KANSAS GEOLOGICAL SURVEY

2023 Status of the High Plains Aquifer in Kansas

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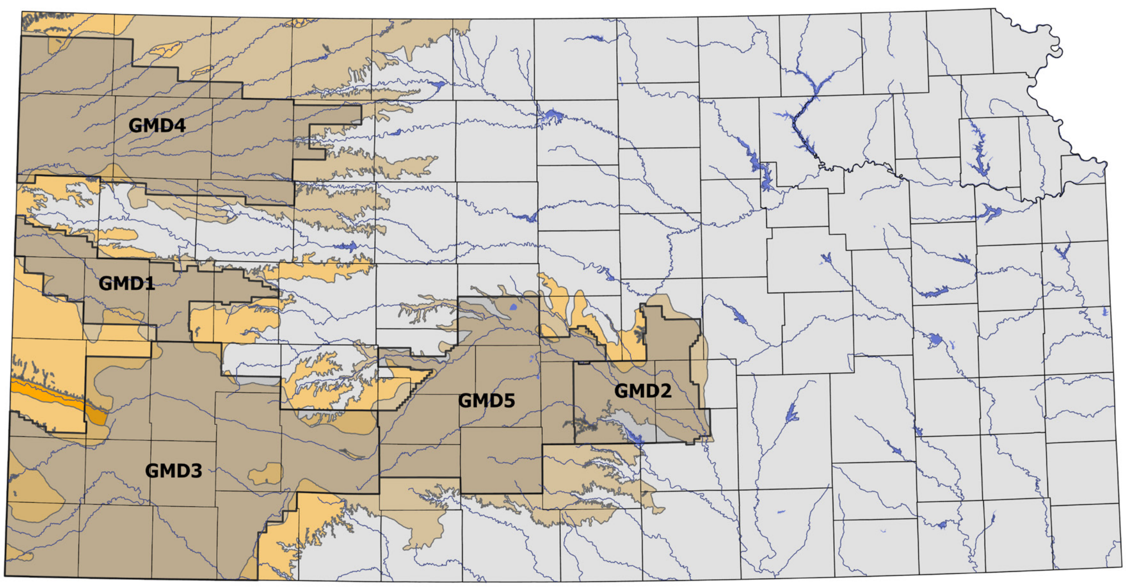

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INTRODUCTION

The High Plains aquifer (HPA), which includes the Ogallala aquifer, is the primary source of water for western Kansas and economically is the most important groundwater resource in the state. This aquifer and the river-reservoir systems located principally in eastern Kansas are identified as the two most critical water resource components of the state's Long-Term Vision for the Future of Water Supply in Kansas (Kansas Water Office, 2015). Two of the keys to implementing the long-term vision are clearly defining the resource conditions and issues, and reviewing and evaluating progress toward achieving the vision's goals. The Kansas Water Office updated the Kansas Water Plan in 2022 (Kansas Water Office, 2022). The first of the plan's guiding principles is "Conserve and extend the High Plains aquifer." In December 2022, the Kansas Water Authority (KWA) voted to place statements in its 2023 Annual Report to the Governor and Legislature (Kansas Water Authority, 2023) concerning the "critical depletion of the Ogallala aquifer." The first of these is "The policy of planned depletion of the Ogallala aquifer is no longer in the best interest of the State of Kansas." The statements also indicate that a "collaborative process is needed to establish data-driven goals, metrics, and actions to halt the" aquifer decline and that the process should engage state agencies, committees, stakeholders, and the KWA. This Kansas Geological Survey (KGS) publication addresses key elements of the long-term vision goals, updated water plan, and annual report to the governor by providing an assessment of the recent and current resource conditions of the HPA that can be used to evaluate progress toward sustaining or prolonging the life of the aquifer.

The KGS published a previous report on the status of the HPA in 2018 that was based on groundwater use data for 1996–2016 and groundwater-level data to winter 2017 (Whittemore et al., 2018). This report is an update of the aquifer status that evaluates water-use data to 2022 and water levels to winter 2023.

The HPA in Kansas covers most of the western third and much of the south-central portion of the state (fig. 1). The area in the western third of the state is known as the Ogallala part of the aquifer; three groundwater management districts (GMDs) operate in this area: Western Kansas GMD1, Southwest Kansas GMD3, and Northwest Kansas GMD4. In the south-central, or Quaternary region, Big Bend GMD5 and Equus Beds GMD2 encompass the Great Bend Prairie and Equus Beds portions of the aquifer, respectively. Although the Ogallala and Quaternary region aquifers are both composed of sand and gravel interbedded with silt and clay, differences in climatic conditions, overlying soil types, and depth to water translate into large differences in the prospects for sustainability. The range in average annual rainfall over the Ogallala region is 17–23 inches compared to 23–35 inches over the Quaternary region.

The availability of high-quality water-level and water-use data for the HPA in Kansas during the last two and a half decades makes it possible to provide a sound assessment of the aquifer status. The KGS and the Division of Water Resources in the Kansas Department of Agriculture (KDA-DWR) each winter measure groundwater levels in approximately 1,400 wells (primarily irrigation wells) (fig. 2). The KGS has been leading the water-level program since 1996. Kansas has more than 35,600 wells with active water rights; most of these (27,613) overlie the HPA, and 24,179 (approximately 88%) of them are used for irrigation (as of September 10, 2023) (fig. 3). Not all of the wells overlying the HPA produce only from the HPA. Based on an analysis of KDA-DWR information for the wells, 88% of the wells are estimated to yield water from the HPA and 8% from both the HPA and underlying bedrock units such as the Dakota aquifer; the rest produce from the bedrock units.

Each water right is required to report water use yearly. In 2022, 99.6% of the wells in the GMDs that reported some amount of water usage did so using totalizing flow meters. Both water-level and water-use data are reviewed for quality to ensure accurate data.

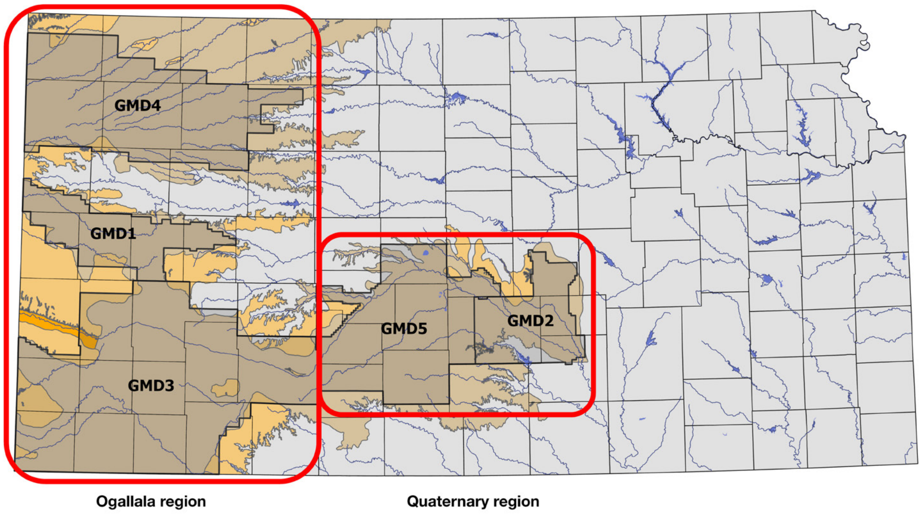

Figure 1. Location of the High Plains aquifer, Ogallala and Quaternary regions, and groundwater management districts in Kansas. The tan area indicates where substantial aquifer thickness existed prior to irrigation development. The light orange areas around the fringes of the main aquifer indicate sediments of similar characteristics but little groundwater. The deep orange along the Arkansas River in far western Kansas is the Arkansas River alluvial aquifer and the paleovalley aquifer to the south of the river.

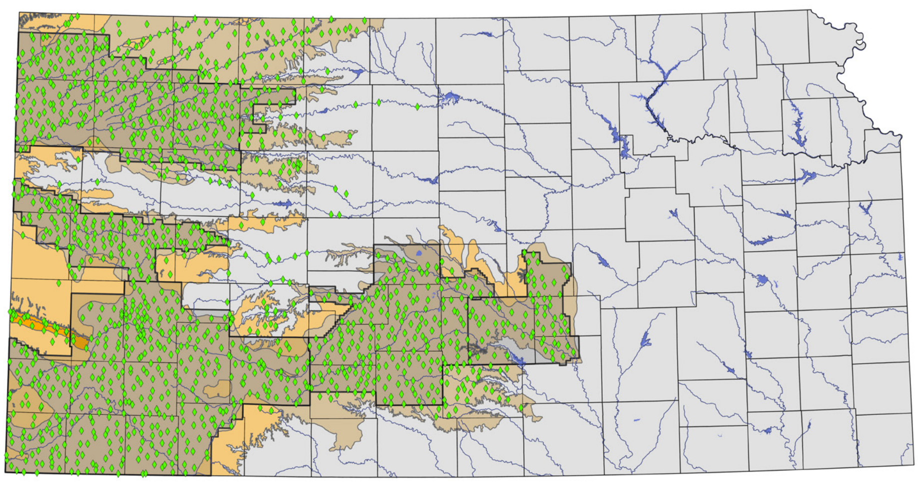

Figure 2. Locations of about 1,400 wells measured each winter in the High Plains aquifer by the KGS and KDA-DWR.

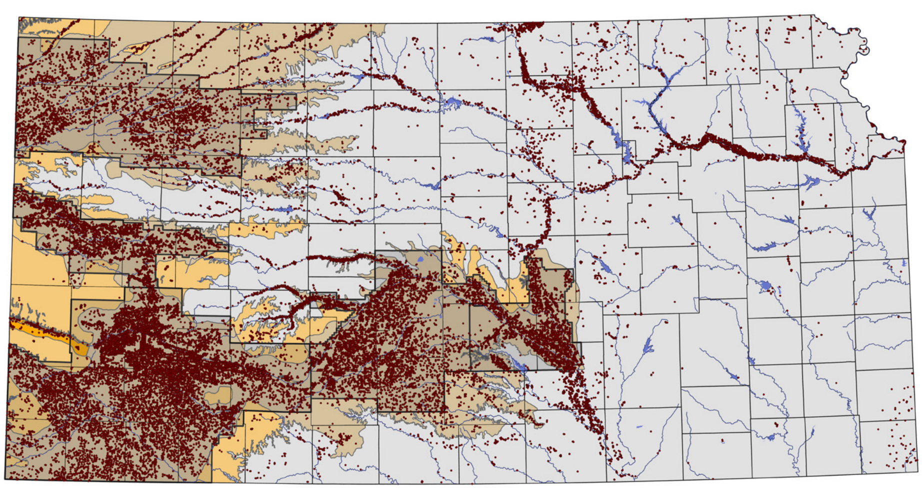

Figure 3. Locations of wells that have active appropriated or vested water rights in Kansas.

OGALLALA REGION OF THE HIGH PLAINS AQUIFER

Variations in Groundwater Levels and Groundwater Use

Groundwater levels have appreciably declined over the Ogallala region of the aquifer since the onset of substantial irrigation pumping (1940s to 1950s in most areas). The water levels have dropped so much in some areas of the Ogallala region that less than 40% of the original aquifer thickness remains (fig. 4).

The total declines in groundwater levels in the Ogallala region since predevelopment to the average water levels during 2021–2023 are 28 ft, 51 ft, and 101 ft for GMDs 4, 1, and 3, respectively. These declines represent a loss in aquifer thickness of 25%, 61%, and 45%, respectively. The average aquifer thicknesses remaining in GMDs 4, 1, and 3 are 75 ft, 32 ft, and 142 ft, respectively. During the 27 years for which the KGS has determined water-level changes in the HPA (1996–2022), the trends in the average annual water-level decline and the cumulative water-level declines (figs. 5 and 6, respectively) for these three GMDs have been the following (to the nearest tenth of a foot):

- GMD4: steady decline rate; average -0.5 ft/yr; cumulative -13.1 ft
- GMD1: steady decline rate; average -0.6 ft/yr; cumulative -15.0 ft
- GMD3: slightly increasing rate of decline; average -1.8 ft/yr; cumulative -47.2 ft

The above values are based on all wells in the HPA for which water levels have been measured for the period (see Appendix 1), excluding wells that are screened only in the bedrock, such as the Dakota aquifer. These values are also based on revisions to the data used in the first HPA status report (Whittemore et al., 2018). Those revisions are described in Appendix 1.

The annual variation in the water-level decline rates (fig. 5) and the change in the slope of the curves for the cumulative change (fig. 6) are directly related to precipitation, which is the primary driver of the annual amount of irrigation water pumped and the resultant water-level changes. This relationship can be seen in the similar patterns in the rainfall for the three western climate divisions in Kansas (fig. 7) and the annual water-level changes in each of the GMDs that lie within those divisions (fig. 5). Precipitation is represented by the Standardized Precipitation Index (SPI) in fig. 7; the SPI is a climatic index that quantifies precipitation surpluses and deficits and is normalized by long-term records (McKee et al., 1993).

