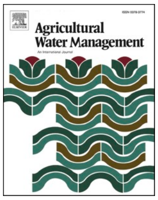
Agricultural Water Management 287 (2023) 108408

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat



Are we saving water? Simple methods for assessing the effectiveness of groundwater conservation measures

Donald O. Whittemore [*], James J. Butler Jr., Geoffrey C. Bohling, Blake B. Wilson

Kansas Geological Survey, University of Kansas, 1930 Constant Ave., Lawrence, KS, 66047, USA

ARTICLE INFO

Handling Editor - B.E. Clothier

Keywords:
Water conservation
Radar precipitation
Irrigation
High Plains aquifer

ABSTRACT

Substantial storage reductions by irrigation pumping in many of the world's major aquifers jeopardize future food production. As a result, new conservation measures are being utilized to reduce pumping and extend aquifer lifespans. The key question is how effective are these practices in attaining true water conservation (i.e., water use reduction) for a given area? Relationships between pumping and precipitation help provide an answer, as precipitation explains most of the variation in annual irrigation water use for aquifers in semi-arid to sub-humid climates when surface water supplies are limited. Our objective is to utilize correlations between radar precipitation and irrigation groundwater use at a range of spatial scales to assess the effectiveness of conservation approaches in the High Plains aquifer in the central USA. Linear regressions between pumping and precipitation for a conservation area established in 2013 in northwest Kansas indicate that water use and water use per irrigated area were over 27 % less and 25 % less, respectively, during 2013–2021 compared to the same climatic conditions during 2005–2012. Similar regressions found over a 38 % reduction and 23 % reduction in irrigation water use and use per irrigated area, respectively, during 2018–2021 compared to the same conditions during 2005–2017 in a west-central Kansas county with conservation areas. A decrease in irrigated area accounted for most of the difference between these reductions. Higher R^2 values after conservation area establishment imply that irrigation tracks precipitation better due to use of soil moisture sensors and other measures as part of increased irrigation efficiency and enhanced water management. The precipitation and water use relationships, which are statistically significant for a wide range of spatial scales, have great potential for assessing the effectiveness of conservation practices in areas with high-quality water use and precipitation data.

1. Introduction

Substantial water-level declines in many of the world's aquifers imperil future food production (Butler et al., 2021a; Cotterman et al., 2017; Gleeson et al., 2012). In response, new conservation measures are being implemented to reduce pumping (Ajaz et al., 2020; Deines et al., 2019). A challenge is determining the effectiveness of these practices for achieving true water conservation (i.e., water use reduction) for a given area.

Meteorological conditions, primarily precipitation, are usually the major drivers of variation in the annual volume of groundwater pumped for irrigation in sub-humid to semi-arid conditions, particularly in areas with limited surface water supplies. As a result, relationships between precipitation and water use appear to have great potential for demonstrating the effectiveness of conservation measures. We have previously shown that correlations between climatic indices and annual water use can be valuable tools for assessing the response of the High Plains aquifer (HPA) in the central United States (US) to various climatic conditions in the semi-arid and sub-humid portions of the state of Kansas (Whittemore et al., 2016). Precipitation coverages, such as radar precipitation and PRISM (http://prism.oregonstate.edu/), also yield good correlations with water use for a range of spatial scales (Whittemore et al., 2021). We use precipitation for correlations in this work because it explains a high degree of the variability in irrigation water use and does not require additional data and calculations. Thus, the correlations can be readily applied by state and local agencies over a range of spatial scales for groundwater management. We used radar rather than PRISM precipitation data because it can be more accurate at smaller scales as explained in the methods section.

Reliable measurements of annual pumping are required for correlations with precipitation. Although water-level measurements are often available over aquifer areas in the US and elsewhere, accurate water-use

---

[*] Corresponding author.
E-mail address: dwhitt@ku.edu (D.O. Whittemore).

https://doi.org/10.1016/j.agwat.2023.108408
Received 13 April 2023; Received in revised form 6 June 2023; Accepted 7 June 2023

data are not (Foster et al., 2020). Water use is typically estimated with a variety of approaches, such as energy use for groundwater pumping and evapotranspiration estimates from remotely sensed images of cropland. However, considerable uncertainty can be introduced into analyses based on those pumping estimates. Kansas is an outlier in this regard as it has some of the best water use data for aquifers in the US (USDA, 2019) and, likely, the world. These data, along with high-quality precipitation records available online, provide the basis for the precipitation and water use correlations discussed in this paper. We use radar precipitation because of its ease in scaling and spatial detail, allowing application from large regions down to areas as small as irrigated fields surrounding an individual well (Butler et al., 2015; Whittemore et al., 2021). The objective of this paper is to demonstrate a simple approach for assessing the effectiveness of water conservation efforts based on precipitation and water use correlations that could be used in other areas with sufficient data for its application.

1.1. Study area and aquifer regulation

The HPA is one of the world's largest aquifers and covers parts of eight states in the Great Plains region of the US (Fig. 1). The aquifer primarily provides water for irrigation with much smaller amounts for drinking, stock, and industrial water supplies. It is the most heavily pumped aquifer in the US, accounting for nearly 15 % of the nation's annual groundwater use (Lovelace et al., 2020). However, pumping from much of the HPA greatly exceeds inflows, which has caused large water-level declines in many areas (McGuire and Strauch, 2022). The current withdrawal rates cannot be sustained and will be further exacerbated by projected climate change (e.g., Rosenberg et al., 1999, 2003, Brunsell et al., 2010, Logan et al., 2010, Ou et al., 2018). Irrigation pumping, which made up almost 95 % of total withdrawals in 2015 (Lovelace et al., 2020), is the main driver of water-level changes in the HPA. Irrigation water primarily supplements precipitation for fall-harvested row crops, thus pumpage is concentrated during the summer growing season.

The Kansas HPA, which is the focus of this work, can be divided into two regions (Whittemore et al., 2018). The Ogallala region of the aquifer covers much of the western third of Kansas (Fig. 1) where three groundwater management districts (GMDs) are located (GMDs 1, 3, and 4). The climate is semi-arid with mean annual precipitation in the range

