occur now and into the near-term future. Future food security depends on irrigation decisions made today (Steward et al., 2013).

In another paper that addresses irrigation in the Great Plains, S. R. Evett et al. (2020) discuss the history of groundwater-based irrigation in the region. Their paper, "Past, Present, and Future of Irrigation on the U.S. Great Plains," examines how water supply in the region has changed over time and discusses how changes in land use, technology, and agronomy—among other topics—have affected the High Plains Aquifer. The study covers the period from 1900 up to the present. In particular, the paper focuses on irrigation efficiency, the relationship between crops and water demand, and the overall agricultural productivity provided by irrigation water. Improvements in irrigation equipment have improved water use efficiency and have increased agricultural output from the Great Plains region. The paper also addresses how water storage in the High Plains Aquifer has changed over time.

The aquifer has continued to be the main source of irrigation water for the Great Plains region, although not all sub-regions are as dependent on the aquifer as others. Nebraska, for example, is much less dependent on the High Plains Aquifer for crop irrigation in spite of increases in irrigated cropland over the decades since groundwater pumping began. While increases in irrigation efficiency have contributed to this lower dependence, regulation and a focus on aquifer recharge in the Nebraska Sand Hills region and from rivers in Nebraska have also contributed to Nebraska's better balance between recharge and withdrawal, as compared to the other states that depend on the aquifer. In comparison to Nebraska, western Kansas, eastern Colorado, and the Oklahoma and Texas Panhandles are in a much less secure position. Because these regions draw down the aquifer at a rate that exceed its recharge capacity, the aquifer is declining there.

Over time, irrigation technology has improved, and irrigation water management practices combined with changes in crop varieties have made crop production in the Great Plains less dependent, to a degree, on mined groundwater. It is possible that these kinds of positive changes will continue into the future as government specialists, land grant universities, and private industry are expected to continue their efforts to increase irrigation efficiency and to find ways to increase the productivity of irrigated crop lands. The authors of the study also anticipate that changes in public policy will result in additional regulations that will reduce aquifer drawdown by discouraging groundwater consumption and encouraging improvements to on-farm irrigation efficiency. They state that there is reason to believe that the rate of depletion of the aquifer's stored water can be reduced, meaning that irrigated crops can be sustained in the region further into the future than is currently projected based on past rates of depletion. They conclude that irrigation will be economically important in the region for some time to come rather than having to be largely curtailed as some research has predicted. The authors state that retaining irrigation on a sustainable basis is vital to future crop production in the Great Plains region because pumped irrigation water provides much higher productivity than would be feasible if farms depended on precipitation with no groundwater pumping. Slowing the depletion rate for the aquifer will ensure that food production in this critical region can continue at a sustainable level and can set an example that could benefit similar agricultural regions worldwide (Evett et al., 2020).

In "Optimizing Ogallala Aquifer Water Use to Sustain Food Systems," Gowda et al. (2019) discuss the degree to which groundwater pumping from the Ogallala Aquifer has increased since the 1950s. Pumping at a rate that exceeds aquifer recharge has created a situation in which water levels have declined over time in various regions of the aquifer. Extending the availability of irrigation water from the aquifer could potentially be the most significant challenge in natural resource management in the U.S. at the present time, and impacts from how this challenge is met could have far-reaching effects on food security at a global level.

In the region that depends on the High Plains Aquifer, a complex system connecting groundwater, agriculture, industry, and socioeconomics has evolved over time. There are other places in the world where this type of complicated network results in similar dependencies and threats to sustainable food production in the future. If management changes in the Ogallala region manage to extend the life of the aquifer for crop production purposes, they can be used as an example that other arid regions around the world can learn from. The unique geology and hydrological structures in the region, combined with climate patterns and events above the subterranean reservoir, have led to expansive grain cultivation punctuated by periodic adverse impacts to agricultural output, such as was experienced during the Dust Bowl in the 1930s and during prolonged drought in more recent times. Irrigation water drawn from the aquifer has tempered the effects from increasingly varied drought patterns. Current predictions indicate that the region that depends on the aquifer will experience drier conditions in general, and there is a potential for longer and more severe droughts over time. Should this prediction turn out to be accurate, pressure on groundwater drawdown will increase in the future (Gowda et al., 2019).