During 1996–2022, the total annual water use generally declined for the three GMDs in the Ogallala region (fig. 8); the following trends are based on the 1996 and 2022 endpoints of the best-fit lines through the data:

- GMD4: decline of about 14.4%
- GMD1: decline of about 49.4%
- GMD3: decline of about 18.7%

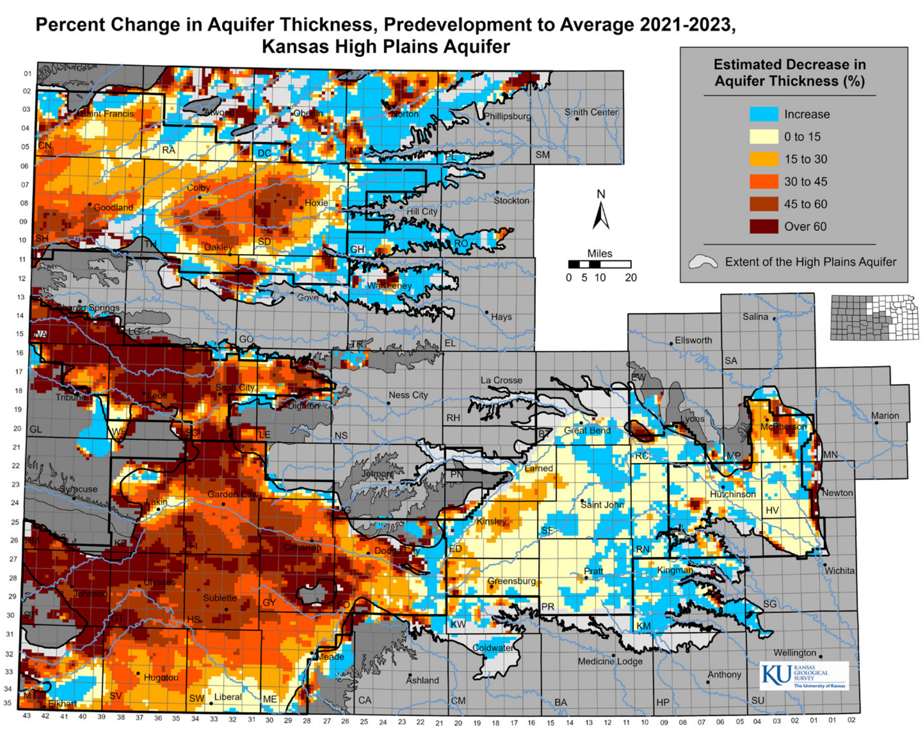

Figure 4. Percent change in aquifer thickness in the High Plains aquifer from predevelopment to the average for winter water-level conditions for 2021–2023. The areas of increase in the western third of the state are areas of thin aquifer with little to no groundwater development and are not of practical importance. The areas of dark gray have similar sediments but little groundwater.

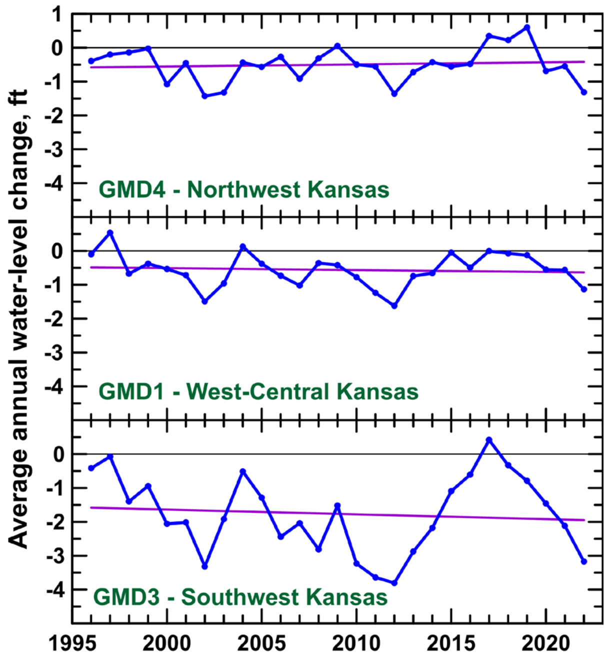

Figure 5. Average annual water-level change for the three GMDs in the Ogallala region of the High Plains aquifer. The values are for all wells in the HPA measured each winter from 1996 on (see Appendix 1 for further details). The best-fit trend in the data is shown as a purple line, and the line for zero change is black.

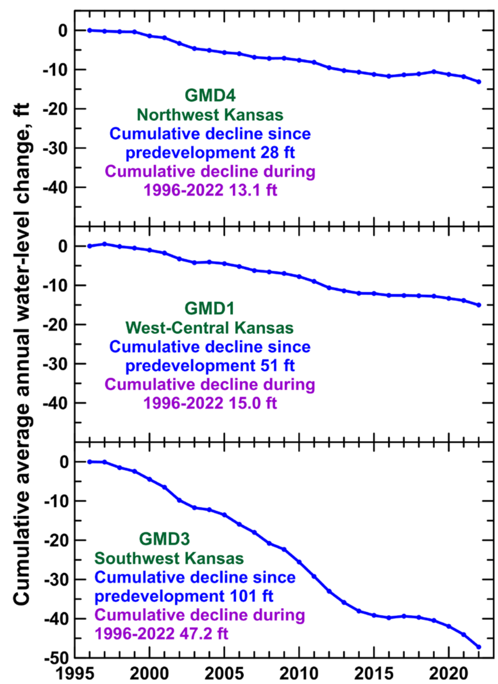

Figure 6. Cumulative change in average annual water levels for the three GMDs in the Ogallala region of the High Plains aquifer. The values are for all wells in the HPA measured each winter since 1996 (see Appendix 1 for details).

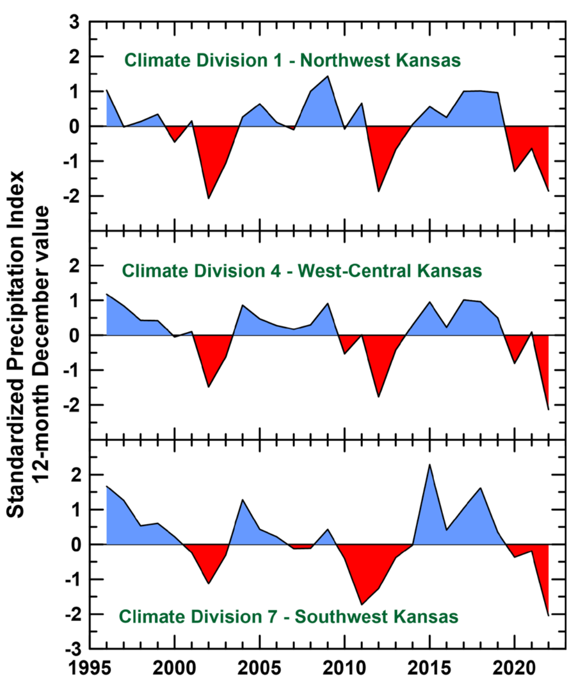

Figure 7. Standardized Precipitation Index for the 12-month period ending in December for the three western climatic divisions in Kansas in the Ogallala region of the High Plains aquifer. Long-term average precipitation is represented by zero. Positive values represent wetter than average, whereas negative values indicate drier than average. The average SPI values for 1996–2022 are -0.02 for Climatic Division 1 (GMD4), 0.08 for Climatic Division 4 (GMD1), and 0.15 for Climatic Division 7 (GMD3).

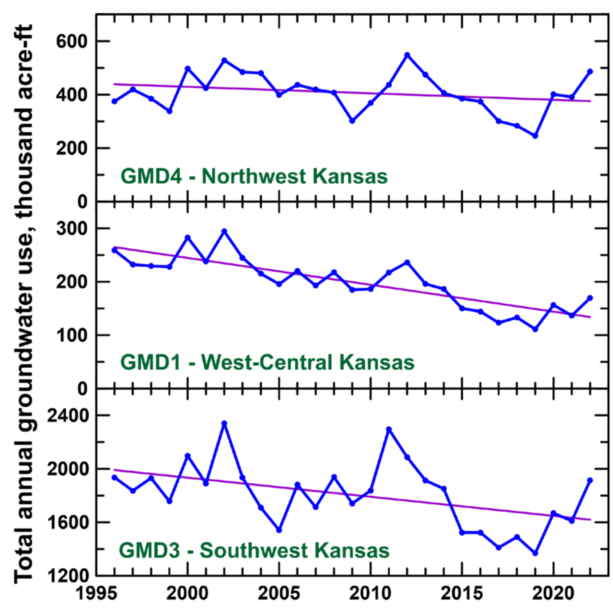

Figure 8. Annual total groundwater use for the three GMDs in the Ogallala region for 1996–2022. The best-fit trend in the data is shown as a purple line. Note that the y-axis scales vary among GMDs.

The cumulative water use during the last two decades in GMD4 has been about twice that of GMD1 (fig. 9); cumulative water use in GMD3 has been more than four times greater than in GMD4 and almost ten times greater than in GMD1. The cumulative use appears nearly linear for GMDs 4 and 3, whereas a bend toward lower use for GMD1 is apparent. As with water levels, water-use values were excluded for wells in the HPA region that are screened only in bedrock units.

Most of the water use in the three western GMDs is for irrigation. During 1996–2022, the average percentages of total use for irrigation were 97.9% in GMD4, 96.8% in GMD1, and 96.2% in GMD3. Irrigated acreage was roughly steady during 1996–2011 and then increased in the last decade in GMD4 (fig. 10). In comparison, after several years without a substantial trend, irrigated acreage in GMDs 1 and 3 decreased during the last two decades (fig. 10). The decreases in irrigated area in GMDs 1 and 3 explain much of the declines in water use during 1996–2022. Further evaluation of changes in irrigation water use and irrigated area are discussed in the section Has Irrigation Pumping Been Reduced? beginning on page 8.

Assessment of the Impact of Potential Pumping Reductions

If the lifetime of the HPA in the Ogallala region is to be extended, the only option for the next few decades is to reduce annual irrigation pumping. The key question is how much of a reduction is needed to have a significant impact on decline rates.

There is a high correlation between average annual water-level change and annual groundwater use across the GMDs. A water-balance approach developed by Butler et al. (2016) can be used to determine the level of pumping that would result in stable water levels (an average zero water-level change) in a GMD for the near term (up to a few decades). That water use is equal to the net inflow (all inflows to the aquifer minus all outflows except pumping). Note that if the goal is to reduce the decline rate by one half, then the pumping reduction would be half that required to attain stable water levels. Butler et al. (2016, 2018, 2023a) describe principles of the water-balance equation and the net inflow estimate that can be obtained from plots of average annual water-level change versus annual groundwater use. Appendix 2 provides additional information about net inflow.

The pumping reductions required to attain an average zero water-level change based on net inflow values obtained for the Ogallala region are substantially smaller than previous predictions based on recharge estimates and results of modeling analyses. Part of the reason is that the earlier assessments had not incorporated the long-term drainage from dewatered sediments produced by a declining water table (Liu et al., 2022). As

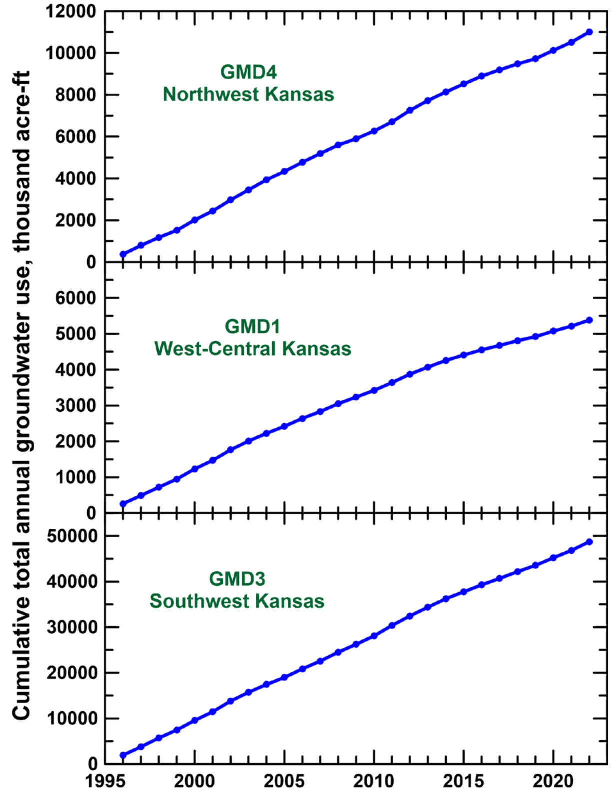

Figure 9. Cumulative annual total groundwater use for the three GMDs in the Ogallala region since 1996. The scales are different for each GMD to show the trend in each line.