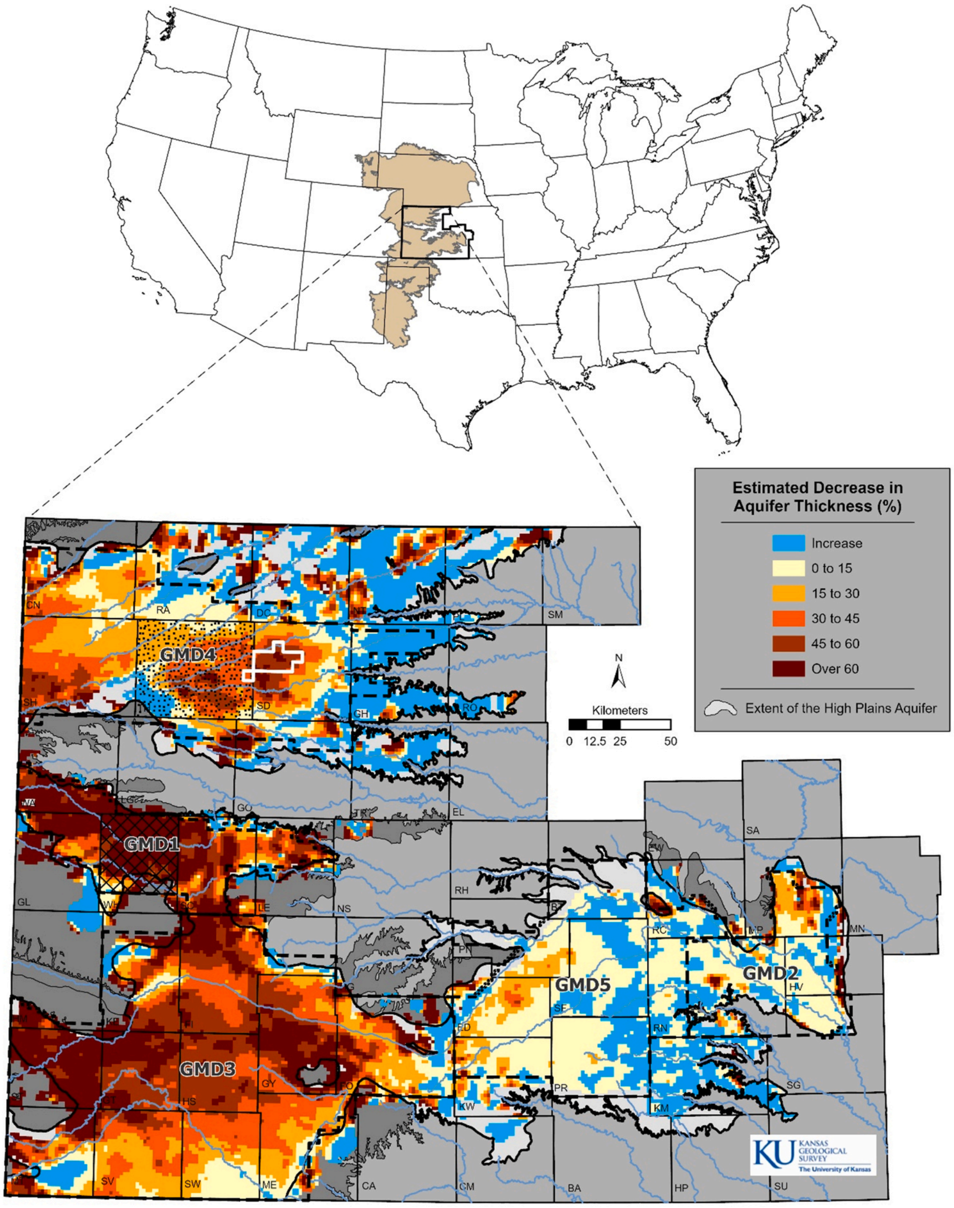


Fig. 1. The High Plains aquifer in the US and Kansas (inset). The five groundwater management districts (GMD# labels) are bounded by dashed lines and the area of the Sheridan-6 LEMA by a solid white line in GMD4 in northwest Kansas. The Kansas HPA also displays the percent change in aquifer thickness from predevelopment to present (2020–2022 average; modified from Butler et al., 2018). Counties are bounded by thin black lines. The crosshatched area is the portion of Wichita County in GMD1. The stippled area is Thomas County (discussed in the supplemental material). Substantial development started in the 1950s. The blue areas in GMDs 1, 3, and 4 have little aquifer thickness.

330–620 mm. The depth to water is generally substantial (>10 m to ~100 m) and most rivers and stream courses are ephemeral; those that did flow in the past are now usually dry due to substantial water-level declines in the aquifers that originally supplied them with water (Zipper et al., 2021). The thickness of the aquifer in the Ogallala region has substantially decreased in the last seven decades as shown in Fig. 1. Fig. 2 displays the thickness change starting with the mean for 2004–2006 and then for each individual year to 2021 for the three GMDs in the Ogallala region of western Kansas based on the water-level surface for wells with continuous annual winter measurements and the bedrock surface generated from well logs. The absolute thickness decline for GMD1 (2.6 m) during the period resulted in a decline of 20.4 %. The thickness drop for GMD4 (2.1 m) was smaller than for GMD1 and resulted in a decline of 8.9 %. Although the absolute thickness decrease for GMD3 (8.6 m) was substantially greater than for the other two GMDs, it amounted to a drop (16.1 %) that was less than that for GMD1. The absolute aquifer thicknesses remaining in 2021 for GMDs 1, 3, and 4 were 10.1 m, 44.9 m, and 21.1 m, respectively. No surface water is used (based on water right permits) in GMDs 1 and 4, and average surface water use comprised 2.1 % of total (groundwater and surface water) water use in GMD3 during 2005–2021. Irrigation groundwater use was 95.1 %, 93.7 %, and 97.6 % of total use in GMDs 1, 3, and 4, respectively, in 2005–2021 (Division of Water Resources of the Kansas Department of Agriculture [KDA-DWR]).

The Quaternary region of the aquifer in south-central Kansas (Fig. 1) has a sub-humid climate with mean annual precipitation in the range 620–880 mm. The depth to water is generally shallow (<20 m) and rivers and streams still flow in most of the region, providing active stream-aquifer interaction. Two GMDs (2 and 5) cover the Quaternary region. Although the aquifer thickness has decreased appreciably in some areas, the thickness has not changed significantly in most of the region, but fluctuates depending on extended wet and dry periods (Whittemore et al., 2018). The absolute thicknesses remaining in 2021 in GMDs 2 and 5 were 28.6 m and 33.1 m, respectively, which were greater than for GMDs 1 and 4. The thickness decreases during 2005–2021 were very small for GMD2 (0.3 m, 1.0 %) and GMD5 (0.08 m, 0.2 %). Surface water use was 1.1 % and 2.7 % of total water use in GMDs 2 and 5, respectively, in 2005–2021. Irrigation groundwater use comprised 65.2 % and 96.0 % of total use in GMDs 2 and 5, respectively, during 2005–2021 (KDA-DWR).

Substantial data exist for water use across the HPA in Kansas. The reported water use data and their accuracy over the HPA in Kansas are estimated to be the best for any large aquifer in the US based on the high percentage of wells with totalizing flowmeters (now ~98 %) and the supporting regulatory framework (Butler et al., 2016; USDA, 2019). Kansas has used water right permits, based on the prior appropriation system, for water use since 1945; the filing of annual water use reports for these permits became mandatory in 1988 (Peck, 1995). The KDA-DWR, which receives the water use reports, began a program of reviewing the reports for accuracy in 1990; annual water use reports for all permitted wells are available since then. Stiff penalties exist for failure to provide accurate data, including tampering with flowmeters (KDA-DWR, 2021). This dataset provides an excellent basis for examining precipitation as the meteorological driver of irrigation pumping.

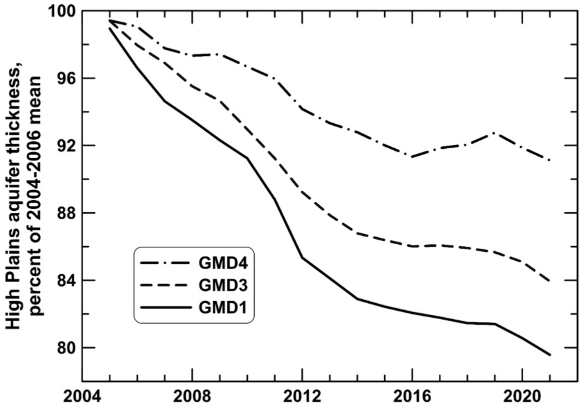


Fig. 2. Percent change in HPA thickness starting from the 2004–2006 mean and then for each individual year to 2021 for the GMDs in the Ogallala region of the HPA.

