Kansas Geological Survey

High Plains Aquifer Index Well Program: 2022 Annual Report

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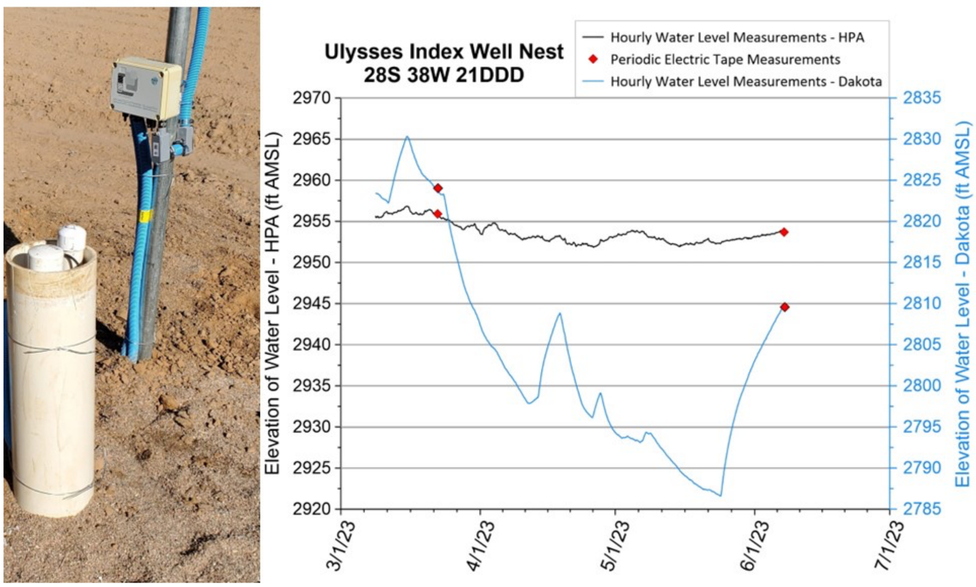

Ulysses HPA-Dakota Well Nest and Hydrographs

Kansas Geological Survey Open-File Report No. 2023-55
August 2023

GEOHYDROLOGY

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KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 2023-55

Acknowledgments

We are grateful for the support, assistance, and cooperation of the staff of the Kansas Water Office; the Kansas Department of Agriculture, Division of Water Resources; the managers and staff of Groundwater Management Districts 1, 2, 3, 4, and 5; and, especially, for the cooperation of the many landowners for making their properties available for installation of the wells. John Woods of the Kansas Geological Survey (KGS) assisted with processing water-level and radar precipitation data, and Julie Tollefson of the KGS edited the report. Josh Olson of the Kansas Water Office provided instructive comments on the draft report. The State of Kansas Water Plan Fund provides financial support for this project.

Executive Summary

The index well program of the Kansas Geological Survey (KGS) is directed at developing improved approaches for measuring and interpreting hydrologic responses at the local scale (section to township) in the High Plains aquifer (HPA) in western and south-central Kansas. The program is supported by the Kansas Water Office (KWO) with Water Plan funding as a result of the agency's interest in and responsibility for long-term planning of groundwater resources in western and south-central Kansas. The Kansas Department of Agriculture, Division of Water Resources (DWR), provides assistance, as do the five Groundwater Management Districts (GMDs) and the Kansas State University Northwest Research-Extension Center (KSU-NWREC). The United States Geological Survey (National Ground-Water Monitoring Network) provided funding to help support drilling activities in the second half of 2022.