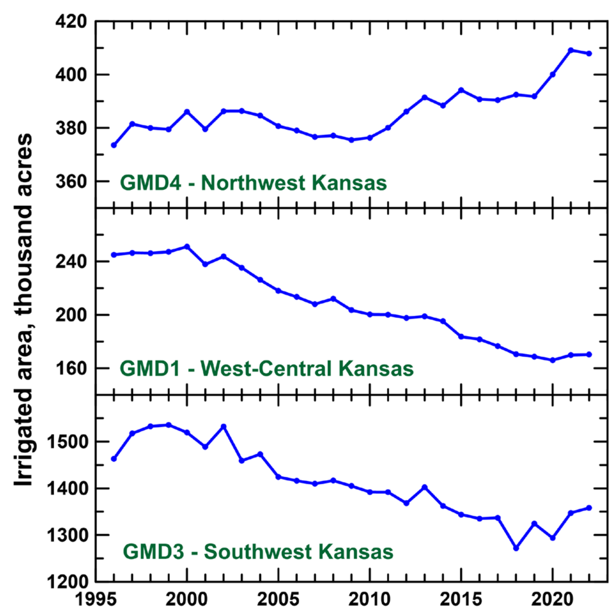

Figure 10. Annual irrigated acreage in the three GMDs in the Ogallala region for 1996–2022. The scales are different for each GMD to show the trend in each line.

a result, earlier modeling analyses have required a considerably larger pumping reduction to attain the same decrease in the rate of water-level decline.

Net inflow will eventually decrease in response to pumping reductions because of decreases in irrigation return flow, drainage from newly dewatered sediments, and other factors (see Appendix 2). The approach of Butler et al. (2016, 2018, 2023a), however, enables decreases in net inflow to be recognized from plots of average annual water-level change versus annual pumping. If such decreases are identified, further reductions in pumping will likely be needed (Butler et al., 2020a).

A plot of the average annual water-level change versus annual water use for 2005–2022 for GMD4 (fig. 11) shows that water use explains 89% of the variation in water-level changes (estimate based on R^2, the coefficient of determination). The reduction in average pumping required to achieve stable water levels is approximately 18%. As indicated above, this reduction is substantially smaller than the results of earlier modeling analyses and recharge estimates. The near-coincidence of the 2005, 2015, and 2022 data points in fig. 11 indicates that net inflow has changed little over this period. Note that the percent pumping reduction will vary with changes in the average annual pumping even if the net inflow remains approximately constant.

The correlation in the 2005–2022 plot of annual water-level change versus annual total groundwater use for GMD1 is much lower (R^2 = 0.49) than for GMD4. Variations in water-level changes during 2005–2008 are thought to be responsible for the lower correlation; GMD1 has fewer measurement wells so measurement errors in several wells can introduce a greater percentage of error than in the larger GMDs with a greater number of wells. Figure 12 displays the water-level change and water-use relationship for 2009–2022; the R^2 is much higher (0.72) than for 2005–2022. The pumping reduction needed to achieve short-term stabilization of water levels for GMD1 is 32% based on 2009–2022 data (fig. 12), which is much greater than that for GMD4 (fig. 11) but much smaller than predictions from earlier analyses.

Figure 13 shows the 2005–2022 plot of water-level change versus annual total groundwater use for GMD3. Like GMD4, the variation in annual water use explains more than 80% of the variation in annual water-level change (R^2 = 0.83). The pumping reduction to attain short-term stabilization of water levels is 25%, which is again much smaller than predictions based on earlier analyses.

The importance of the reductions needed for short-term stabilization of water levels described above is that agricultural economic analyses have shown reductions of 15–20% are achievable without substantially affecting net income (Golden, 2016, 2017). Such reductions would decrease water-level decline rates by half or more

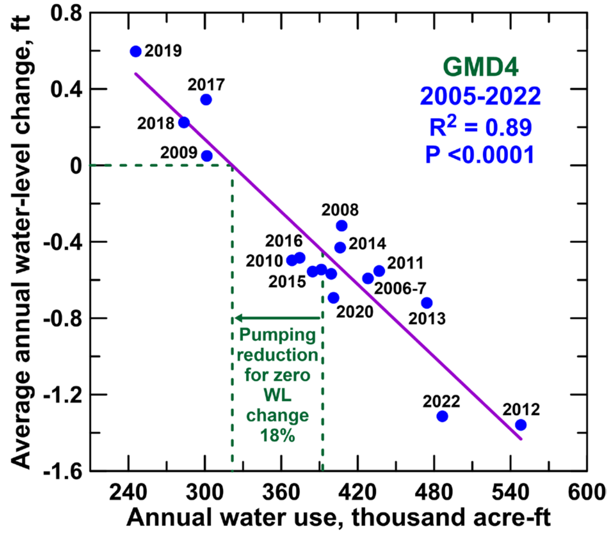

Figure 11. Average annual water-level change versus annual total groundwater use for GMD4 for 2005–2022. Water-level data are for all wells in the HPA measured each year from 2005 on (see Appendix 1 for details). The solid line is the best-fit line (linear regression in this and following figures) to the plot. Heavy snows delayed the 2007 water-level measurements in northwest Kansas, which affected the 2006 and 2007 water-level change values; the average of 2006 and 2007 was used in the plot and is indicated by the label 2006-7. Points for the years 2005 and 2021 are unlabeled; 2005 is to the right of 2015 and 2021 is to the right of 2005. The pumping reduction from the average water use for 2005–2022 needed to achieve a zero water-level change is shown by the difference between the two vertical dashed green lines.

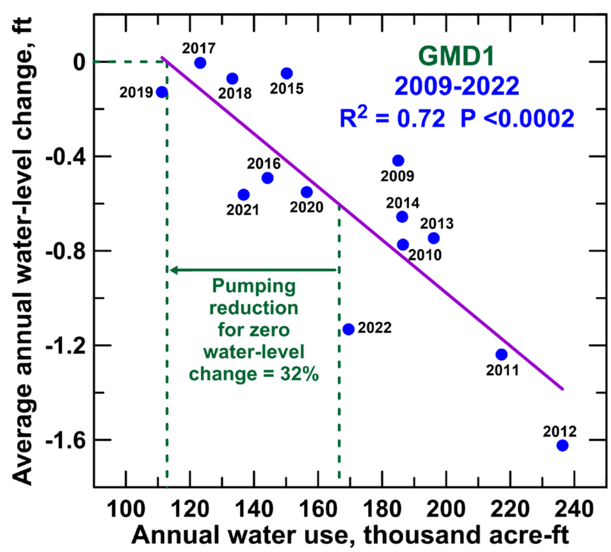

Figure 12. Average annual water-level change versus annual total groundwater use for GMD1 for 2009–2022. Water-level data are for all wells in the HPA measured each year from 2009 on (see Appendix 1 for details). The solid line is the best-fit line to the plot. The pumping reduction from the average water use for 2009–2022 needed to achieve a zero water-level change is shown by the difference between the two vertical dashed green lines.

for the three western GMDs and appreciably lengthen the usable life of the aquifer. Larger reductions will be required in areas in which average annual pumping is considerably greater than the districtwide average.

The average annual pumping totals for 2005–2022 for GMDs 4, 1, and 3 expressed as depths across the entire GMD area are 1.5, 1.8, and 3.9 in./yr, respectively. The estimated net inflows needed to balance the pumping and stabilize water levels (from figs. 11–13) are 1.2, 1.1 (2009–2022), and 2.9 in./yr for GMDs 4, 1, and 3, respectively. The differences between these inflows and the value of about a half inch commonly assumed for annual precipitation recharge in this region indicates the importance of the additional factors contributing to inflows discussed in Appendix 2.

Analyses of hydrographs of water-level changes measured in index wells in the Ogallala area and assessment of the correlations between water use and water-level changes show that net inflow has been relatively constant across the HPA during the last few decades (Butler et al., 2016, 2018, 2020b, 2021, 2023a). Episodic recharge (correlated with precipitation events) has been observed in only one out of the more than two dozen index wells for which hydrographs are available (Butler et al., 2023b). In that case, the recharge is attributed to a nearby impoundment of an ephemeral stream drainage. Episodic recharge also may occur directly below playas with relatively shallow depth to water but that has not been observed in the KGS well network in western Kansas. One reason for the apparent lack of episodic recharge is the heterogeneous mixture of low and high permeability sediments in the thick zone above the water table. Thus, interannual variations in infiltration of water below the root zone are largely smoothed out before reaching the water table (see Appendix 2 for further discussion).

If the average annual irrigation pumping for 2005–2022 is expressed as a depth over the average reported irrigated acreage (i.e., irrigation application rate), the values are 11.9, 10.4, and 14.6 in./yr for GMDs 4, 1, and 3, respectively. These depths are 53.1%, 48.8%, and 71.5% of the average annual radar precipitation in GMDs 4 (22.3 in.), 1 (21.4 in.), and 3 (20.4 in.), respectively. Thus, the total amount of annual irrigation plus precipitation in GMDs 4, 1, and 3 averaged 34.2, 31.8, and 35.0 in., respectively, for 2005–2022. The sum of irrigation and precipitation varies less than the annual precipitation (fig. 14) because of the inverse relationship between irrigation water use and precipitation. For example, the irrigation and precipitation sum for the drought year of 2011 in GMD3 was not substantially below the average sum for 2005–2022.

The net inflow for GMD3 (2.9 in./yr) is about 2.5 times higher than that for GMDs 4 (1.2 in./yr) and 1 (1.1 in./yr). The greater net inflow rate in GMD3 is likely mainly due to a higher rate of delayed drainage from

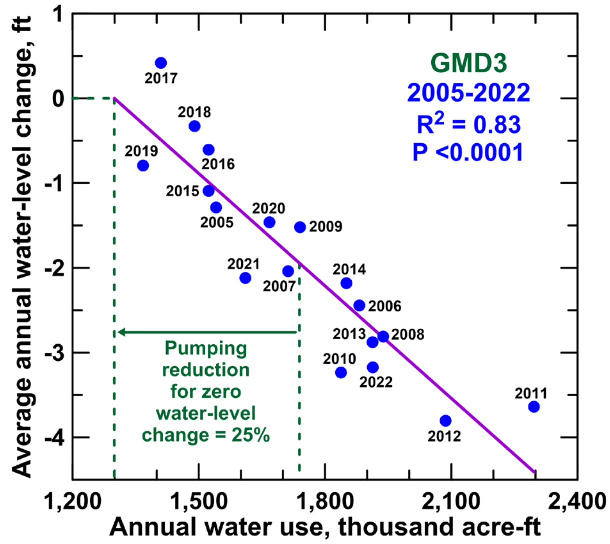

Figure 13. Average annual water-level change versus annual total groundwater use for GMD3 for 2005–2022. Water-level data are for all wells in the HPA measured each year from 2005 on (see Appendix 1 for details). The solid line is the best-fit line to the plot. The pumping reduction from the average water use for 2005–2022 needed to achieve a zero water-level change is shown by the difference between the two vertical dashed green lines.

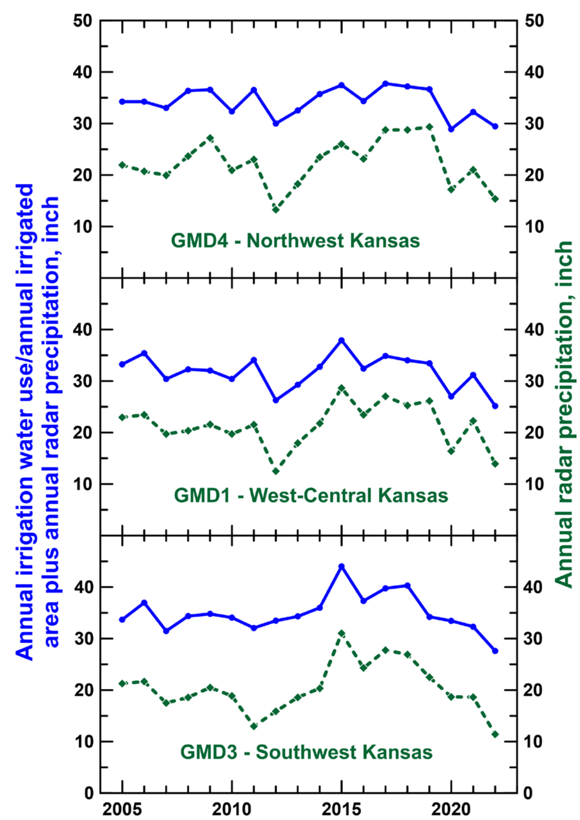

Figure 14. Annual irrigation water use/annual irrigated area plus annual radar precipitation (left y-axis) and annual radar precipitation (right y-axis) for 2005–2022 for the three GMDs in the Ogallala region.

dewatered sediments because the cumulative water-level decline since 1996 was much larger in GMD3 (47.2 ft) than in GMD4 (13.1 ft) and GMD1 (15.0 ft) (fig. 6). The impact of water seeping from the Arkansas and Cimarron rivers into the aquifer, and that of upflow from the Dakota aquifer, is much smaller than delayed drainage, as explained in Appendix 2. In all three GMDs, net inflow to the aquifer underlying the irrigated acreage would be expected to be larger due to irrigation return flow, enhanced precipitation recharge over irrigated areas, increased lateral flow, and drainage of newly dewatered sediments caused by water-level decline, as described in Appendix 2.

Has Irrigation Pumping Been Reduced?

Irrigation pumping can be reduced by decreasing irrigation acreage (see GMDs 1 and 3 in fig. 10) or increasing irrigation efficiency. The former must be done without increasing the irrigation rate, so that it does not offset the reduction in acreage. The latter must be done without offsetting the efficiency gains by irrigating crops with greater water requirements or expanding the irrigated acreage. In both cases, the objective is true water conservation—less irrigation use than previously under similar climatic conditions.