Irrigation efficiency has substantially increased in recent decades, but this has not often led to true water conservation because pumping was not reduced either due to irrigating more water-needy crops or expanding the irrigated area (Ward and Pulido-Velazquez, 2008; Pfeiffer and Lin, 2014; Sears et al., 2018). In response to continued declines in the water table in the Ogallala region of the Kansas HPA, the two GMDs for which the estimated usable lifetime of the aquifer is the shortest (GMDs 1 and 4; Buchanan et al., 2023) began to implement water conservation measures using new management frameworks established by the Kansas Legislature (Butler et al., 2018; Griggs, 2021). The first was the Local Enhanced Management Area (LEMA) program established in 2012 to facilitate pumping reductions. A LEMA is initiated by stakeholders who propose a plan for pumping reductions. The plan is approved by the GMD in which the LEMA is located and then accepted (or rejected) by the Chief Engineer of the KDA-DWR after hearings. A LEMA includes regulatory oversight to ensure that all irrigators in the area follow the agreed-upon reductions. A later legislative initiative established the Water Conservation Area (WCA) program, which allows any water right owner or group of owners to develop a management plan to reduce pumping. A WCA is typically smaller than a LEMA, independent of a GMD, and only needs the approval of the Chief Engineer.

The first LEMA, the Sheridan-6 (SD-6) LEMA, started in 2013 in a 255 km^2 area in GMD4 in northwest Kansas (Fig. 1). The goal was to reduce the average annual groundwater use by 20 %. In 2018, a district-wide LEMA was initiated in GMD4 with a more modest reduction goal that varied among townships (area of a township is ~93 km^2). A series of WCAs were established in Wichita County in GMD1 (crosshatched in Fig. 1) starting in 2017, followed by a county-wide LEMA in 2021. The formation of a four-county LEMA in GMD1 is currently in the hearing process of the KDA-DWR. The effectiveness of these LEMAs and WCAs will be assessed in the following sections.

2. Methods

The methods involved selection and retrieval of precipitation and irrigation water use data (including irrigated acreage) for determining the correlations of radar precipitation with water use and water use per irrigated area, estimating the relative importance of water savings from improved water efficiency compared to those from decreases in irrigated area, and assessment of linear regressions of precipitation versus water use by statistical models.

We used monthly values of multi-sensor precipitation observations (primarily radar data) that are available for download from the Advanced Hydrologic Prediction Service (AHPS) of the National Weather Service (NWS) (http://water.weather.gov/precip/) for the US. These data have been served online since 2005 for the conterminous US, Puerto Rico, and Alaska in spatial images and digital coverages. Precipitation data are based on hourly estimates from WSR-88D NEXRAD that are compared to and then corrected for ground rainfall gauge reports. Where radar coverage is not available or limited, precipitation estimates incorporate satellite observations. The radar data are available at a spatial resolution of ~4 × 4 km (gridded values for 2005–2016; raster format thereafter), thereby capturing the spatial variability in precipitation that can occur between precipitation gauges.

PRISM precipitation data could also be used for the correlations. However, a comparison to radar data found that PRISM values are typically less than those of radar precipitation for areas within the Kansas HPA, regardless of their size (see Supplemental material). The region overlying the Kansas HPA has short but intense spring through fall thunderstorms that can have areas of influence smaller than the distance between many of the PRISM precipitation stations. Thus, the radar precipitation dataset may better capture the precipitation distribution across the region.

Total irrigation groundwater use and irrigated area data were acquired from the KDA-DWR through the online Water Information Management and Analysis System (WIMAS) available on the Kansas Geological Survey website (https://geohydro.kgs.ku.edu/geohydro/wimas/). Water use and water use per irrigated area were plotted against radar precipitation and linear regressions and confidence intervals for the lines at the 95 % confidence interval were determined for the plots.

The typical irrigation season over the Kansas HPA starts from mid-March to the beginning of May and ends during late August to mid-September based on water-level hydrographs from a network of monitoring wells (Butler et al., 2021b). However, precipitation in January and February can also affect water use. Dry conditions during these months can result in irrigators pumping water in March and April to build up soil moisture before planting row crops. Substantial rain and snow during January and February that provides ample soil moisture obviates the need for the pre-planting irrigation. Although the primary crops are corn, soybeans, and sorghum grown during the main irrigation season (March–September), winter wheat and hay (such as alfalfa) may be irrigated in January and February during especially dry periods. Thus, the sum of January through September precipitation was considered the most appropriate quantity for use in correlations with groundwater pumping. Different sums of contiguous monthly precipitation within the main irrigation season of March–September were also examined for water use reductions to compare with those based on January–September precipitation as a means of evaluating uncertainty in the reduction values; this is discussed in the Supplemental material.

Reductions in irrigation water use have two main components; that produced by more effective water-use strategies and that resulting from decreases in irrigated area. The first component is evaluated by plotting irrigation water use per irrigated area versus precipitation. The second component is obtained by plotting total irrigation water use versus precipitation. The relative contribution of each can be determined by subtracting the reduction computed from the first plot from that for the second.

Other factors besides precipitation and irrigation efficiency can affect annual water use from year to year, most notably changes in irrigated area and crop types. Although the mixture of crop types has not changed substantially during the last two decades (Rogers and Aguilar, 2017), irrigated area has generally decreased in GMDs 1 and 3, increased in GMDs 2 and 4, and remained approximately constant in GMD5 based on data from WIMAS. The correlations were performed with both annual irrigation water use and annual irrigation water use divided by the irrigated area for each year (i.e., depth of applied water) to remove the effect of changing irrigated area. The emphasis in this paper is on the correlations for water use per irrigated area because of the uncertainty in whether water use reductions due to decreases in irrigated area were associated with conservation measures or due to the abandonment of irrigation as a result of insufficient aquifer thickness. Correlations of total irrigation groundwater use with precipitation are also included for comparison.

We illustrate the impacts of conservation primarily through graphical comparison of the water use (per area or total) versus precipitation regressions for the pre-conservation and conservation periods in SD-6, Wichita County, and GMD1. To support the conclusions drawn from these comparisons, we have used F tests (Draper and Smith, 1981) to assess the improvement in fit of two alternative models, one with separate intercepts but a common slope for the two periods (the parallel-slopes model) and one with separate intercepts and slopes (the full model), over a model in which all the data are fit with a single line (the reference model). We take the significance of this improvement as the indication of the impact of conservation measures. The details of this procedure are given in the Supplemental material.