The project began with the installation of three monitoring ("index") wells in western Kansas in summer 2007. Each well has an integrated pressure transducer-datalogger unit for continuous monitoring of water levels that is connected to telemetry equipment to allow real-time viewing of well conditions on a publicly accessible website. Since late 2012, wells have been systematically added to the network. The index well network was enlarged in the late summer and fall of 2022 by the drilling of two well nests in southern GMD3; each nest has one well at the bottom of the HPA and one well in the underlying Dakota aquifer. The network now consists of 29 wells with telemetry equipment and real-time data access from the KGS website and 6 wells without telemetry equipment (water-level data downloaded approximately quarterly and displayed on the KGS website). The vision of the index well program is that these wells, and others that will be added to the network over time, will be monitored for the long term. Shorter-term monitoring will be done at additional wells (expansion wells); three expansion wells are currently continuously monitored in GMD1. A major focus of the program is to use these data for the development of criteria or methods to evaluate the effectiveness of management strategies at the local scale in the HPA in western and south-central Kansas. These data also are used to develop a better understanding of the major mechanisms affecting water levels in the Kansas HPA. This improved understanding can then be incorporated into data analyses and numerical models to obtain a better picture of what the future holds for the aquifer.

This report provides a concise description of conditions as of late spring 2023. The majority of the report consists of an update and interpretation of the hydrographs for all of the index wells and the GMD1 expansion wells. In addition, the report presents a discussion of the relationships among precipitation (as characterized by radar data), annual water-level changes, and nearby water use at the three original index wells and three additional wells, and the implications of those relationships for efforts to moderate water-level declines by pumping reductions.

The major findings of the index well program to date are as follows:

1. Water-level data collected using an integrated pressure transducer-datalogger unit provide a near-continuous record of great practical value that can help in the assessment of the continued viability of the HPA as a source of water for large-scale irrigation.
2. Interpretation of index well hydrographs enables important insights to be drawn concerning hydrogeologic conditions, the major mechanisms affecting water levels, and the long-term viability of the aquifer in the vicinity of the index wells. For example, there is little indication of episodic recharge at most index wells in the western Kansas HPA.

3. The annual water-level measurement network data, in conjunction with reliable water-use data, can be used to evaluate the effect of management decisions on the township and larger scale using an approach developed from water-level responses collected as part of this program; this approach is now widely used in the western Kansas HPA.
4. The standardized precipitation index and radar precipitation data are good indicators of the climatic conditions that drive pumping in the High Plains aquifer in Kansas. In addition, these quantities can be used in precipitation versus water use relationships to identify changes in pumping produced by management decisions or storm-induced crop damage.

In addition to the concise description in this report, these findings are discussed in previous program reports, KGS publications (Whittemore et al., 2018; Buchanan et al., 2023), and scientific journal articles resulting from program work (Butler, Stotler et al., 2013; Whittemore et al., 2016; Butler, Whittemore, Wilson et al., 2016, 2018; Butler, Bohling et al., 2020a,b; Bohling et al., 2021; Butler, Knobbe et al., 2021; Butler et al., 2023). In late spring 2023, a scientific journal article related to recent program work was accepted for publication (Whittemore et al., 2023). That article is provided as an appendix to this report.

The focus of activities for the remainder of 2023 and the first half of 2024 will be on the continuation of monitoring at all program wells; continued analysis of hydrographs from all wells; installation of equipment for real-time monitoring at an existing well in GMD5; the drilling and installation of equipment for real-time monitoring of one well in Cheyenne County in GMD4 and one well in eastern Gray or western Ford County in GMD3; and further assessment of the relationships among radar-determined precipitation, annual water-level change, and water use.

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1 Introduction and Background

Groundwater withdrawals in the Ogallala–High Plains aquifer (hereinafter, High Plains aquifer or HPA) in Kansas have resulted in large water-level declines that call into question the viability of the aquifer as a continuing resource for irrigated agriculture (Butler, Stotler et al., 2013; Buchanan et al., 2023; Butler et al., 2023). The index well program of the Kansas Geological Survey (KGS), which is a response to this condition, is directed at developing improved approaches for measuring and interpreting hydrologic responses in the HPA at the local (section to township) scale to aid in the development of management strategies. The study is supported by the Kansas Water Office (KWO) with Water Plan funding as a result of KWO's interest in and responsibility for long-term planning of groundwater resources in western and south-central Kansas. The Kansas Department of Agriculture, Division of Water Resources (DWR), provides assistance, as do all five Groundwater Management Districts (GMDs) and the Kansas State University Northwest Research-Extension Center (KSU-NWREC). The United States Geological Survey (National Ground-Water Monitoring Network) provided funding to help support drilling activities in the second half of 2022.