While the Gowda et al. (2019) note the importance of conserving the aquifer's supply of irrigation water, they point out that there is no unified policy that protects the aquifer from excessive depletion. Governing policies vary from state to state, as does how legal ownership of the water supply contained in the aquifer. In some regions, groundwater is a public resource, owned by the state, and in other regions served by the aquifer, groundwater is private property. Similarly, policies on water conservation and approved irrigation technologies also vary. Because of these differences across the region, no single policy or set of policies will be likely to successfully address the threat posed by aquifer drawdown and rapid depletion. To solve these problems, government agencies, producers, and university specialists—as well as the irrigation industry and the agricultural industrial complex—will have to develop a range of strategies. It will take a diverse set of disciplines and a flexible approach to regulation across the region to decrease the rate of drawdown and extend the lifespan of intensive and essential crop production in the region. The long-term sustainability and security of the U.S. food supply depend on accomplishing this daunting task (Gowda et al., 2019).

In their paper, "Policy, Technology, and Management Options for Water Conservation in the Ogallala Aquifer in Kansas, USA," Steiner et al. (2021) focus on the importance of innovations in water policy. In particular, they focus on how promoting the adoption of efficient irrigation and encouraging innovations in how water is managed are in slowing down the rate at which the aquifer is being depleted in Kansas (Steiner et al., 2021). In Kansas, water can be owned by either the State or by individuals. Water management falls under the provisions of the 1945 Water Appropriation Act. As is the case in multiple western states, water allocation and use are regulated based on the prior appropriation doctrine. In 1972, the Groundwater Management District (GMD) Act provided openings for using local input on a greater level than before in the development of policies related to water management. There are now five GMDs in Kansas. Three of them affect management of the Ogallala Aquifer. Water policy in Kansas has a long history of looking for ways to reduce the rate of depletion of the Ogallala aquifer (Table 1 in that text), beginning in 1945 with the Kansas Water Appropriation Act. In 1972, Kansas passed the state-level Groundwater Management Act, followed in 1978 by the passage of policy creating groundwater use control areas in the state. Three years later, in 1981, both the Kansas Water Office and the Kansas Water Authority were established. Legislation establishing minimum streamflow levels was passed in 1984. A temporary measure to assist in the permanent retirement of water rights was enacted in 2006 and expired in 2022, and in both 2012 and 2015, additional legislation was passed to further encourage and support water conservation measures. Details on the passage of each of these policies is included in the Steiner et al. (2021) paper.

In effect, Kansas's water policy both establishes the State's authority to regulate water use and gives local water authorities the leeway to incorporate water conservation into their operations in ways that reflect local circumstances and needs. Rather than simply cutting off access to water, the State has emphasized using a wide range of technological innovations, including irrigation systems, soil moisture monitors, and improved agronomic practices to reduce water demand without severe economic consequence.

The highest level of success has been seen where agricultural producers and water managers have established Local Enhanced Management Areas (LEMAs). Under LEMAs, not only has groundwater depletion been either reduced or eliminated, but some farmers have also been able to maintain their previous level of net income. Irrigators under LEMAs and other conservation programs have met or exceeded their water conservation goals. By working together with private landowners, federal agencies, universities, and other organizations, the State of Kansas has fostered a transfer of improved agronomic technologies and informed water management to irrigators in the state. This cooperative approach to water management has allowed Kansas to move closer to sustainable use of the Ogallala aquifer. (Steiner et al., 2021).