3. Results and discussion

Water use and precipitation relationships were first examined for the areas in the Kansas HPA in which groundwater conservation measures have been implemented. The SD-6 LEMA was the earliest established management area and had the largest reduction goal. The plot of irrigation pumping per unit area versus precipitation for the pre-LEMA (2005–2012) and LEMA (2013–2021) periods demonstrates that true water conservation has been achieved (Fig. 3). The reduction in water use as indicated by the offset in the two regression lines at the mean precipitation during January–September for 2005–2021 is 25.0 %. The average irrigated area decreased after the LEMA started based on irrigator reports (WIMAS data) and satellite information (Deines et al., 2019). The additional water savings from the smaller irrigated area is 2.4 % based on the correlation of annual irrigation groundwater use with January–September precipitation, giving a reduction in the total irrigation groundwater use of 27.4 % (Fig. 4). Although some of the scatter in the points for the pre-LEMA period could be produced by uncertainty in the water use reporting (flowmeter performance has been more closely checked after establishment of the LEMA), much of the scatter is likely related to irrigators not tracking soil-moisture conditions as well as during the LEMA. For example, simple measures, such as cutting off pumps when it starts to rain, which were not always done in the past, have been important (L Letourneau, Water Appropriations Program Manager, KDA-DWR, personal communication). Deines et al. (2019) found that farmers attained most of their pumping reductions from increases in irrigation efficiency while generally maintaining irrigated area, consistent with our correlation results. Soil moisture sensors allowed the irrigators to adjust water applications and track the precipitation variation closely as evidenced by precipitation explaining 90 % of the variation in water use during the LEMA. The water conservation measures implemented in the SD-6 LEMA have slowed water-level declines in the aquifer compared to pre-LEMA declines, especially after adjustment for changes in annual climatic conditions (Butler et al., 2023).

As described in the Supplemental material, formal statistical testing confirms that there is a significant difference between the water use per

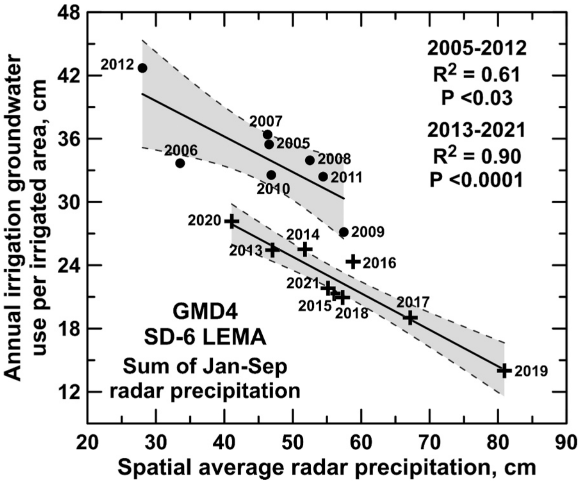


Fig. 3. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation for the SD-6 LEMA for 2005–2021. The solid lines are for the linear regressions. Shaded confidence intervals for the regression lines are bounded by dashed lines for the 95 % level. The regression equations are $W/A = -0.3367 \times P + 49.67$ for 2005–2012 and $W/A = -0.3463 \times P + 42.19$ for 2013–2021, where W is water use, A is irrigated area, and P is precipitation.

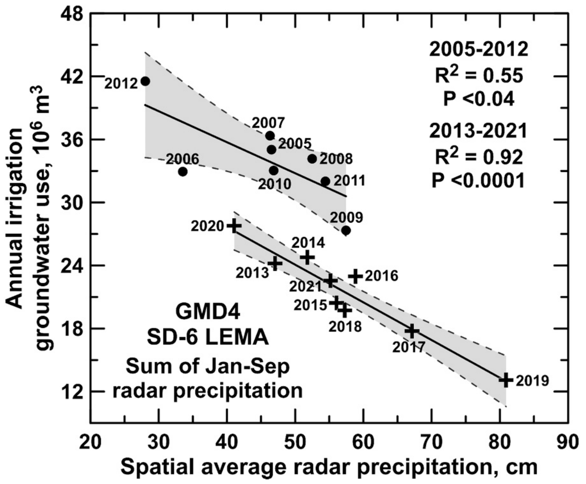


Fig. 4. Annual irrigation groundwater use versus January–September radar precipitation for the SD-6 LEMA for 2005–2021. The regression equations are $W = -0.2952 \times P + 47.54$ for 2005–2012 and $W = -0.3587 \times P + 42.02$ for 2013–2021. See Fig. 3 for explanation of solid lines, shaded intervals, and regression equation terms.

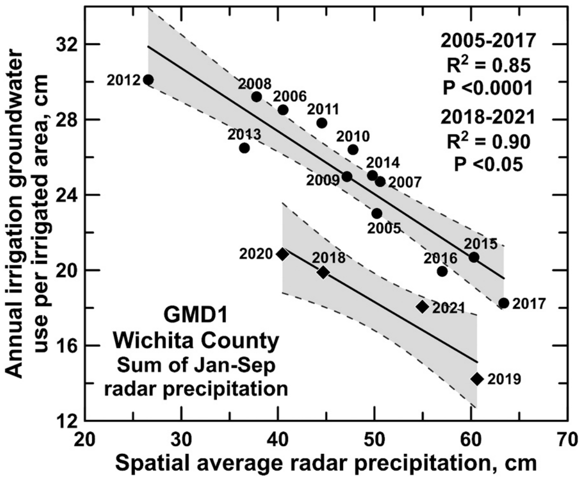


Fig. 5. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation for Wichita County within GMD1 for 2005–2017 and 2018–2021. The regression equations are $W/A = -0.3341 \times P + 40.75$ for 2005–2017 and $W/A = -0.3008 \times P + 33.36$ for 2018–2021. See Fig. 3 for explanation of solid lines, shaded intervals, and regression equation terms.

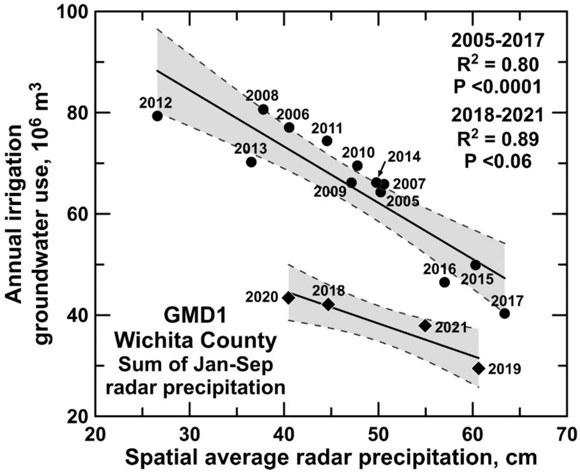


Fig. 6. Annual irrigation groundwater use versus January–September radar precipitation for Wichita County within GMD1 for 2005–2017 and 2018–2021. The regression equations are $W = -1.1124 \times P + 117.8$ for 2005–2017 and $W = -0.6427 \times P + 70.49$ for 2018–2021. See Fig. 3 for explanation of solid lines, shaded intervals, and regression equation terms.

area versus precipitation regressions for the pre-LEMA and LEMA periods. The F test assessing the significance of the improvement in fit of the parallel-slopes model over the reference model yields a p value of 1.2×10^{-5} and that comparing the full model (which produces regression lines equivalent to those in Fig. 3) to the reference model yields a p value of 9.9×10^{-5} (table S4) (a smaller p value indicates a more significant difference in fit). For total water use, the corresponding F tests yield p values 4.1×10^{-6} and 3.3×10^{-5} (table S5), confirming a significant reduction in total water use as well. In both cases, the full model fails to provide a significant improvement over the parallel-slopes model, meaning the conservation impacts can be characterized as a constant reduction in use per area or total use with no significant change in slope. The intercept difference estimates from the parallel-slopes models indicate reductions of 8.0 cm in use per area and 8.7×10^6 m^3 in total use.