Selected areas of the GMDs in the Ogallala region have begun to employ true water conservation measures based on initiatives of the Kansas Legislature (Butler et al., 2018; Griggs, 2021). The first legislative initiative was the establishment of the Local Enhanced Management Area (LEMA) program in 2012 that allows stakeholders to develop a plan for pumping reductions. Under this program, a plan is submitted to the relevant GMD for approval, followed by hearings conducted by the KDA-DWR and then acceptance (or rejection) by the KDA-DWR chief engineer. A LEMA includes compliance monitoring and enforcement by the GMD and the KDA-DWR (KDA-DWR, 2023a). Regulatory oversight includes water-level measurements and metering of all non-domestic water use. Another legislative initiative was the establishment of the Water Conservation Area (WCA) program in 2015. This program allows a water right owner or group of owners to develop a pumping-reduction plan. WCAs are typically smaller than LEMAs and only need the approval of the chief engineer (Whittemore et al., 2023). A WCA also includes compliance monitoring and enforcement (KDA-DWR, 2023b).

The first LEMA (Sheridan-6 or SD-6) was established in a 63,057 acre (98.5 square mile) area in GMD4, primarily in Sheridan County (fig. 15), and began operation in 2013. It is the first known management plan that involved reductions in groundwater pumping (i.e., true water conservation) in a substantial irrigated area of the Kansas HPA. Prior management programs aimed at reducing water use by increasing water efficiency were not successful because the saved water often was applied to other irrigated areas or to increase application rates for more water-intensive crops (e.g., Peterson and Ding, 2005). The proposed pumping reduction in the SD-6 LEMA was an average of 20% over five years. The first five years of the LEMA successfully met the reduction target. As a result, the LEMA was renewed for

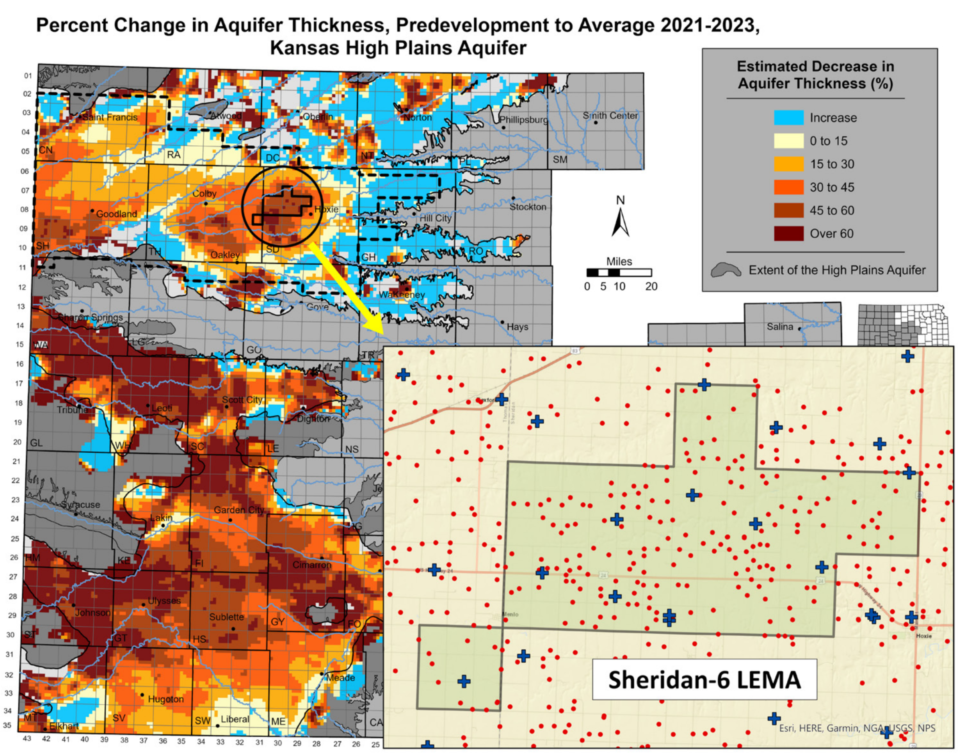

Figure 15. Location of the Sheridan-6 LEMA in GMD4 on a map of the percent change in thickness of the High Plains aquifer from predevelopment to the average for winter conditions for 2021–2023. The dashed lines are the boundary of GMD4. The inset is an expanded view of the LEMA displaying the locations of pumping wells (red circles) and wells monitored for water levels (blue pluses). Water-level measurements in additional wells were used in fig. 17.

another five years beginning in 2018 and then renewed again for another five years beginning in 2023 to sustain the general pumping reductions.

Figure 16 illustrates the change in irrigation groundwater use, irrigated area, irrigation water use per irrigated area (irrigation application rate), and annual precipitation based on weather station data (PRISM precipitation) during the pre-LEMA and LEMA operation for 2002–2022. Irrigation use averaged 98.6% of total use within the LEMA area during 2002–2022. The average total groundwater use in the SD-6 LEMA in 2013–2022 was 19,104 acre-ft in comparison to 29,925 acre-ft for 2002–2012, resulting in a reduction of 36%; the reduction in irrigation water use was 37%. Irrigated acreage also fell after the LEMA began but has grown during the last three years. The average irrigated area decreased by 2.7% from 2002–2012 to 2013–2022. Irrigation efficiency, as represented by irrigation water use per irrigated area, improved once the LEMA started. Although the 2020 and 2022 rates of water application rose as a result of lower precipitation, the rates were less than in the comparable dry year of 2012.

Figure 17 displays the annual water-level change versus total water use plot for the SD-6 LEMA for 2002–2022. The figure shows that water-level declines during 2013–2022 generally were substantially smaller than those during 2002–2012 as a result of reduced pumping. The average decline during 2013–2022 was 0.6 ft compared to 1.4 ft in 2002–2012 (not including 2006 and 2007 values because heavy snow in 2006 prevented measurement of all wells) for a reduction of 65%. The pumping reduction required for a zero water-level change from the average of the pre-LEMA period is 48.1% (using the best-fit line in fig. 17). The pumping reduction required to obtain a zero water-level change for the LEMA period (2013–2022) is 18.7%. If this reduction value held for the next several decades, it would be equivalent to extending the aquifer lifetime by more than a factor of two. The near-coincidence of the 2005, 2008, and 2022 data points on fig. 17 indicates that net inflow was relatively constant during the entire period (3.0 in./yr). This net inflow is substantially greater than that for all of GMD4 (1.2 in. for 2005–2022) because of the appreciably greater pumping and water-level declines in the region now covered by the SD-6 LEMA, which resulted in greater recharge associated with irrigation, lateral flow into the area, and drainage from the newly dewatered sediments.

Plots of annual irrigation water use or irrigation water use/irrigated area versus precipitation are valuable for assessing water savings relative to climatic conditions. Water use and precipitation have been shown to have a statistically significant inverse correlation in the HPA (Whittemore et al., 2016, 2023). Linear correlations based on these data allow the assessment of whether water use has statistically decreased because

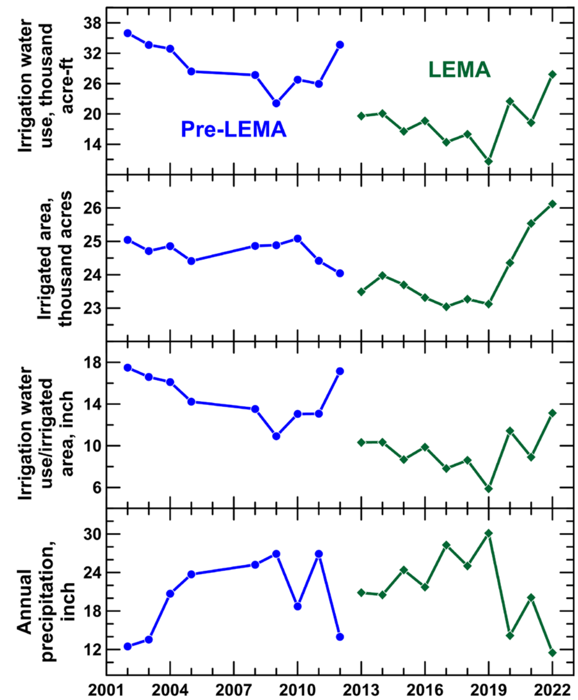

Figure 16. Annual irrigation groundwater use, annual irrigated area, annual irrigation groundwater use per irrigated area, and annual PRISM precipitation for 2002–2022 in the SD-6 LEMA. The pre-LEMA period is represented by the blue circles and lines and the LEMA operation by the green diamonds and lines. PRISM precipitation was used for this plot because the data extend to before radar precipitation became readily available online (2005).

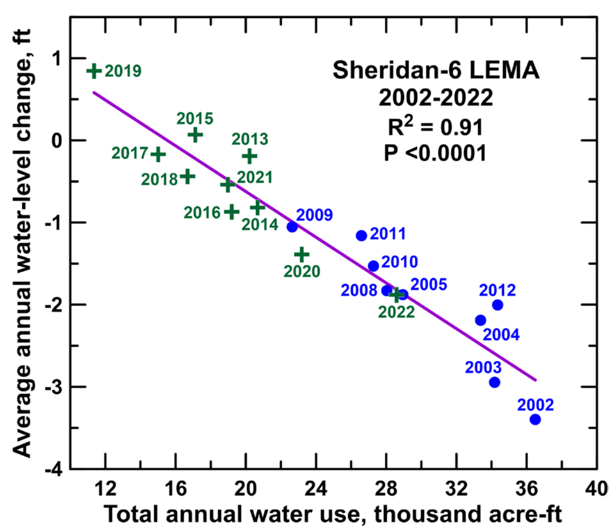

Figure 17. Average annual water-level change versus total annual groundwater use for the SD-6 LEMA in GMD4. The solid line is the best-fit line for the 2002–2022 data. The blue circles represent the average water-level change for wells measured every year during the pre-LEMA period of 2002 through 2012; the green pluses represent the average water-level change for the wells during the LEMA in 2013–2022. Heavy snow delayed the 2007 water-level measurements, so the values for 2006 and 2007 are not shown. Further details are provided in Butler et al. (2018, 2023a).

the water use at similar precipitation can be compared for different time periods. For this purpose, the KGS has been using radar precipitation data that have been available for download from the U.S. National Weather Service since 2005. Radar precipitation may better represent the distribution of precipitation than data primarily based on weather stations (PRISM precipitation) because the area captured by radar is typically smaller than the distance between stations in Kansas. Thus, radar could capture the precipitation from intense thunderstorms that occur between weather stations during the irrigation season (Whittemore et al., 2023).

Two plots are used to assess how pumping reductions were achieved. A plot of annual irrigation water use versus precipitation will reveal whether pumping was reduced and by how much for similar climatic conditions. A second plot of annual irrigation water use/irrigated area versus precipitation will reveal how much of those reductions were achieved by increases in water use efficiency, again controlling for climatic conditions. The difference between the total pumping reduction determined from the first plot and the efficiency-achieved reduction determined from the second plot is the reduction achieved by decreases in irrigated area. The power of this pair of plots is further described in Whittemore et al. (2023).

A plot of annual irrigation water use versus radar precipitation for the SD-6 LEMA (fig. 18) displays two best-fit lines that are offset from one another, blue representing the pre-LEMA period and green representing the LEMA period. The radar precipitation is the sum for the months of January through September; this sum was considered the most appropriate for use in pumping versus precipitation correlations in the Ogallala region as explained in Whittemore et al. (2023). Statistical confidence intervals (at the 95% level) are included for both best-fit lines in fig. 18 to help show the differences in irrigation water use for the pre-LEMA and LEMA periods.

The best-fit line for the LEMA period in fig. 18 is shifted downward from the best-fit line for the pre-LEMA years. This indicates that for the years in which climatic conditions of 2013–2022 were similar to those for 2005–2012, the annual water use was lower. The offset in the two best-fit lines for the SD-6 LEMA (fig. 18) at either the average January–September radar precipitation for the overlapping interval of the two lines or the average precipitation for the entire period can be used to estimate the water savings for the LEMA; the total savings was 23.7–25.0% for the two approaches. Thus, the LEMA achieved more than the average pumping reduction target of 20%, even when controlling for climatic conditions.

The plot of irrigation water use per irrigated area versus precipitation shows that the reduction in water use based on irrigation efficiency is 23.2–23.9% based on the average precipitation for the overlapping interval of the two best-fit lines and for the entire period of 2005–2022 (fig. 19). Thus, most of the water savings was achieved by increased efficiency and the additional 0.5%–1.1% (23.7%–23.2% and 25.0%–23.9%) of savings

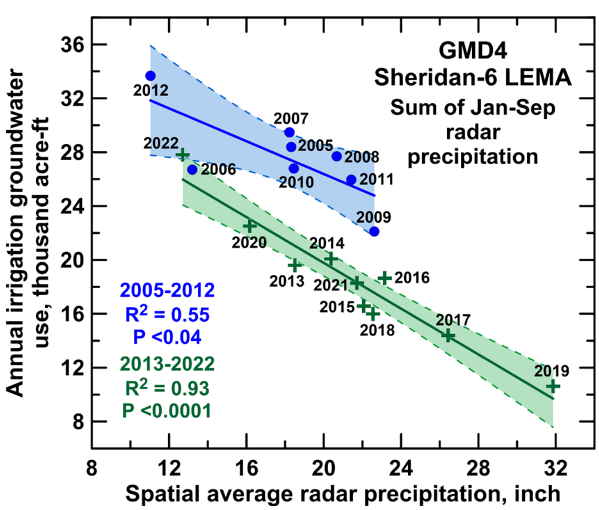

Figure 18. Annual irrigation groundwater use versus January–September radar precipitation for the SD-6 LEMA for 2005–2022. The solid lines are for the best fits to the data. Shaded confidence intervals for the best-fit lines are bounded by dashed lines for the 95% confidence interval. The total water savings is determined by the groundwater use between the two best-fit lines both at the average precipitation for the overlapping interval of the lines (19.07 in.) and the average precipitation for 2005–2022 (19.97 in.).