As did Steiner et al. in 2021, in their paper, "2023 Status of the High Plains Aquifer in Kansas," Whittemore et al. (2023) address water management in areas of Kansas that depend in part on groundwater to meet irrigation needs. According to the authors, and aligning with the literature on the subject, the most important groundwater resource in Kansas is the High Plains aquifer, which includes the Ogallala. The 2023 Annual Report of the Kansas Water Authority expressed concern about the depletion of the Ogallala aquifer and outlined the critical need for stopping this depletion. The authors discuss the long-term goals for helping to extend the life of the aquifer by establishing and then using measures of the health of the High Plains aquifer. Such measures can be used to measure progress toward stabilization or restoration of groundwater levels in the High Plains aquifer. The 2023 report is an update of previous reports on the status of the aquifer's depletion using groundwater demand data through the year 2022 plus data on water levels through the winter of 2023 (Whittemore et al., 2023).

Three ground-water management districts were established in the western third of Kansas, which is over the Ogallala portion of the High Plains aquifer. Change in climate conditions will significantly impact the possibility of sustainably managing the aquifer. Over the past 25 years, the Kansas Geological Survey has led a program that monitors the level of water in the aquifer. Close monitoring is important: in Kansas there are more than 35,000 wells with legal water rights, and around 88 percent of those wells are being used for irrigation. Since the establishment of groundwater pumping, starting in the 1940s, the Ogallala portion of the aquifer in Kansas has been significantly depleted. In some places, the water level has fallen to the point where less than 40% of the original aquifer is left. In their paper, Whittemore et al. (2023), go on to provide an in-depth account of conservation measures that have been taken to reduce depletion rates in the regions served by the Ogallala and quaternary regions of the HPA. To briefly summarize, various conservation programs combined with retirement of agricultural use has resulted in reductions in depletion ranging from 5 or 6 percent—at the lower end of the continuum—to as high as nearly 50 percent in some parts of the aquifer. These gains in conservation and reduced demand for pumped aquifer water are expected to result in a longer life for the aquifer as an essential source of water for irrigation and municipal uses (Whittemore et al., 2023).

Federal Agency-funded Efforts

In 2021, the USDA sponsored a two-day online summit on the Ogallala Aquifer. In "Ogallala Aquifer depletion: Situation to manage, not problem to solve," Ledbetter (2021) summarizes the topic of discussion and the conclusions reached during the summit. The article, published in AgriLife Today, concludes that the keys to solving the dilemmas faced by aquifer managers and users are "courage, experimentation, [and] voices needed to drive change" (Ledbetter, 2021).

The summit was led by the Ogallala Water Coordinated Agriculture Project, an effort of Colorado State University and Texas A&M AgriLife with financial support from the National Institute of Food and Agriculture at USDA. Partnering with the Kansas Water Office and the Ogallala Aquifer Program, which is funded by the Agricultural Research Service, Texas A&M planned this event with support from organizations and individuals from all of the states that overlie the aquifer.

According to John Tracy, director of the Texas Water Resources Institute, the factors that determine how the aquifer is managed and used—and that could lead to positive change—include developments in technology, socioeconomics, improvements in infrastructure, and so on. Some of the messages delivered during the summit included encouragement to aquifer users and managers to embrace change in the interest of sustainability, a recognition that adaptation over time will be more beneficial than reactive decisions, and that shared learning amongst various governmental and other organizations can lead to better outcomes for the aquifer and the people who depend on it. In addition, presenters pointed out that better data and improved access to information can lead to better policy decisions and improved outcomes for producers who depend on the aquifer for irrigation water in comparison to what will likely occur if current condition in data acquisition and management persist into the future.