A series of WCAs were established in Wichita County in GMD1 starting in March 2017, although the bulk of the enrolled area was after the 2017 irrigation season. A LEMA was then approved for Wichita County in February 2021. The plot of pumping per irrigated area versus precipitation for January–September demonstrates that true water conservation has again been achieved (Fig. 5). In this case, the reduction in water use as indicated by the offset in the two regression lines is 23.4 % at the mean precipitation during 2005–2021. The irrigated area also decreased during the study period; the additional water savings from the smaller irrigated area is 15.1 % based on the correlation of irrigation groundwater use with January–September precipitation, giving a total groundwater use reduction of 38.5 % (Fig. 6).

For use per area in Wichita County, the F tests comparing the parallel-slopes and full models to the reference model yield p values of 4.5×10^{-6} and 4.0×10^{-5}, respectively (Table S4), and the corresponding tests for total use yield p values of 3.4×10^{-6} and 1.6×10^{-5} (Table S5), again confirming that conservation measures have had significant impact. As in SD-6, the full models fail to yield significant improvements over the parallel-slopes models, again indicating approximately constant reduction across the range of precipitation values. The reductions indicated by the parallel-slopes models are 5.7 cm in use per area and 24.0×10^6 m^3 in total use.

GMD4 established a district-wide LEMA in 2018, but legal challenges to the LEMA were not resolved until the fall of 2019. These legal challenges possibly delayed the participation of some irrigators as the plot of pumping versus precipitation reveals that little water conservation was achieved in the first four years of the LEMA (Fig. 7). In addition, the annual maximum rates of irrigation applications allowed during the initial 5-year LEMA period were greater than the actual mean irrigation water use per unit area during 2005–2021. Thus, only those irrigators with particularly high application rates were required to reduce their rate. Several WCAs have been established in two counties in GMD4 but their total area is not yet large enough to significantly affect water consumption; those WCAs with individual sizes exceeding 400 ha were developed during 2018–2022. GMD4 includes parts or all of ten counties in northwest Kansas. Some of these counties show a separation between 2005–2017 and 2018–2021 plots of water use per irrigated area versus precipitation. However, a series of hailstorms during the late spring and early summer of 2018 destroyed crops in local areas across GMD4 resulting in some cessation of pumping. Additional years of data will be needed to determine if the apparent reductions in water use per irrigated area are statistically significant in the individual counties.

There is no district-wide LEMA for GMD1, but the district has proposed that one be established in four of the five counties in the GMD.

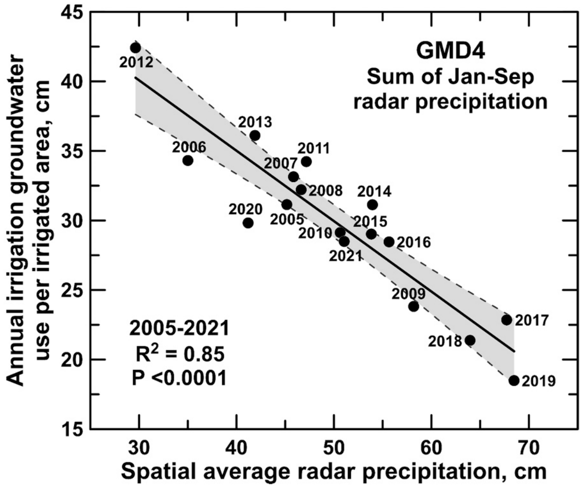


Fig. 7. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation annual water use per irrigated area for GMD4 for 2005–2021. The regression equation is W/A = −0.5063 x P + 55.27. See Fig. 3 for explanation of solid lines, shaded intervals, and regression equation terms.

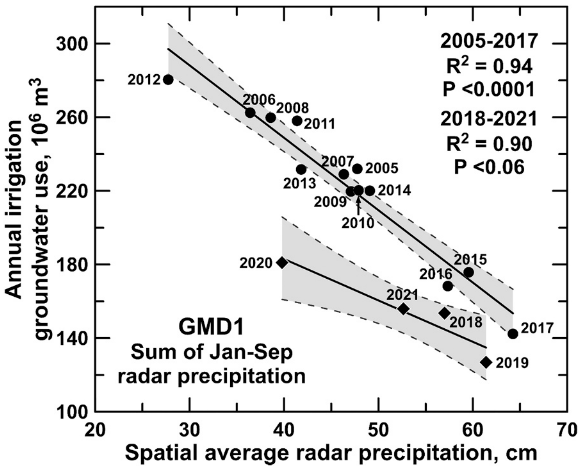


Fig. 9. Annual irrigation groundwater use versus January–September radar precipitation for GMD1 for 2005–2017 and 2018–2021. The regression equations are W = −3.932 x P + 406.1 for 2005–2017 and W = −2.248 x P + 272.9 for 2018–2021. See Fig. 3 for explanation of solid lines, shaded intervals, and regression equation terms.

Despite that, there is a separation between the 2005–2017 and 2018–2020 regression lines for GMD1 (Fig. 8). This separation is mainly produced by the Wichita County WCAs (Fig. 5), as well as the two counties to the east and the county to the west, which have apparently adopted some conservation measures during this period. The conservation measures appear to start in 2018 (WCAs started partway through 2017) and are likely partly driven by the relatively small thickness of the HPA in those areas, which has forced some irrigators to reduce their water use. The estimated reduction in the district-wide water use per irrigated area for 2018–2021 for the same climatic condition during 2005–2017 is 10.1 % based on Fig. 8. The water use reduction based on a correlation of irrigation water use versus January–September precipitation is 24.1 % (Fig. 9); the additional 14.0 % is undoubtedly due to the decrease in irrigated area in the district.

For GMD1, the F tests comparing the parallel-slopes and full models to the reference model for use per area yield p values of 8.0×10^{-4} and 4.1×10^{-3}, respectively (Table S4), still significant but less so than for SD-6 or Wichita County. For total water use, the corresponding F tests yield p values of 1.1×10^{-5} and 8.5×10^{-6} (Table S5), reflecting the greater percentage reduction in total water use compared to use per area. In this case, the full model for use per area still fails to yield a significant improvement over the parallel-slopes model, but that for total use yields a marginally significant improvement, with a p value of 0.03 (and thus significant at the 5 % level). The reductions indicated by the parallel-slopes models are 2.6 cm in use per area and 46.3 × 10^6 m^3 in total use.

There are no LEMAs in the other three GMDS (2, 3, and 5), and WCAs represent a small proportion of the total area in each of these districts. As a result, water conservation efforts do not yet appear to have had a substantial impact. The plot of water use per unit area versus radar precipitation for GMD3, which is also in the Ogallala region of the HPA where large water-level declines occur, shows no statistically significant indication of water conservation (Fig. 10); the plots for GMDs 2 and 5 are similar (Figs. 11 and 12). Plots of water use versus climatic indices for 1996–2012 also show no indication of water conservation in these districts (Whittemore et al., 2016). Although individual producers have adopted water conservation measures in GMD3, and points for the years

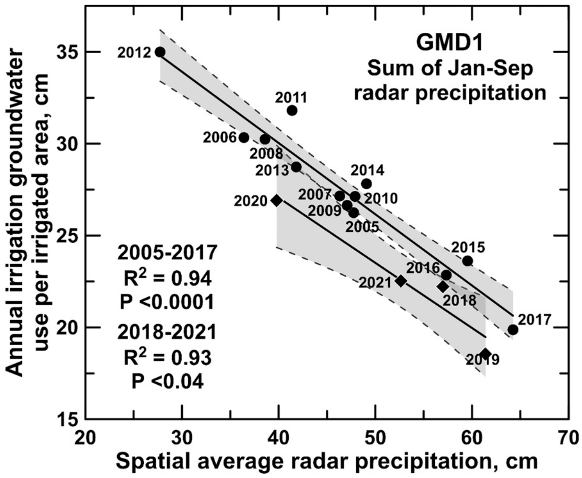


Fig. 8. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation for GMD1 for 2005–2017 and 2018–2021. The regression equations are W/A = −0.3877 x P + 45.55 for 2005–2017 and W/A = −0.3545 x P + 41.24 for 2018–2021. See Fig. 3 for explanation of solid lines, shaded intervals, and regression equation terms.