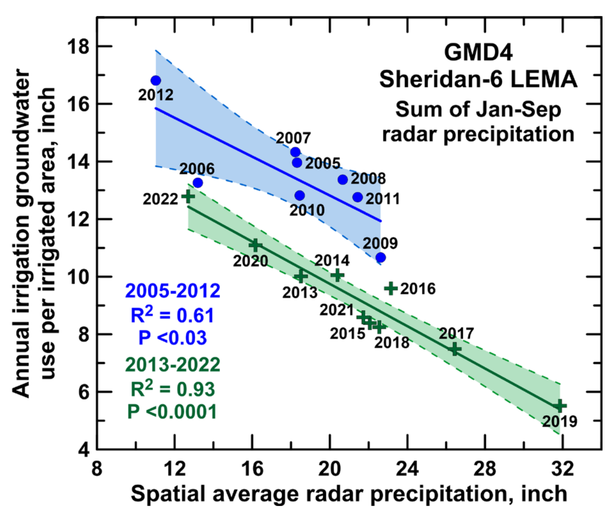

Figure 19. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation for the SD-6 LEMA for 2005–2022. The solid lines are for the best fits to the data. Shaded confidence intervals for the best-fit lines are bounded by dashed lines for the 95% confidence interval. The percent reduction in water use based on improved irrigation efficiency is determined by the groundwater use between the two best-fit lines both at the average precipitation for the overlapping interval (19.07 in.) and the average precipitation for 2005–2022 (19.97 in.).

was related to decreases in irrigated area (there was a 2.7% decrease in reported irrigated area).

The scatter in the points for the LEMA period in figs. 18 and 19 is substantially smaller than that for the pre-LEMA years. Some of the smaller scatter could be due to lower uncertainty in water-use reporting because the irrigators were more carefully checking flow meter performance. However, use of soil moisture sensors and other measures to better track and control field moisture conditions is probably the main factor for precipitation explaining more than 90% of the variation in water use during the LEMA period (figs. 18 and 19).

A districtwide LEMA was established in GMD4 in 2018 for an initial five-year period and was recently renewed for another five years with the same conditions. The annual maximum irrigation applications allowed in the GMD4 LEMA vary depending on the location within the district but are more than the actual average irrigation water use per area for 2005–2022. Thus, only irrigators with particularly high irrigation application rates are affected. The plot of annual irrigation water use versus precipitation (fig. 20) indicates that no statistically significant change in irrigation water use has yet occurred districtwide, although plots for some of the 10 individual county areas within GMD4 do show some separation between 2005–2017 and 2018–2022. Annual updating of fig. 20 and the companion plot of irrigation water use/irrigated area versus precipitation (fig. S1 in the Supplemental Figures section at the end of this book) will allow a determination of when significant water savings are apparent for GMD4.

Substantial decreases in aquifer thickness and irrigated area have led to the establishment of two LEMAs in GMD1. The first was established in Wichita County in early 2021, and the second was established in the four other counties of the district in spring 2023. WCAs were established prior to these LEMAs in all five counties. The largest WCA (11,391 acres) began in Wichita County in spring 2017 and includes 25 different individual areas, most of which were implemented during 2017 while the others joined up before the end of 2018.

The plot of irrigation water use versus precipitation for GMD1 shows that water use for the last five years (2018–2022) is significantly less than that for 2005–2017 for similar climatic conditions (fig. 21). The total irrigation water savings at the average January–September radar precipitation for the overlapping interval of the two best-fit lines and at the average January–September precipitation for 2005–2022 are both 24.3%. The companion plot (fig. S2 in Supplemental Figures) of irrigation water use per irrigated area reveals that a 10.5% pumping reduction (at both the precipitation averages for the overlapping interval and the entire period) was produced by increases in irrigation efficiency. Thus, a 13.8% pumping reduction can be attributed to decreases in irrigated acreage, which is consistent with the 15.1%

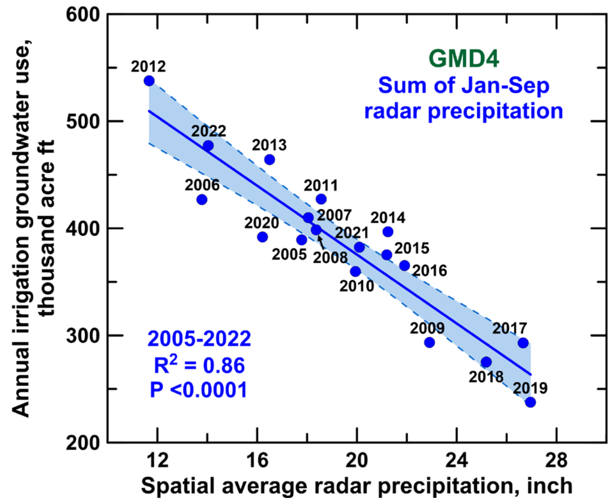

Figure 20. Annual irrigation groundwater use versus January–September radar precipitation for GMD4 for 2005–2022. The solid line is for the best fit to the data. The shaded confidence interval for the best-fit line is bounded by dashed lines for the 95% confidence interval.

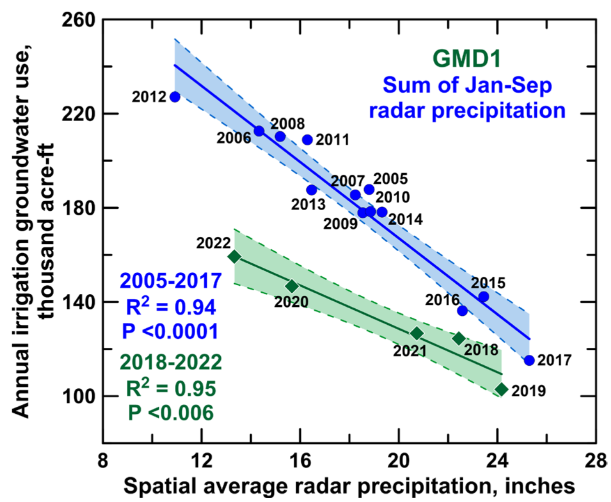

Figure 21. Annual irrigation groundwater use versus January–September radar precipitation for GMD1 for 2005–2022. The solid lines are for the best fits to the data. Shaded confidence intervals for the best-fit lines are bounded by dashed lines for the 95% confidence interval. The total water savings is the groundwater use between the two best-fit lines both at the average precipitation of the overlapping interval (18.65 in.) and at the average precipitation for 2005–2022 (18.59 in.).

decrease in the average reported irrigated area in GMD1 from 2005–2017 to 2018–2022 (fig. 10).

The plot of irrigation water use versus precipitation for Wichita County shows that water use for the last five years (2018–2022) was significantly less than the 2005–2017 period for similar climatic conditions (fig. 22). The total irrigation water savings was 39.5% (at both the average January–September precipitation for the overlapping interval of the two best-fit lines and at the average January–September precipitation for 2005–2022), which is considerably greater than that found for GMD1 as a whole. The companion plot of irrigation water use per irrigated area versus precipitation (fig. S3 in Supplemental Figures) indicates that a 23.9%–24.0% pumping reduction was produced by improvements in irrigation efficiency based on the average precipitation for the overlapping interval and for 2005–2022. Thus, a 15.5%–15.6% pumping reduction can be attributed to decreases in irrigated area, which is reasonably consistent with the 19.9% decrease in reported irrigated area.

No LEMAs have been established in GMD3. However, a number of WCAs have been, although their total area is small relative to that of GMD3 as a whole. In addition, water rights for irrigation wells were retired in the Conservation Reserve Enhancement Program (CREP) along the upper Arkansas River corridor in GMD3 during 2008–2022. The total area enrolled in CREP in GMD3 is 22,076 acres, which comprises part of the decrease in irrigated acreage shown in fig. 10. The plot of irrigation groundwater use versus precipitation for GMD3 (fig. 23) suggests that water savings have been achieved from 2005–2018 to 2019–2022; the offset in the two best-fit lines equates to 12.3%–13.0% at the average January–September precipitation for the overlapping interval and for 2005–2022. This value includes more uncertainty than for the water savings determined for the SD-6 LEMA, GMD1, and Wichita County because the points for 2005 and 2007 fall within the 95% confidence interval for the best-fit line for 2019–2022, which is based on only four points. More years of data that consistently plot at lower water use than the confidence interval for 2005–2018 are needed to confirm the trend in water savings. The companion plot (fig. S4 in Supplemental Figures) of irrigation groundwater use per irrigated area versus precipitation does not indicate a statistically significant change in irrigation efficiency from 2005–2018 to 2019–2022, again pointing to the need for additional years of data. Thus, it is unclear how much of the apparent water savings has been obtained through improvements in water-use efficiency and how much through reductions in irrigated area.

The irrigation application rates (irrigation groundwater use per irrigated area) differ substantially across the Ogallala region. Figure 24 illustrates this by

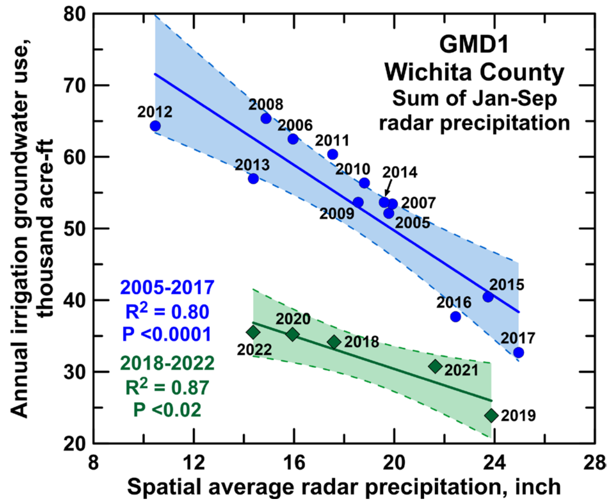

Figure 22. Annual irrigation groundwater use versus January–September radar precipitation for Wichita County within GMD1 for 2005–2022. The solid lines are for the best fits to the data. Shaded confidence intervals for the best-fit lines are bounded by dashed lines for the 95% confidence interval. The total water savings is the groundwater use between the two best-fit lines both at the average precipitation of the overlapping interval (18.69 in.) and at the average precipitation for 2005–2022 (18.50 in.).

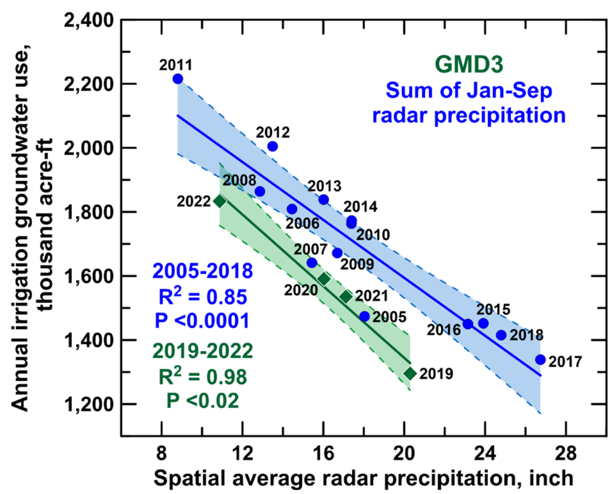

Figure 23. Annual irrigation groundwater use versus January–September radar precipitation for GMD3 for 2005–2022. The solid lines are for the best fits to the data. Shaded confidence intervals for the best-fit lines are bounded by dashed lines for the 95% confidence interval. The total water savings is the groundwater use between the two best-fit lines both at the average precipitation of the overlapping interval (16.68 in.) and at the average precipitation for 2005–2022 (17.41 in.).

comparing the best-fit lines from the irrigation groundwater use per irrigated area versus precipitation plots discussed earlier. The slopes of all but the line for GMD4 are nearly parallel with each other. The steeper slope for GMD4 may represent irrigators in the district being better able to conserve water during wet periods than dry. The GMD with the greatest application rate is GMD3, followed by GMD4, with GMD1 having the smallest rate. This order is the same as the current aquifer thickness, from GMD3 with the largest to GMD1 the least. The relatively small aquifer thickness in GMD1 has caused irrigators to operate with lower pumping rates than in the other GMDs. This is especially true in Wichita County, where the application rate for 2005–2017 was even lower than that for the SD-6 LEMA during 2013–2022; the rate for 2018–2022 in Wichita County is by far the lowest of the areas. Water-level declines during the irrigation season in Wichita County bring the aquifer thickness down to a small enough level that pumping enough water for crops is a challenge. The water savings of the two periods for the SD-6 LEMA and Wichita County area are relatively similar, as indicated by similar offsets in the lines. However, the appreciably thicker remaining aquifer in the SD-6 LEMA allows the irrigators to pump at a substantially greater rate than in Wichita County. The relatively large aquifer thickness in GMD3 has apparently not yet compelled enough irrigators to diminish the irrigation rate down to near the pre-LEMA period of the SD-6 or closer to that for GMD4; although, given equal aquifer thicknesses and character, the rate might be expected to be somewhat greater in GMD3 because precipitation is lower (as described earlier) and the average fraction of precipitation lost to evapotranspiration is higher (Sanford and Selnick, 2013).