The summit also focused on the essential nature of water and that there is a minimum amount of water needed to support rural economies, industry, and the economic structures that have developed within the Ogallala Aquifer region. While many industries benefit from the aquifer, farmers are the most-dependent on it and—at the same time—they are the greatest drivers of economic activity in the region because they can produce a high level of agricultural output with the water they draw from the aquifer. Making farms sustainable into the future will be a key to maintaining economic viability for the communities and regional economies that rely on both agricultural production and fundamental operational needs that are made possible by the aquifer. In addition, the summit identified the need to engage with younger people in the region to help them understand the critical nature of the aquifer and the need to develop a "conservation mindset" that will lead to better decisions in the future. Today's youth will need to know how to work effectively in coming years with others who also depend on the Ogallala for meeting their basic needs.

Improving future prospects for both the aquifer and the people who depend on it will require changing how people think about the aquifer. For people to make good choices about how to manage, use, and protect the aquifer, it will be necessary to make them aware of the aquifer, stimulate interest in it, and educate them regarding its critical role in their lives and the economies that are built on a reliable supply of water. Developing leadership characteristics amongst the younger people whose generations will determine the future of the aquifer will be a critical aspect of ensuring that the water they and subsequent generations will need will be available to them.

Schipanski et al. (2021) participating in the Ogallala Water Coordinated Agricultural Project (CAP)—an effort led by Colorado State University and that was funded by USDA's National Institute for Food and Agriculture—(as summarized in, "Collaborative, engaged research for groundwater conservation and sustaining agricultural communities in the Ogallala aquifer region, Ogallala Water Coordinated Agricultural Project (CAP) Executive Summaries,") focused on the many challenges facing the region served by water from the Ogallala. They found that no single solution can successfully address the multiple, complex issues that dependence on groundwater in the region have created over the last 100 or more years. That being said, however, applying a broad range of strategies and management tools could help to create both climate-resilient and potentially profitable systems that would supplement or even replace the current systems that are not sustainable because they depend on a finite supply of mined water.

The CAP team found that water managers in the Ogallala region could benefit from more-flexible policies at the state level as well as from gaining access to both state and federal programs that would reward better groundwater stewardship. Programs could include voluntary agreements that would limit pumping, additional options that would support reductions of risk through better crop insurance programs, and programs that would encourage farmers to optimize their profits rather than focusing on maximizing crop yields, which could extend access to the aquifer and support rural economies and communities in the future (Schipanski et al., 2021).

Another aspect of this project is the proposed development of climate-related datasets in support of the CAP effort. Kansas State University's climate team, led by Dr. Xioamao Lin, contributed to the CAP by acquiring and storing data on historical and projected climate conditions in the Ogallala region. These data are essential to developing integrated models and completing analysis while also facilitating the creation of climate-based tools to assist farmers in making better production and farm management decisions. This group produced multiple publications including research on the "spatial and temporal variability" of weather conditions that ultimately determine the level of groundwater pumping from the aquifer. These climate datasets were made available to the public in 2021 through the Ogallala Water Data Portal. This interface provides information to the public regarding the objectives of the CAP and the overall efforts of its participants and partners.

The CAP project was a large-scale effort with many organizations and individuals contributing to its overall objectives. The summit held in 2021 and the papers and other data products that came out of it comprise a rich source of information regarding the Ogallala Aquifer and possible strategies for obtaining better outcomes in the future than will be realized if the status quo—an unsustainable drawdown that will be further augmented by climate change, if models are accurate—is left in place.[1]

In a connected effort, under a USGS cooperative agreement with the South Central Climate Adaptation Science Center, Colorado State University developed an "Ogallala Data Directory," to assemble data about the aquifer in a wide range of types and formats to provide user-friendly information that would help aquifer users, researchers, and managers in all aspects of analyzing the aquifer's status and future as well as informing decisions about aquifer management. Because the Ogallala is a critical element of human and non-human ecological systems in the region, knowing what is happening with the aquifer in

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[1] In 2024, after this paper was first drafted, another Ogallala Aquifer summit was held. The proceedings from the 2024 summit are not included in this writing but should be considered by readers as a potential additional source of information on the status and future of the aquifer.

real time, as well as accurately modeling what the future will hold for the aquifer under different management scenarios, will largely determine whether decisions will lead to the desired outcomes or not. Data from this directory served the needs of the CAP in terms of assembling metadata. The metadata do not tend to be user-friendly. There is still a great deal of improvement needed in terms of adding more metadata and to make the system more easily accessible to interested parties. More can be done in the interest of fulfilling the potential of the vision for establishing a broad, far-reaching data repository that would provide sufficient information to those interested in the Ogallala and its future (USGS, 2018).