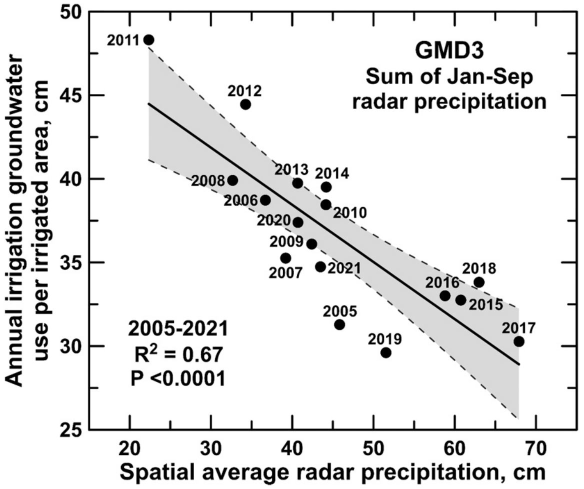


Fig. 10. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation for GMD3 during 2005–2021. The regression equation is W/A = −0.3418 x P + 52.12. See Fig. 3 for explanation of solid lines, shaded intervals, and regression equation terms.

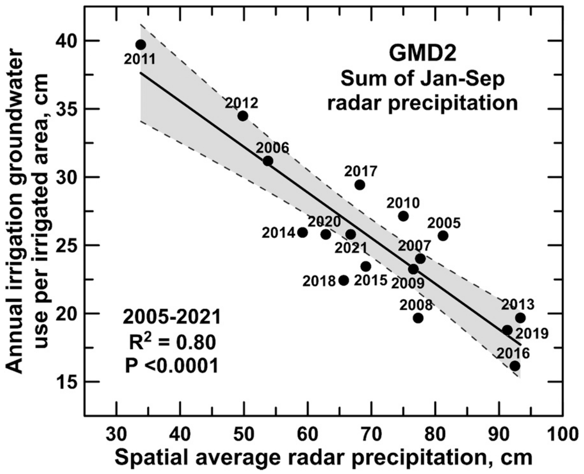


Fig. 11. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation for GMD2 during 2005–2021. The regression equation is W/A = −0.3344 x P + 48.94. See Fig. 3 for explanation of solid lines, shaded intervals, and regression equation terms.

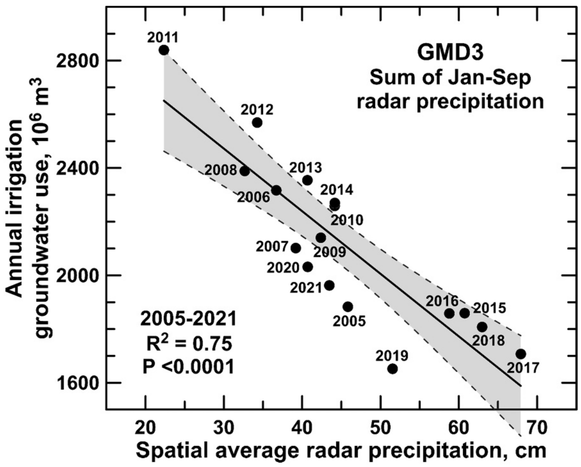


Fig. 13. Annual irrigation groundwater use versus January–September radar precipitation for GMD3 for 2005–2021. The regression equation is W = −23.31 x P + 3171. See Fig. 3 for explanation of solid lines, shaded intervals, and regression equation terms.

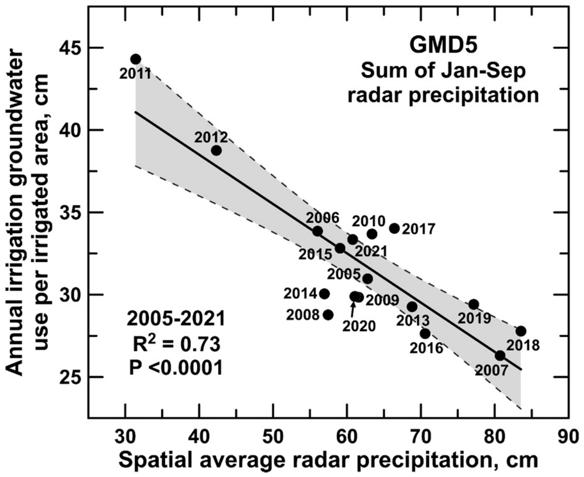


Fig. 12. Annual irrigation groundwater use per irrigated acre versus January–September radar precipitation for GMD5 during 2005–2021. The regression equation is W/A = −0.2994 x P + 50.48. See Fig. 3 for explanation of solid lines, shaded intervals, and regression equation terms.

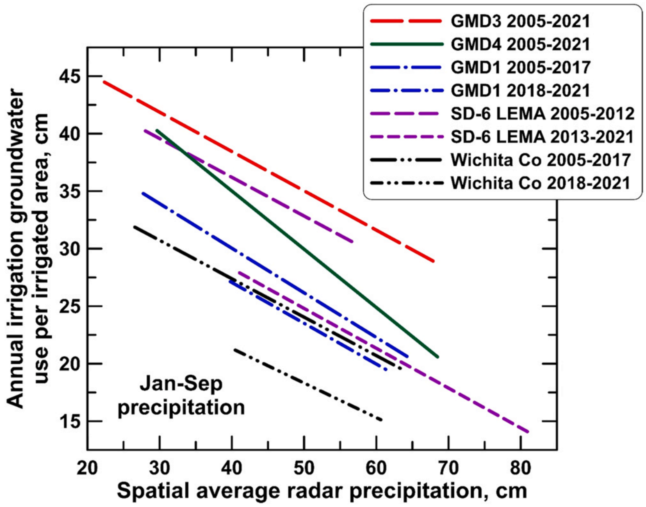


Fig. 14. Regression lines for irrigation water use per area versus January–September radar precipitation for the three GMDs in the Ogallala region of the HPA, the SD-6 LEMA in GMD4, and Wichita County in GMD1. The regression lines are the same as those in Figs. 3, 5, 7, 8, and 10.

2019–2021 for GMD3 plot below the regression line in Fig. 10, their impact on district-wide conditions for irrigation application rate is too small to show a statistically significant separation from prior conditions based on data for 2005–2021. However, points for these three years fall appreciably below the lower confidence interval boundary in a graph of irrigation water use versus precipitation for GMD3 (Fig. 13), indicating a general decrease in irrigated area in GMD3 since 2018.