A major focus of the program is the development of methods for evaluating the effectiveness of management strategies at the local scale in a timely fashion. Changes in water level—or the rate at which the water level is changing—are considered the most direct and unequivocal measures of the effect of management strategies. Because of the economic, social, and environmental importance of water in western and south-central Kansas, the effects of any modifications in patterns of water use need to be evaluated promptly and accurately. The program has also provided valuable information about the mechanisms that control changes in water levels in the vicinity of each well. That information, which is helpful for assessing the effect of management strategies at the local scale, can also provide a check on some of the assumptions incorporated in groundwater models developed for the Kansas HPA. The program thus aims to provide accurate and timely information that can complement and significantly enhance the information provided by the annual water-level measurement program.

At the time of this report, monitoring data (hourly frequency) from up to fifteen full recovery and pumping seasons and one additional ongoing pumping season have been obtained. With increasing data, the index well program has demonstrated the following:

1. Water-level data collected using an integrated pressure transducer-datalogger unit provide a near-continuous record of great practical value that can help in the assessment of the continued viability of the HPA as a source of water for large-scale irrigation.
2. Interpretation of index well hydrographs enables important practical insights to be drawn concerning hydrogeologic conditions, the major mechanisms affecting water levels, and the long-term viability of the aquifer in the vicinity of the index wells. For example, there is little indication of episodic recharge at the index wells in the western Kansas HPA.
3. The annual water-level measurement network data, in conjunction with reliable water-use data, can be used to evaluate the effect of management decisions on the sub-county and larger scale using an approach developed from observed water-level responses as part of this program; this approach is now widely used in the western Kansas HPA.

4. The standardized precipitation index and radar precipitation data are good indicators of the climatic conditions that drive pumping in the High Plains aquifer in Kansas. In addition, these quantities can be used in precipitation versus water use relationships to identify changes in pumping produced by management decisions or storm-induced crop damage.

The index well network was enlarged in 2022 by the drilling of two well nests in GMD3 (Ulysses and Satanta sites). Each nest consists of two wells, one installed just above the bottom of the HPA and one installed in the underlying Dakota aquifer. Note that the term “index well” is used here to designate a dedicated, non-pumping well at which monitoring is anticipated to continue for many years. There are additional wells, designated here as “expansion wells,” at which monitoring is not likely to continue over the long term because of constraints imposed by well depth (i.e., water level is anticipated to drop below the bottom of the well screen), logistics, or management issues. Both types of wells are considered in this report.

This report provides a concise description of conditions as of late spring 2023. The majority of the report consists of an update and interpretation of the hydrographs for all of the index wells and the GMD1 expansion wells. In addition, this report discusses the relationships among precipitation (as characterized by radar data), annual water-level changes, and nearby water use at the three original index wells and three additional wells and the implications of those relationships for efforts to moderate water-level declines by pumping reductions. In late spring 2023, a scientific journal article related to recent program work was accepted for publication (Whittemore et al., 2023). That article is provided as an appendix to this report.

2 Program History

The index well program began in summer 2007 with the installation of three transducer- and telemetry-equipped wells, designed and sited to function as HPA monitoring wells (hereinafter, original index wells). One well was installed in each of the three western GMDs, with locations deliberately chosen to represent different water use and hydrogeologic conditions and to take advantage of related past or continuing studies (stars in fig. 1). The original experimental design envisioned use of the index wells to anchor and calibrate the manual measurements of annual program wells in their vicinity, thus providing more consistency and confidence in the calculation of the water-table surface and its changes in those general areas. However, the scope of the project was quickly expanded to also focus on the mechanisms that control changes in water level in the vicinity of each well. Further information about the characteristics of the original sites and the experimental design can be found in previous annual reports (Young et al., 2007, 2008; Buddemeier et al., 2010).