Regional water managers have requested scientific information to assist in the planning process for future use and management of the aquifer. Much of this information is currently available but is unorganized and difficult to access. This project will organize and synthesize information on datasets from the Ogallala Aquifer region into a single, searchable database. The Ogallala Data Directory will act as a virtual “phone book” of Ogallala region data. It will allow users to easily locate and integrate datasets relevant to their area of interest, and to address emerging issues within the region, such as the effects of climate change and reduced aquifer water availability on human health or ecosystem services. Researchers will also create targeted visualizations using the data in the directory, to display information such as the economic impacts of aquifer depletion for land management agencies and agriculture. The directory will be built with the help of Colorado State University’s Natural Resources and Ecology Laboratory and an advisory committee of stakeholders from the region who will provide input and feedback to ensure that the final product is both useful and user-friendly. This project will provide water resource managers in the Ogallala Aquifer region with easy access to information about the aquifer that will support science-informed water management decisions in the Great Plains region.

Implications and Conclusions

In, “Structural impediments to sustainable groundwater management in the High Plains Aquifer of western Kansas,” Sanderson and Frey (2014) pinpoint what they think is the crux of the problem of the Ogallala Aquifer, namely that the aquifer is a common resource, managed by an array of disconnected, independent government bodies and individual farmers, ranchers, corporations, and anyone else who has a right to draw from the aquifer without consultation or coordination with others who are affected by their decisions. Although many coordination efforts have been initiated and attempted over the years, as evidenced by the array of literature discussed above, the problem still remains that the level of the aquifer is dropping in some regions and that it is a common resource managed in disparate ways across the states, counties, municipalities, and private properties that overlay the Ogallala.

The authors point out that western Kansas has been one of the most crucial food sources for the U.S. and, according to them, for many regions of the world. Because this area is generally arid, agricultural production there has depended on mined groundwater rather than on annual precipitation and surface water sources. It is projected that the aquifer will be 70 percent depleted by the year 2070. This means that crop production in this region is, by definition, unsustainable. Problems created by depletion of the aquifer have been a focus of attention from many decisionmakers at every level of government for multiple decades and have resulted in multiple new policies and efforts to better manage this essential resource. The authors of this study explain that there are deep, structural origins of how the aquifer has been used and managed.

They point to structural human ecology theory combined with observed data from Southwest Kansas to demonstrate that crop production in the region is based on a fundamentally incompatible set of demands that create tradeoffs between farmers and others who depend on the aquifer (Sanderson and Frey, 2014).

In this overview we have examined a range of publications on the topic of the Ogallala Aquifer. These papers and reports connected the aquifer's history, its current status, and predictions about its future to climate change and ways in which increasingly stochastic climate conditions and conflicts between current and future demands on the aquifer mean that the ways in which people manage and use the aquifer will be required to change at one point in time or another. This will happen either because people choose to extend the life of the aquifer or because the aquifer is depleted and can no longer provide life-sustaining water to the socioeconomic systems that depend on it.

Near-term changes in technologies, infrastructure, agronomic practices, cultural habits, and acceptance of geophysical limits can contribute to an improved outlook for the Ogallala Aquifer as a primary source of water in support of agriculture as well as meeting urban and suburban demands in the future. These options comprise a significant challenge but offer hope of achieving a sustainable future for the region. Hopefully, these challenges will be successfully met to help safeguard future agricultural output from the region.

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