The water use and precipitation relationships are also useful for comparing irrigation rates among different areas for similar climatic conditions. Irrigation rates have ranged widely for the different GMDs, counties, and the SD-6 LEMA in the Ogallala region of the HPA as indicated by the relative positions of the regression lines for the radar precipitation and irrigation water use per irrigated area correlations in Fig. 14. GMD3 has had the largest application rate (Fig. 10) and GMD1 the smallest (Fig. 8) of the three western GMDs. The order of the irrigation rates is the same as the remaining aquifer thickness, GMD3 has the greatest and GMD1 the least. The relatively small aquifer thickness in GMD1 at predevelopment has decreased substantially as indicated in Fig. 1, especially in Wichita County, including a decrease of over 20 % from 2005 to 2021 (Fig. 2). This has compelled irrigators in GMD1 to reduce pumping to maintain sufficient aquifer thickness for irrigation, even without a district-wide LEMA; the significant change in reduction occurred starting around 2018. The water use application reduction during the SD-6 LEMA (2013–2021) brought the regression line down from above the rate for GMD4 to close to that for Wichita County and GMD1 during 2005–2017 but still higher than that for GMD1 during 2018–2021 (Fig. 14). The irrigation water use per area in Wichita County during 2005–2017 was already less than that for GMD1 during 2005–2017. The addition of a substantial number of WCAs then caused a significant reduction from 2017 to 2018; the application rate during 2018–2021 is the lowest of any areas discussed in this paper. Therefore, although LEMAs and WCAs can lead to sizable water use reductions, diminishing aquifer thickness, particularly in areas where that thickness was already small, can also lead to sizable reductions. Some areas of GMD3 have seen relatively large decreases in aquifer thickness, leading to the establishment of a number of WCAs, but the involved area is too small relative to the size of the large district to produce a discernable change in the overall water use rate.

4. Conclusions

The correlation of radar precipitation and water use in heavily irrigated areas of the HPA in Kansas is highly statistically significant for a wide range of scales, from groundwater management districts (several thousand to over 20,000 km^2 in area) to sub-county areas of a few hundred km^2. Although not discussed here, similar results have been found for areas as small as a few km^2 around individual wells (Butler et al., 2021b). The coefficients of determination range from about 0.7 to over 0.9, indicating that precipitation is the main driver of variations in water use.

The radar precipitation and water use relationship has allowed the impact of new approaches to groundwater management in the Kansas HPA to be assessed. We have shown that water use for a 255 km^2 Local Enhanced Management Area (LEMA) has decreased over 27 % in comparison to the pre-LEMA use. Recently established Water Conservation Areas (WCAs) have produced reductions of over 23 % relative to the pre-WCA use based on application rate alone, and even more if some of the decrease in irrigated area is related to conservation measures. We have also found that these recent water use reductions are now becoming apparent on a considerably larger scale than those of the LEMA and WCAs. This could be a product of emulation of the practices used in the conservation areas or simply the result of the aquifer thickness getting to a point that previous pumping rates cannot be maintained and fewer acres are irrigated. The reduction in this case has been as large as 24 % for GMD1. The implemented water conservation measures that are producing significant water savings are also slowing water-level declines in the aquifer (e.g., Butler et al., 2023).

The reductions in water use identified here have two components. The reduction produced by more effective water-use strategies appears to be responsible for more than 40 % to over 90 % of the observed decreases in water use. These strategies can be implemented either by more efficient irrigation of the same crops using soil-moisture sensors and other measures or by irrigating less water-needy and more drought-tolerant crops. The other component is the reduction produced by decreases in irrigated area. The first component can be evaluated by plotting irrigation water use per irrigated area versus precipitation. Insight into the magnitude of the second component can be obtained by plotting total irrigation water use versus precipitation, and subtracting the reduction computed from the first plot from that for the second. This approach could also be used in assessing where an increase in irrigation efficiency leads to an increase in overall water use due to increases in irrigated area as an example of Jevons paradox (Dumont et al., 2013; Sears et al., 2018).

Linear regressions of water use versus precipitation allow prediction of future water use for climatic conditions in which only mean precipitation changes. More importantly, however, these relationships should allow the impact of climate change to be identified. If, as climate change models forecast, temperatures continue to rise and the frequency and length of arid conditions increases, resulting in more soil water stress, a shift in the linear regression for an area will occur even without substantial changes in management practices.

These relationships are dependent on high-quality precipitation and groundwater use data. High-quality precipitation data are often available, but reliable groundwater use data are not. As we have stressed repeatedly in earlier publications (e.g., Butler et al., 2018, 2023), greater attention needs to be placed on the monitoring of groundwater use. We have previously demonstrated that monitoring of a subset of the pumping wells in an aquifer can be a cost-effective strategy that yields reliable data on groundwater use (Bohling et al., 2021). When high-quality pumping data are available, we have shown here that radar precipitation and water use relationships can provide insights of great practical value.

Funding

This work was supported, in part, by the Kansas Water Plan under the Ogallala-High Plains Aquifer Assessment Program (OHPAAP), USA; the Kansas Water Office (KWO), USA; and the United States Department of Agriculture (USDA), United States. and the United States National Science Foundation (NSF), United States. under USDA-NIFA/NSF INFEWS subaward RC108063UK, and the NSF under award RISE-2108196. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the OHPAAP, KWO, USDA, or NSF.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: None.

Data Availability

Data will be made available on request.

Acknowledgements

We appreciate the assistance of John Woods at the Kansas Geological Survey in downloading and processing radar precipitation data. We thank the two anonymous reviewers for comments that helped improve the paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108408.

References

Ajaz, A., Datta, S., Stoodley, S., 2020. High Plains aquifer – State of affairs of irrigated agriculture and role of irrigation in the sustainability paradigm. Sustainability 12 (9), 3714. https://doi.org/10.3390/sul2093714.

Bohling, G.C., Butler Jr., J.J., Whittemore, D.O., Wilson, B.B., 2021. Evaluation of data needs for assessments of aquifers supporting irrigated agriculture. Water Resour. Res. 57 (4) https://doi.org/10.1029/2020WR028320.

Brunsell, N.A., Jones, A.R., Jackson, T.L., Feddema, J.J., 2010. Seasonal trends in air temperature and precipitation in IPCC AR4 GCM output for Kansas, USA: evaluation and implications. Int. J. Climatol. 30, 1178–1193.

Buchanan, R.C., Wilson, B.B., Butler Jr., J.J., 2023. The high plains aquifer. Kans. Geol. Surv. Public Inf. Circ. 18, 6.

Butler Jr., J.J., Whittemore, D.O., Reboulet, E., Knobbe, S., Wilson, B.B., Stotler, R.L., Bohling, G.C., 2015. High plains aquifer index well program: 2014 annual report. Kans. Geol. Surv. Open-file Rep. 2015-3 135. ⟨http://www.kgs.ku.edu/Hydro/Publications/2015/OFR15_3/index.html⟩.

Butler Jr., J.J., Whittemore, D.O., Wilson, B.B., Bohling, G.C., 2016. A new approach for assessing the future of aquifers supporting irrigated agriculture. Geophys. Res. Lett. 43 (5), 2004–2010. https://doi.org/10.1002/2016GL067879.

Butler Jr., J.J., Whittemore, D.O., Wilson, B.B., Bohling, G.C., 2018. Sustainability of aquifers supporting irrigated agriculture: a case study of the High Plains aquifer in Kansas (https://:). Water Int. 43 (6), 815–828. https://doi.org/10.1080/02508060.2018.1515566.