The demonstrated value of continuous monitoring at the original three index wells led to a significant expansion of the index well network. In the spring of 2012, we started to explore adding a group of wells along the Kansas-Oklahoma border to the network. These wells were in four well nests originally installed by the U.S. Geological Survey (USGS; National Water-Quality Assessment [NAWQA] program) in 1999 just north of the Oklahoma border. The USGS, which had not used these wells for more than a decade, agreed that the KGS could use the wells for both annual water-level measurements and continuous monitoring. The well nests are located in Seward, Stevens, and Morton counties (circles and triangles along the Kansas-Oklahoma border in fig. 1—from east to west, Cimarron, Liberal, Hugoton, and Rolla sites). These monitoring locations were important additions to the index well network because they provide valuable information about responses in the areas of thick aquifer intervals in southernmost GMD3.

In early December 2012, we installed transducers in one well at each site and a barometer at the site near Hugoton. The two criteria used to select the well for monitoring at each site were 1) the nature of pumping-induced water-level responses determined from an examination of manual water-level data collected by the USGS in 1999 and 2000 (McMahon, 2001, fig. 8) and 2) the position of the well within the HPA (the objective was to have a well that would provide information about conditions in the main body of the HPA). All four of these wells have been added to the annual water-level measurement network and, since January 2013, have been measured as part of the annual program.

In early August 2013, we placed transducers in one additional well each at the Hugoton and Liberal sites. In the third week of December 2013, working cooperatively with the USGS, we installed telemetry equipment at the Liberal and Hugoton sites and began to obtain real-time water-level data from the four monitored wells at those sites. The telemetry equipment remained in these wells until late summer 2017, when it was removed because of insufficient funds for the USGS to continue the real-time monitoring. Barometers were added to the Rolla and Cimarron sites in February 2014 and November 2015, respectively. The Rolla barometer was removed in early December 2015 because it appeared to be malfunctioning. The Hugoton site barometer was turned off by USGS personnel in November 2015 but was restarted in 2016. The Hugoton and Liberal sites were previously operated cooperatively by the KGS and USGS but, as of late summer 2017, they are now operated solely by the KGS. Telemetry equipment was added back to the Hugoton well in the main body of the HPA on April 25, 2019; telemetry equipment was added back to the Liberal well in the main body of the HPA on September 27, 2019. On December 26, 2018, the transducer at the additional Liberal index well (Liberal 160) failed. Given the limited information provided by that well since 2013, we decided to remove that well from the index well program. Data from the Cimarron and Rolla sites can be viewed up to the latest download on the KGS website.

In February 2014, the KGS and staff at the KSU-NWREC facility in Colby began to discuss adding the long-time manually measured well at that facility to the index well network. An integrated pressure transducer-datalogger unit was installed in the well in August 2014 shortly before the centennial celebration of the facility. Unlike at the other index wells, the datalogger uses the facility's wi-fi system to communicate with network servers housed at the KGS. In early February 2015, the facility completed running a power cable nearby and installing a wi-fi transmitter. The wi-fi system was successfully tested concurrent with the February 11, 2015, download. However, the integration of the wi-fi system with the transducer-datalogger unit proved challenging. On September 9, 2015, the integration was successfully completed. Continuous measurements are now available on the KGS website.

In the spring of 2014, GMD5 expressed interest in expanding the index well program into its area. KGS and GMD5 staff worked together to identify a monitoring well that was drilled 20 years earlier by the KGS north of Belpre and just south of the Edwards-Pawnee county line. The well is in an area of groundwater-level declines that is of concern to the district. An integrated transducer-datalogger unit and telemetry equipment were installed in July 2014. As described in the 2014 report (Butler, Whittemore et al., 2015), the Belpre data transfers to the KGS network servers could not be automated because of limitations of the telemetry system vendor's website. After considerable efforts to resolve the problems, the decision was made to switch vendors in late summer of 2015. The data have been accessible from the KGS and GMD5 websites since September 18, 2015.