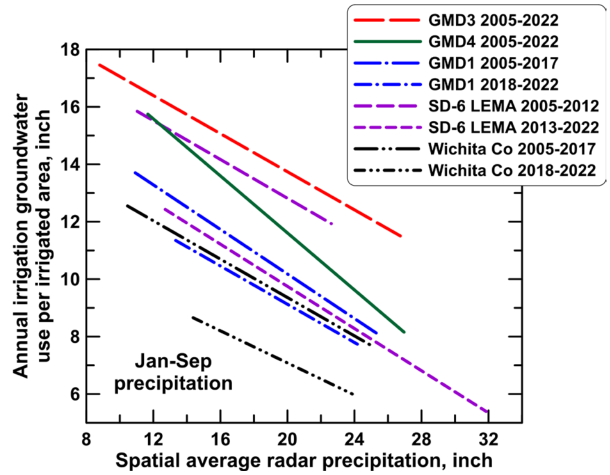

Figure 24. Best-fit lines for irrigation groundwater use per irrigated area versus January–September radar precipitation for the three GMDs in the Ogallala region, the SD-6 LEMA in GMD4, and Wichita County in GMD1 for 2005–2022.

QUATERNARY REGION OF THE HIGH PLAINS AQUIFER

Variations in Groundwater Levels and Groundwater Use

Groundwater levels in the Quaternary region of the HPA in south-central Kansas have declined appreciably only in parts of the western portion of GMD5 and in localized areas such as around McPherson in GMD2 (fig. 4). Areas of both small declines and increases in water level are displayed in fig. 4; these vary from year to year depending on whether dry or wet conditions are prevalent. Fluctuations in the annual water-level change for the Quaternary region (fig. 25) are substantially greater than for the Ogallala region (fig. 5). Although the annual groundwater-level declines of up to about 3 ft in GMDs 2 and 5 have not been as great as the more than 3 ft annual declines in GMD3, annual water-level rises have at times reached about 3 ft, whereas maximum annual rises in the Ogallala region since 1996 have been only somewhat above 0.5 ft. The Quaternary region has greater precipitation and shallower depths to water than the Ogallala region, and dune sand overlies the aquifer in some areas. This results in substantial recharge to the aquifer and greater water-level rises during wet years. Discharge of groundwater to streams is substantial in the Quaternary region during dry periods, adding to the effect of pumping to create substantial water-level declines.

The total declines in groundwater levels in the Quaternary region since predevelopment to the average water levels for 2021–2023 are 6.9 ft for GMD2 and 5.8 ft for GMD5. The current average aquifer thicknesses are 94 ft for GMD2 and 116 ft for GMD5. The trends in the average annual water-level change (fig. 25) and the cumulative changes (fig. 26) for the two GMDs in the Quaternary region for 1996–2022 are as follows:

- GMD2: very slight decline in the best-fit line although the average change is insignificant (a rise of 0.04 ft/yr); cumulative increase of 0.75 ft
- GMD5: slight decline; average -0.15 ft/yr; cumulative decline of 5.0 ft

Although fig. 25 shows a slight declining trend for GMD2, fig. 26 indicates that the cumulative annual water-level change has generally been above the water level of 1996; the cumulative change since predevelopment is a 6.9 ft decline. In comparison, the cumulative trend for GMD5 has been a definite decline since 1996, although the cumulative decline since predevelopment (5.8 ft) is smaller than that of GMD2.

Just as for the three western GMDs, the annual variation in the water-level change (fig. 25) and the changes in direction of the cumulative change (fig.

26) are directly related to precipitation. This relationship can be seen in the generally similar patterns for the Standardized Precipitation Index for south-central Kansas climate division 8 (fig. 27) and the water-level changes in GMDs 2 and 5 that lie within this division (fig. 25). Although the average SPI values for the three western GMDs in the Ogallala region for 1996–2022 are all less than 0.16 (about normal), the average 12-month December SPI for the same period in climate division 8 is 0.41, which is slightly wet, as apparent in the distribution of greater blue (wetter than normal) areas versus red (drier than normal) areas in fig. 27.

During the same period (1996–2022), the following trends (based on the 1996 and 2022 endpoints of the best-fit lines through the data) have been seen in the total annual groundwater use for the two GMDs in the Quaternary region (fig. 28):

- GMD2: increase of 5.9%
- GMD5: increase of 6.4%

Cumulative groundwater use for 1996–2022 in GMDs 2 and 5 has followed a general linear trend (fig. 29). The cumulative use in GMD5 has been nearly three times that of GMD2, mainly reflecting the much larger area of GMD5.

As with the Ogallala region, most of the water use in the GMDs in the Quaternary region is for irrigation. During 1996–2022, the average percentages for

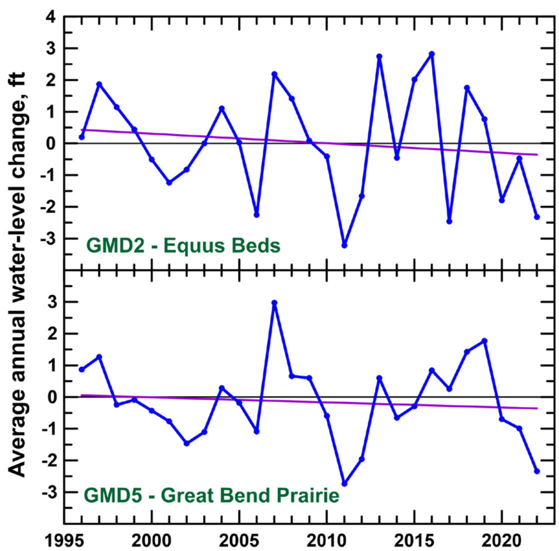

Figure 25. Average annual groundwater-level change for the two GMDs in the Quaternary region of the High Plains aquifer. The values are for all wells measured each year in the HPA from 1996 on. The best-fit trend in the data is shown as a purple line, and the line for zero change is black.

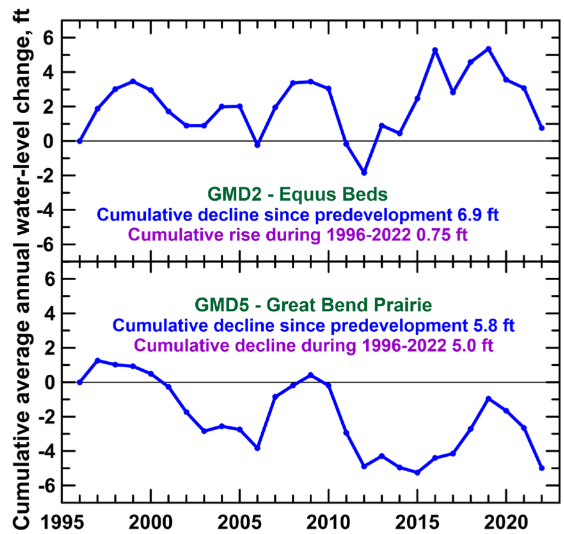

Figure 26. Cumulative change in average annual water levels for the two GMDs in the Quaternary region. The values are for all wells in the HPA measured each year since 1996.

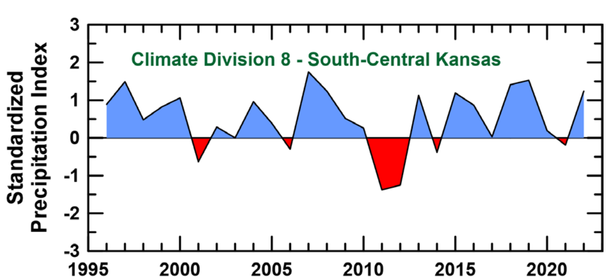

Figure 27. Standardized Precipitation Index for the 12-month period ending in December for climatic division 8 in Kansas. GMDs 2 and 5 lie within this climatic division. Long-term average precipitation is represented by zero. Positive values represent wetter than average, whereas negative values indicate drier than average. The average SPI value for 1996–2022 is 0.41.

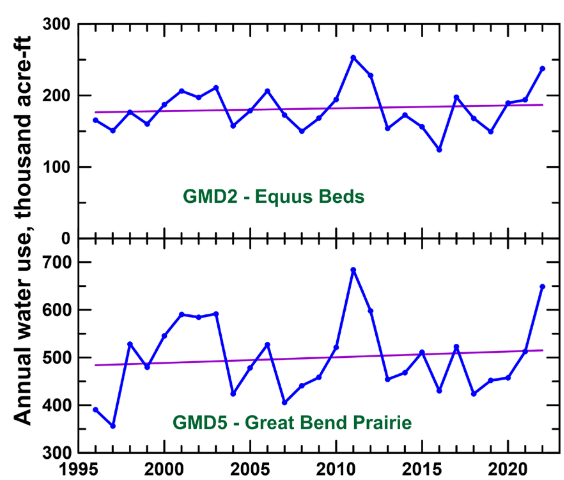

Figure 28. Annual total groundwater use in the two GMDs in the Quaternary region of the High Plains aquifer for 1996–2022. The best-fit trend in the data is shown as a purple line.

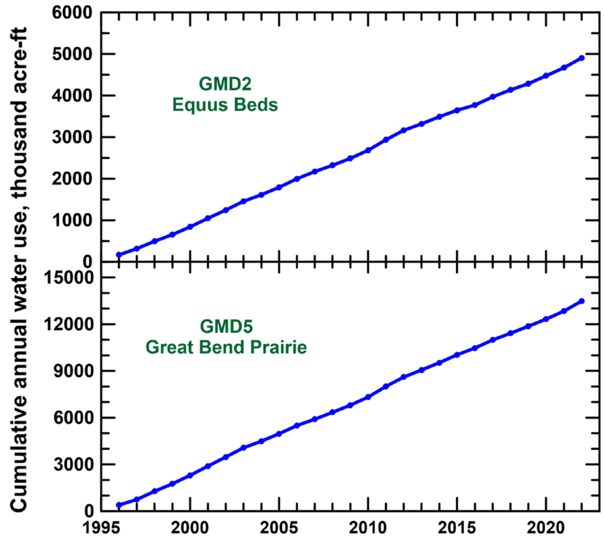

Figure 29. Cumulative annual total groundwater use in the two GMDs in the Quaternary region since 1996. The scale for GMD2 is different to show the trend in the line.

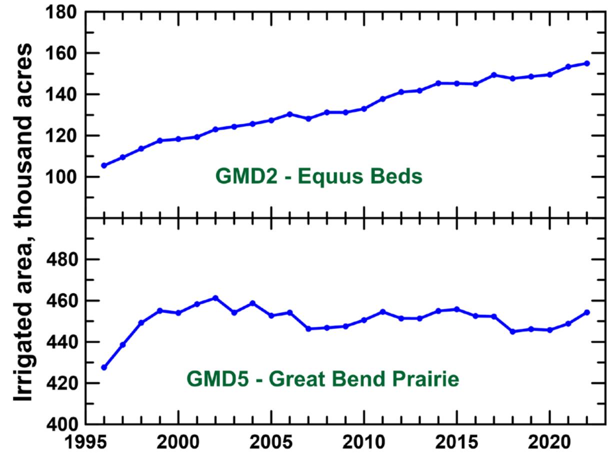

Figure 30. Annual irrigated acreage in the two GMDs in the Quaternary region during 1996–2022. The scale for GMD2 is different to show the trend in the line.

irrigation use out of total use were 59.8% in GMD2 and 95.7% in GMD5. The percentage of irrigation use in GMD2 is substantially smaller than for the four other GMDs because municipal and industrial uses are much greater. For example, the City of Wichita wellfield in southwest Harvey County and northwest Sedgwick County pumps a substantial amount of groundwater each year for municipal use. Irrigated acreage in GMD2 has steadily risen during 1996–2022 (fig. 30). This rise could explain the small increasing trend of water use in GMD2 (fig. 28). In comparison, after a rise from 1996 to 1999, the irrigated area in GMD5 has remained relatively constant. Thus, the small increasing trend in water use in GMD5 may not be related to change in irrigated area but to other factors such as type of crops or a higher irrigation application rate.

Assessment of the Impact of Potential Pumping Reductions

As with the Ogallala region, plots of annual water use versus average annual water-level change can be used to assess the impact of potential pumping reductions in the Quaternary region. A plot of average annual water-level change versus annual water use for 2005–2022 for GMD2 (fig. 31) indicates that pumping is within 1% of that which would produce stable water levels (zero water-level change). This suggests that the pumping in GMD2 during the last 18 years has, in general, been in balance with the net inflow.