Butler Jr., J.J., Gomez-Hernandez, J.J., Perrone, D., Hyndman, D.W., 2021a. Introduction to special section: the quest for sustainability of heavily stressed aquifers at regional to global scales. Water Resour. Res. 57 (8) https://doi.org/10.1029/2021WR030446.

Butler Jr., J.J., Whittemore, D.O., Reboulet, E., Knobbe, S., Wilson, B.B., Bohling, G.C., 2021b. High Plains aquifer index well program: 2020 Annual report. Kans. Geol. Surv. Open-file Rep. 2021-8 108. ⟨https://www.kgs.ku.edu/Publications/OFR/2021/OFR2021-8.pdf⟩.

Butler Jr., J.J., Bohling, G.C., Perkins, S.P., Whittemore, D.O., Liu, G., Wilson, B.B., 2023. Net inflow: an important target on the path to aquifer sustainability. Groundwater 51 (1). https://doi.org/10.1111/gwat.13233.

Cotterman, K.A., Kendall, A.D., Basso, B., Hyndman, D.W., 2017. Groundwater depletion and climate change: future prospects of crop production in the Central High Plains aquifer. Clim. Change 146 (1), 187–200. https://doi.org/10.1007/s10584-017-1947-7.

Deines, J.M., Kendall, A.D., Butler Jr., J.J., Hyndman, D.W., 2019. Quantifying irrigation adaptation strategies in response to stakeholder-driven groundwater management in the US High Plains Aquifer. Environ. Res. Lett. 14, 044014 https://doi.org/10.1088/1748–9326/aafe39.

Draper, N., Smith, H., 1981. Applied Regression Analysis, Second edition. John Wiley & Sons, New York, p. 709.

Dumont, A., Mayor, B., López-Gunn, E., 2013. Is the rebound effect or Jevons paradox a useful concept for better management of water resources? Insights from the irrigation modernisation process in Spain. Aquat. Procedia 1, 64–76. https://doi.org/10.1016/j.aqpro.2013.07.006.

Foster, T., Mieno, T., Brozović, N., 2020. Satellite-Based Monitoring of irrigation water use: assessing measurement errors and their implications for agricultural water management policy. Water Resour. Res. 56 https://doi.org/10.1029/2020WR028378.

Gleeson, T., Wada, Y., Bierkens, M.F.P., van Beek, L.P.H., 2012. Water balance of global aquifers revealed by groundwater footprint. Nature 488, 197–200. https://doi.org/10.1038/nature11295.

Griggs, B.W., 2021. Reaching consensus about conservation: high plains lessons for California's sustainable groundwater management act. Univ. Pac. Law Rev. 52 (3), 495–547. 〈https://scholarlycommons.pacific.edu/uoplawreview/vol52/iss3/7〉.

KDA-DWR (Kansas Department of Agriculture – Division of Water Resources), 2021. Rules and regulations, Kansas Water Appropriation Act. 〈https://agriculture.ks.gov/docs/default-source/statues-water/kwaa_rules_regs57c3ada8d515.pdf?sfvrsn=fb12aac1_24〉.

Logan, K.E., Brunsell, N.A., Jones, A.R., Feddema, J.J., 2010. Assessing spatiotemporal variability of drought in the U.S. central plains. J. Arid Environ. 74, 247–255. https://doi.org/10.1016/j.jaridenv.2009.08.008.

Lovelace, J.K., Nielsen, M.G., Read, A.L., Murphy, C.J., Maupin, M.A., 2020. Estimated groundwater withdrawals from principal aquifers in the United States, 2015 (ver. 1.2, October 2020). U. S. Geol. Surv. Circ. 1464, 70 https://:10.3133/cir1464.

McGuire, V.L., Strauch, K.R., 2022. Water-level and recoverable water in storage changes, High Plains aquifer, predevelopment to 2017 and 2015–17. U.S. Geological Survey Scientific Investigations Report 2022–5080, 15 p. 〈https://pubs.er.usgs.gov/publication/sir20225080〉.

Ou, G., Munoz-Arriola, F., Uden, D.R., Martin, D., Allen, C.R., Shank, N., 2018. Climate change implications for irrigation and groundwater in the Republican River Basin, USA. Clim. Change 151, 303–316. https://doi.org/10.1007/s10584-018-2278-z.

Peck, J.C., 1995. The Kansas water appropriation act: a fifty-year perspective. Univ. Kans. Law Rev. 43 (4), 735–756.

Pfeiffer, L., Lin, C.-Y.C., 2014. Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence. J. Environ. Econ. Manag. 67, 189–208. https://doi.org/10.1016/j.jeem.2013.12.002.

Rogers, D.H., Aguilar, J., 2017. Kansas irrigation trends. Kans. State Univ. Agric. Exp. Station MF2849 (Rev.), 8. 〈https://bookstore.ksre.ksu.edu/pubs/MF2849.pdf〉.

Rosenberg, N.J., Epstein, D.J., Wang, D., Vail, L., Srinivasan, R., Arnold, J.G., 1999. Possible impacts of global warming on the hydrology of the Ogallala aquifer region. Clim. Change 42, 677–692. https://doi.org/10.1023/A:1005424003553.

Rosenberg, N.J., Brown, R.A., Izaurralde, R.C., Thomson, A.M., 2003. Integrated assessment of Hadley Centre (HadCM2) climate change projections on agricultural productivity and irrigation water supply in the conterminous United States I. Climate change scenarios and impacts on irrigation water supply simulated with the HUMUS model. Agric. For. Meteorol. 117, 73–96.

Sears, L., Caparelli, J., Lee, C., Pan, D., Strandberg, G., Vuu, L., Lawell, C.-Y., 2018. Jevons' paradox and efficient irrigation technology. Sustainability 10, 1590. https://doi.org/10.3390/su10051590.

USDA, National Agricultural Statistics Service, 2019. Census of Agriculture, 2018 Irrigation and Water Management Survey, Agricultural Statistics Board, AC-17-SS-1. 〈https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Farm_and_Ranch_Irrigation_Survey/fris.pdf〉.

Ward, F.A., Pulido-Velazquez, M., 2008. Water conservation in irrigation can increase water use. PNAS 105 (47), 18215–18220. 〈https://www.pnas.org/doi/10.1073/pnas.0805554105〉.

Whittemore, D.O., Butler Jr., J.J., Wilson, B.B., 2016. Assessing the major drivers of water-level declines: new insights into the future of heavily stressed aquifers. Hydrol. Sci. J. 61 (1), 134–145. https://doi.org/10.1080/02626667.2014.959958.

Whittemore, D.O., Butler Jr., J.J., Wilson, B.B., 2018. Status of the high plains aquifer in Kansas. Kans. Geol. Surv. Tech. Ser. 22, 14. 〈https://www.kgs.ku.edu/Publications/Bulletins/TS22/index.html〉.

Whittemore, D.O., Butler, J.J., Jr., Wilson, B.B., 2021. Precipitation and pumping relationships: A simple approach to assess the effectiveness of groundwater conservation measures. H12C-05, American Geophysical Union Fall Meeting 2021.

Zipper, S.C., Gleeson, T., Li, Q., Kerr, B., 2021. Comparing streamflow depletion estimation approaches in a heavily stressed, conjunctively managed aquifer. Water Resour. Res. 57 (2) https://doi.org/10.1029/2020WR027591.