The pumping reduction needed to achieve stable water levels for the short term for GMD5 is 1.6% (fig. 32), indicating that GMD5 is pumping slightly more than net inflow, which could reflect the somewhat smaller annual rainfall and recharge in GMD5. The estimated net inflows (from figs. 31 and 32) are 2.0 in. for GMD2 and 2.3 in. for GMD5. These net inflows are about twice those in GMDs 4 and 1 but are about 70–80% of that in GMD3. Although the pumping reductions needed to stabilize water levels are small for both GMDs 2 and 5, these can be highly dependent on the occurrence of a few very wet years (Whittemore et al., 2016). For example, 2007 was such a year in GMD5 (fig. 25).

The pumping reductions for GMDs 2 and 5 shown in figs. 31 and 32 are for the entire district areas. However, selected portions of the districts can require substantially greater reductions, depending on local conditions. For example, greater reductions would be needed in the McPherson County area of GMD2 (Butler et al., 2017). Similarly, the pumping reductions required for zero water-level change in Edwards and Pawnee counties would be expected to be greater than the average for all of GMD5 based on the long-term water-level declines shown in these counties in fig. 4.

The cumulative decline in the water table in GMD2 since predevelopment is 6.9 ft, which decreased groundwater discharge to the Arkansas and Little Arkansas rivers as well as to small streams within the district, thereby decreasing streamflow. The lower water table also has resulted in the flow of naturally saline water into the alluvial aquifer of the Arkansas River and into the Equus Beds aquifer toward the southern edge of the Wichita wellfield (Myers et al., 1996; Klager et al., 2014). The current net inflow appears to be large enough to approximately balance the pumping based on the relatively stable average water level since 1996 (fig. 26). Thus, after the decline in the water table prior to 1996, the district has apparently reached a new balance where the capture of streamflow and possibly smaller sources

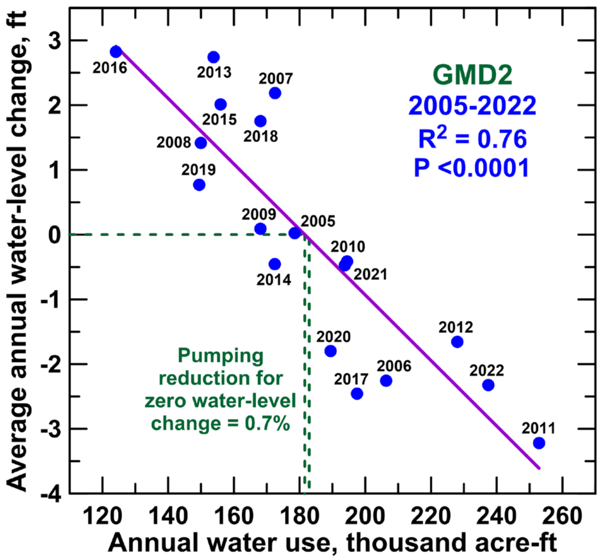

Figure 31. Average annual groundwater-level change versus annual total groundwater use for GMD2 for 2005–2022. Water-level data are for all the wells in the HPA measured each year from 2005 on. The solid line is the best-fit line to the plot. The pumping reduction from the average water use for 2005–2022 needed to achieve a zero water-level change is shown by the difference between the two vertical dashed green lines.

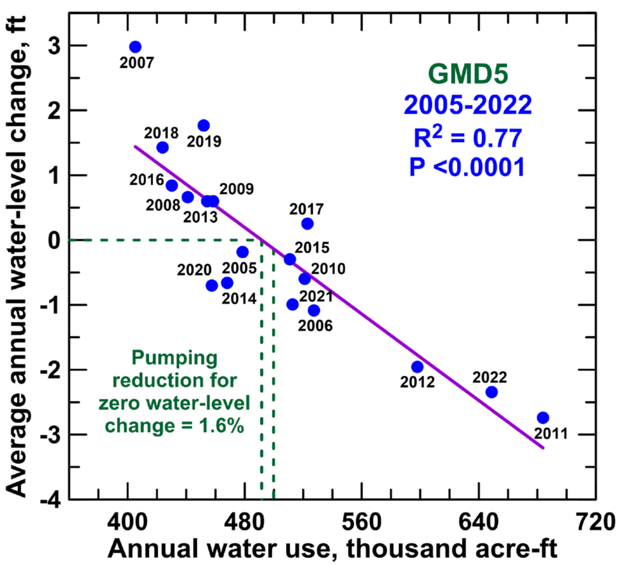

Figure 32. Average annual groundwater-level change versus annual total water use for GMD5 for 2005–2022. Water-level data are for all wells in the HPA measured each year from 2005 on. The solid line is the best-fit line to the plot. The pumping reduction from the average water use for 2005–2022 needed to achieve a zero water-level change is shown by the difference between the two vertical dashed green lines.

of other outflows have offset the pumping. However, if the increases in pumping indicated in fig. 28 and in irrigated area shown in fig. 30 continue, the balance could be upset, leading to future water-level declines.

The cumulative water-level decline of 5.8 ft in GMD5 since predevelopment diminished groundwater discharge to the Arkansas River, Rattlesnake Creek, and other smaller streams in the district, therefore decreasing streamflow. In addition, the lower water-table level could be expected to allow a little more upward intrusion of saltwater into the base of the HPA from the underlying Permian bedrock. The smaller streamflow discharge of saline water from Rattlesnake Creek and other smaller streams receiving saline water intrusion could cause some accumulation of saline water in part of the aquifer relative to predevelopment when more saline water would have been flushed from the system. In comparison to GMD2, GMD5 does not appear to have reached a near balance between net inflow and pumping because water levels have continued to slowly decline since 1996 (fig. 26). Net inflows in GMDs 2 and 5 are not expected to decrease in the future nearly as much as in the Ogallala region because the water table is shallower and changes in delayed drainage from the unsaturated zone created by the smaller cumulative water-level declines would be much smaller.

Has Irrigation Pumping Been Reduced?

The substantially greater precipitation recharge in GMDs 2 and 5 compared to the Ogallala region means that the cumulative declines in groundwater levels caused by pumping have not been nearly as large as in the Ogallala region. Therefore, the need for pumping reductions has not been as great as for the western GMDs, except in selected areas such as western parts of GMD5, in the area around the City of McPherson, in the Wichita wellfield where water-level declines increase the potential for migration of saline water from the Arkansas River valley and the Burrton chloride plume (from past oil-field brine contamination), and in Rattlesnake Creek where pumping-induced declines in streamflow are affecting senior water rights held by the Quivira National Wildlife Refuge. No LEMAs or WCAs have been established in GMDs 2 and 5.

Figure 33, which is a plot of annual irrigation groundwater use versus January–September radar precipitation for GMD2, indicates that no statistically significant change in irrigation water use has occurred in the district. The companion plot (fig. S5 in Supplemental Figures) for annual irrigation groundwater use per irrigated area also shows no change. The same is true for similar graphs for GMD5 (fig. 34 and fig. S6 in Supplemental Figures). Thus, no statistically significant conservation management is apparent for recent years in either of the districts.

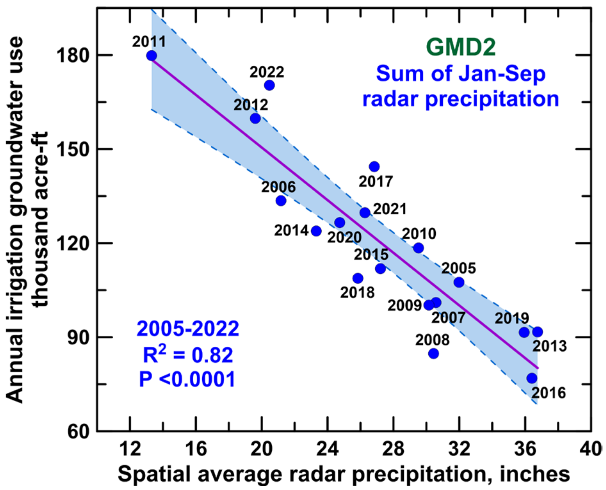

Figure 33. Annual irrigation groundwater use versus January–September radar precipitation for GMD2 for 2005–2022. The solid line is for the best fit to the data. The shaded confidence interval for the best-fit line is bounded by dashed lines for the 95% confidence interval.

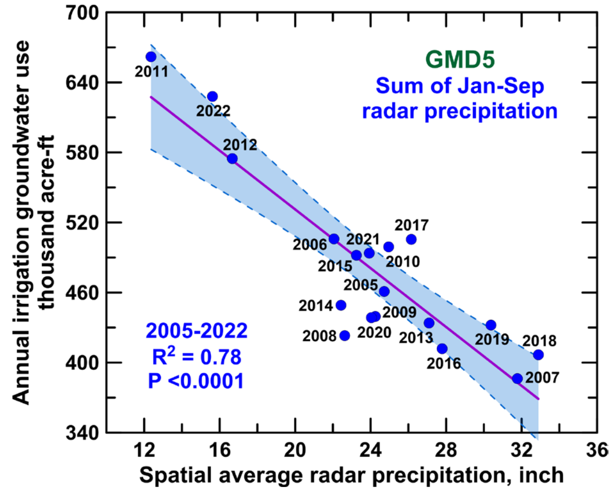

Figure 34. Annual irrigation groundwater use versus January–September radar precipitation for GMD5 for 2005–2022. The solid line is for the best fit to the data. The shaded confidence interval for the best-fit line is bounded by dashed lines for the 95% confidence interval.

Irrigation application rates (irrigation groundwater use per irrigated area) differ substantially across the Quaternary and Ogallala regions in the Kansas HPA. Figure 35 illustrates this by comparing the best-fit lines from the irrigation groundwater use per irrigated area versus precipitation plots discussed earlier for the five GMDs. If the irrigation application rates are compared for the GMDs at a 20-inch January–September precipitation, GMD5 has the highest irrigation application rate, 54% greater than GMD1 (during 2018–2022), 21% larger than GMD4, 11% higher than GMD2, and 2.5% higher than in GMD3. Both GMD3 and GMD5 have substantial areas of dune sand soils, although the percentage in GMD5 is greater. Sandy soils can require a higher irrigation application rate due to faster drainage. However, GMD3 has a higher average fraction of precipitation lost to evapotranspiration compared to GMD5 (Sanford and Selnick, 2013) and a lower average January–September precipitation during 2005–2022 (17.4 in. compared to 24.1 in.), which indicates that GMD3 might be expected to have a higher application rate than GMD5.

The average annual irrigation rates during 2005–2022 for GMDs 2 and 5 expressed as depths for the irrigated areas in the GMDs are 10.2 in. and 12.8 in., respectively, compared to 9.4 in. for GMD1 (during 2018–2022), 14.6 in. for GMD3, and 11.9 in. for GMD4. Based on these averages, the application rate for GMD2 is lower than for GMD4 and the rate for GMD5 is lower than in GMD3. The reason for the different order of GMDs 2 and 5 relative to GMDs 3 and 4 compared to fig. 35 is that the average precipitation is lower for GMDs 3 and 4 than for GMDs 2 and 5. If the average values for January–September precipitation in 2005–2022 for GMDs 2 and 5 are added to the average irrigation rates, the totals are 37.5 in. and 36.8 in., respectively, compared to 28.6 in. for GMD1 (during 2018–2022), 32.0 in. in GMD3, and 31.4 in. in GMD4. These totals represent the amount of water falling on cropland during January–September; the amounts for GMDs 2 and 5 are similar (37.1 ±0.4 in.) and the values for GMDs 3 and 4 are also similar (31.7 ±0.3 in.). Thus, the average total for GMDs 2 and 5 is 17% greater than for the average in GMDs 3 and 4.

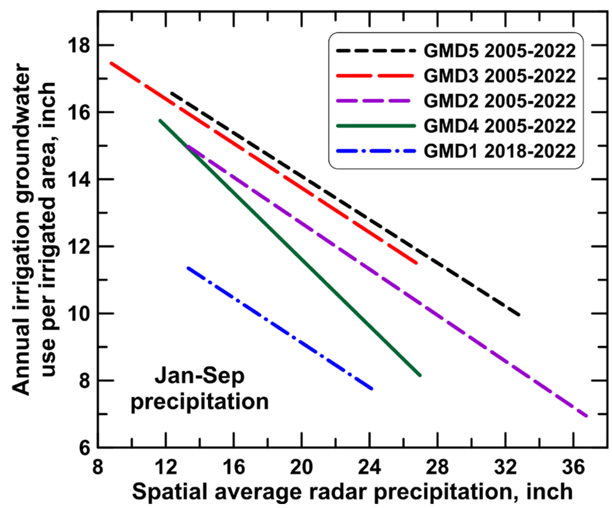

Figure 35. Best-fit lines for irrigation groundwater use per irrigated area versus January–September radar precipitation for GMD1 (2018–2022) and GMDs 3 and 4 (2005–2022) in the Ogallala region and for GMDs 2 and 5 (2005–2022) in the Quaternary region.

SUMMARY

Ogallala Region of the High Plains Aquifer (Western Kansas; GMDs 4, 1, and 3)

- The average aquifer thicknesses remaining in GMDs 4, 1, and 3 are 75 ft, 32 ft, and 142 ft, respectively.
- The cumulative declines in groundwater levels from predevelopment to the 2021–2023 average in GMDs 4, 1, and 3 are 28 ft, 51 ft, and 101 ft, respectively, which represent losses of 25%, 61%, and 45%, respectively, in the aquifer thickness.
- Average annual groundwater levels have declined 0.5–0.6 ft/yr in GMDs 4 and 1 and 1.8 ft/yr in GMD3 since 1996.
- Annual groundwater use has decreased about 14%, 49%, and 19% in GMDs 4, 1, and 3, respectively, since 1996.
- Pumping reductions needed to achieve stable water levels (zero water-level change) for the short term (up to a few decades) districtwide in the Ogallala region are 32% for GMD1, based on 2009–2022 data, and 25% and 18% for GMDs 3 and 4, respectively, based on 2005–2022 data.
- Pumping reductions to achieve stable water levels in more intensively pumped areas are greater than the 18–32% range for the districtwide areas. For example, the reduction required for the Sheridan-6 Local Enhanced Management Area (LEMA) in GMD4 would be 48% based on the 11 years of data preceding the establishment of the LEMA in 2013.
- Conservation management has reduced irrigation pumping 23.7–25.0% and irrigation application rates 23.2–23.9% (both adjusted for climatic conditions) since the establishment of the Sheridan-6 LEMA in 2013 compared to the pre-LEMA years of 2005–2012. These reductions have decreased the rate of groundwater-level decline by about 65%, thereby substantially lengthening the life of the aquifer in that area.
- Conservation management has reduced irrigation pumping by about 24% and the irrigation application rate by approximately 10% districtwide in GMD1 during 2018–2022 compared to 2005–2017. The 14 percentage point difference in water savings between pumping reduction and application rate is mainly due to a reduction in irrigated area.
- Conservation management has reduced irrigation pumping by about 40% and the irrigation application rate by about 24% in Wichita County in GMD1 during 2018–2022 compared to 2005–2017. The 16 percentage point difference in water savings between pumping reduction and application rate is mainly due to a reduction in irrigated area. The improvement in irrigation efficiency in Wichita County and in GMD1 overall is attributed largely to the establishment of many Water Conservation Areas in the county and elsewhere in the district starting in 2017 and to the establishment of the Wichita County LEMA in 2021.
- GMD3 appears to have reduced pumping by nearly 13% during 2019–2022 compared to 2005–2018 but additional years of data are needed to confirm this.
- Data analysis has not yet shown statistically significant indications of districtwide reductions in irrigation application rates in GMDs 3 and 4 (outside of the SD-6 LEMA).

Quaternary Region of the High Plains Aquifer (South-Central Kansas; GMDs 2 and 5)

- The current average aquifer thicknesses in GMDs 2 and 5 are 94 ft and 116 ft, respectively.
- The cumulative declines in groundwater levels from predevelopment to the 2021–2023 average in GMDs 2 and 5 are 6.9 ft and 5.8 ft, respectively, which represent losses of 7% and 5%, respectively, in aquifer thickness.
- Average annual groundwater levels have not changed significantly in GMD2 (average change much less than 0.1 ft/yr) and have slowly declined at a rate slightly less than 0.2 ft/yr in GMD5 during 1996–2022.
- Annual groundwater use has increased by approximately 6% in both GMDs 2 and 5 since 1996.
- Pumping reductions needed to achieve districtwide stable water levels are very small (0.7%) in GMD2 based on 2005–2022 data. Pumping would need to be reduced by 1.6% to attain districtwide stable water levels in GMD5. Maintenance of near-stable water levels in GMDs 2 and 5 is dependent on recharge during very wet years.
- Data analysis has not shown statistically significant indications of districtwide reductions in irrigation pumping and irrigation application rates in GMDs 2 and 5.

ACKNOWLEDGMENTS

This work was supported, in part, by the Kansas Water Office, the Kansas Water Plan under the Ogallala–High Plains Aquifer Assessment Program, the National Science Foundation under award 1039247, and the United States Department of Agriculture (USDA) under subaward RC104693B. John Woods at the Kansas Geological Survey (KGS) provided some of the data used in the graphs. The authors appreciate the comments provided by Julie Tollefson of the KGS, who edited and produced the final publication.

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APPENDICES

This publication and two appendices are available online on the Kansas Geological Survey website: https://kgs.ku.edu/2023-status-high-plains-aquifer-kansas

ADDITIONAL INFORMATION

Additional information and maps for a wide range of factors related to the High Plains aquifer in Kansas can be obtained from the **Kansas High Plains Aquifer Atlas**: www.kgs.ku.edu/HighPlains/HPA_Atlas/index.html

Water-level data can be found on the KGS WIZARD and Index Well Program websites.

WIZARD
http://www.kgs.ku.edu/Magellan/WaterLevels/index.html

Index Well Program
https://www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml

Water-use data are available at https://geohydro.kgs.ku.edu/geohydro/wimas/, a site developed by the KGS and KDA-DWR.

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SUPPLEMENTAL FIGURES

Companion Plots of Irrigation Water Use/Irrigated Area Versus Precipitation

As described in the main document, two plots are used to assess how pumping reductions were achieved. A plot of annual irrigation water use versus precipitation reveals whether pumping was reduced and, if so, by how much for similar climatic conditions; this is the type of plot shown in the main document in figs. 18, 20–23, 33, and 34. A second plot of annual irrigation water use/irrigated area (i.e., irrigation application rate) versus precipitation reveals whether irrigation efficiency improved and, if so, how much of the total water-use reductions were achieved by increases in water-use efficiency (reduction in irrigation application rate), again controlling for climatic conditions; this is the type of plot referred to as a “companion” plot in the main document and shown in fig. 19 in the main document and figs. S1–S6 in this section. The following figures display the companion plots for GMD4, GMD1, Wichita County, GMD3, GMD2, and GMD5. The best-fit lines from these plots are used in figs. 24 and 35 in the main document.

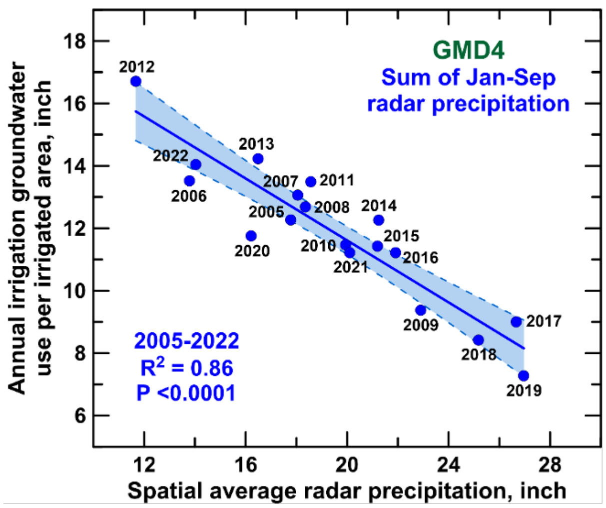

Figure S1. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation for GMD4 for 2005–2022.

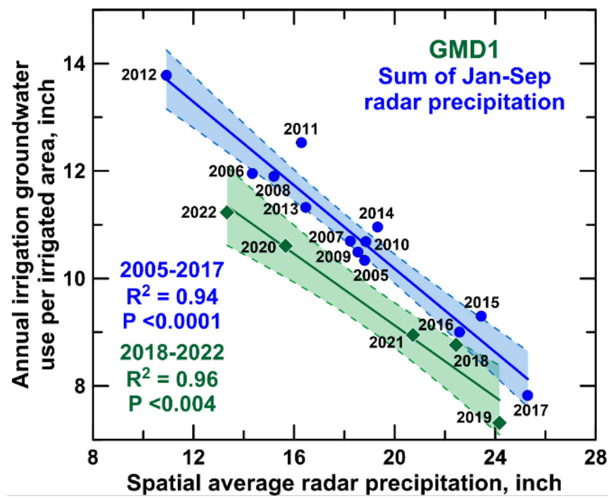

Figure S2. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation for GMD1 for 2005–2022. The percent reduction in water use based on improved irrigation efficiency is determined by the difference in the irrigation application rate between the two best-fit lines both at the average precipitation for the overlapping interval (18.65 in.) and at the average precipitation for 2005–2022 (18.59 in.).

Note: For all supplemental figures, the solid lines are for the best-fits (linear regressions) to the data. Shaded confidence intervals for the best-fit lines are bounded by dashed lines for the 95% confidence interval.

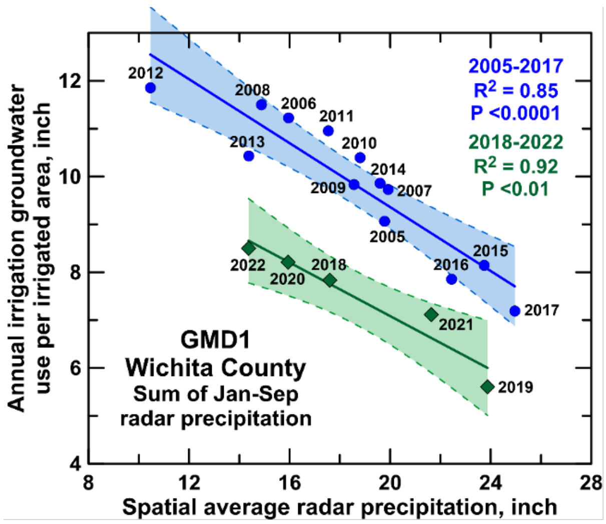

Figure S3. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation for Wichita County for 2005–2022. The percent reduction in water use based on improved irrigation efficiency is determined by the difference in the irrigation application rate between the two best-fit lines both at the average precipitation for the overlapping interval (18.69 in.) and at the average precipitation for 2005–2022 (18.50 in.).

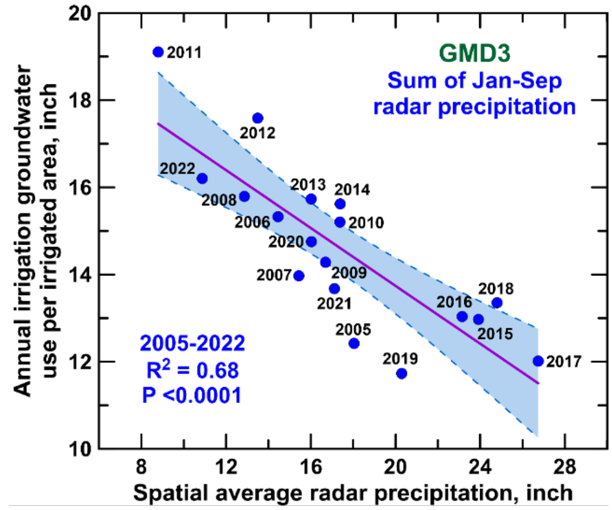

Figure S4. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation for GMD3 for 2005–2022.

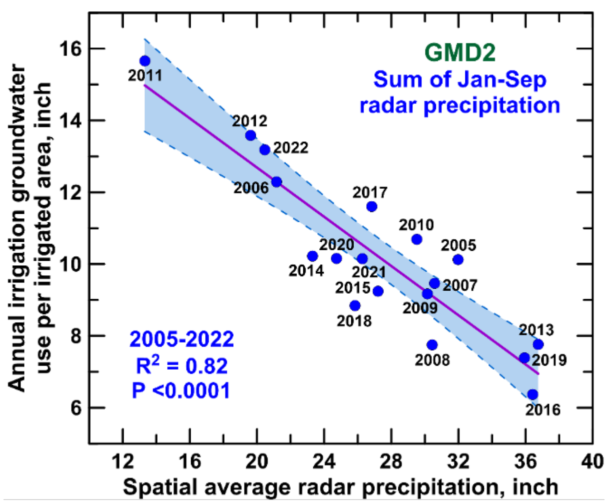

Figure S5. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation for GMD2 for 2005–2022.

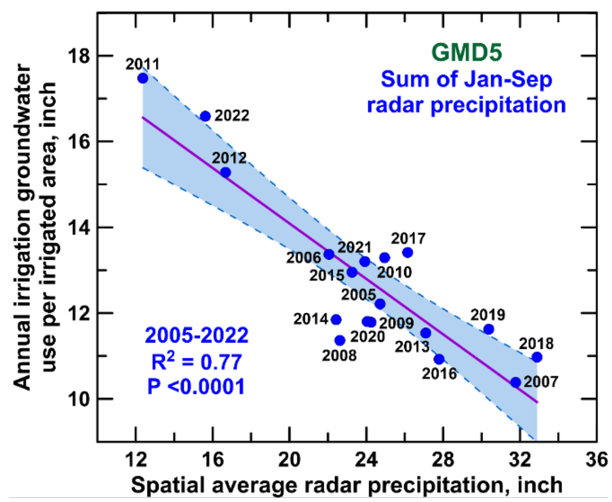

Figure S6. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation for GMD5 for 2005–2022.

Note: For all supplemental figures, the solid lines are for the best-fits (linear regressions) to the data. Shaded confidence intervals for the best-fit lines are bounded by dashed lines for the 95% confidence interval.

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