In 2012, collaboration with GMD4 began on the continuous monitoring of water levels at five observation wells within the Sheridan-6 (SD-6) Local Enhanced Management Area (LEMA). As described in previous reports (Butler, Whittemore et al., 2015; Butler, Whittemore, Reboulet et al., 2016), the records from the sensors that were originally in these wells often had anomalous water-level spikes, primarily during the summer, that were coincidental with high temperatures in the datalogger housings. After the decision was made to incorporate these wells into the index well program, the existing monitoring equipment was replaced in the second half of 2015 and early 2016 with integrated pressure transducer-datalogger units that are similar to those used at all the other index wells. In late October 2016, telemetry equipment was added to the monitoring well located in the west-central portion of the SD-6 LEMA (Seegmiller well). In mid-May 2021, telemetry equipment was added to the westernmost monitoring well in the SD-6 LEMA (Steiger well). Real-time data from these two wells are now accessible from the KGS website. Data from the three other wells in the SD-6 LEMA can be viewed up to the latest download on the KGS website.

In the spring of 2016, we further expanded the program by installing three new wells in Lane, Wallace, and Wichita counties in GMD1. Integrated pressure transducer-datalogger units were placed in the wells in mid-June 2016. Telemetry equipment was installed in the Wallace and Wichita index wells in late July 2016 and in the Lane well in early September 2016. Real-time data from these wells are now accessible from the KGS website.

In the summer of 2016, we converted an existing well on the Willis Water Technology Farm in southern Finney County in GMD3 to an index well. An integrated pressure transducer-datalogger unit and telemetry equipment were added to the well in late July 2016. Real-time data from this well are now accessible on the KGS website.

In late fall of 2016, we further expanded the network by installing a new well in Sherman County southwest of Goodland in GMD4. An integrated pressure transducer-datalogger unit and telemetry equipment were installed in the well in March 2017. Real-time data from this well are now accessible on the KGS website.

In the summer of 2017, we converted a long-time manually measured existing well northwest of Garden City in western Finney County in GMD3 to an index well. An integrated pressure transducer-datalogger unit and telemetry equipment were added to the well in mid-June 2017. Real-time data from this well are now accessible on the KGS website.

In the late spring of 2018, we converted an existing well at the KGS research site along the Arkansas River channel east of Larned in eastern Pawnee County in GMD5 to an index well. An integrated pressure transducer-datalogger unit and telemetry equipment were installed in late May 2018. Real-time data from this well are now accessible on the KGS website.

In the summer of 2019, we converted four existing GMD2 monitoring wells located in McPherson, Harvey, Sedgwick, and Reno counties into index wells. Integrated pressure transducer-datalogger units and telemetry equipment were placed in the Mount Hope (Sedgwick County) and Pretty Prairie (Reno

County) index wells on August 20, 2019. An integrated pressure transducer-datalogger unit and telemetry equipment were placed in the McPherson County index well on August 21, 2019. Telemetry equipment was installed in the Harvey County index well on August 21, 2019, and an integrated pressure transducer-datalogger unit was installed on September 26, 2019. In late summer 2020, we installed an integrated pressure transducer-datalogger unit and telemetry equipment in an existing GMD2 monitoring well located in Sedgwick County (Bentley index well, recording began on September 12, 2020). Real-time data from these five wells are now accessible from the KGS website.

In the second half of 2021, we converted two existing GMD5 monitoring wells to index wells. On August 11, 2021, an integrated pressure transducer-datalogger unit and telemetry equipment were placed in the Trousdale index well in southeast Edwards County. On December 2, 2021, an integrated pressure transducer-datalogger unit and telemetry equipment were placed in the Rozel index well in western Pawnee County. Real-time data from these two wells are now accessible from the KGS website.

In late winter to early spring of 2022, we converted existing wells in northeast Sherman County and northwest Wichita County to index wells (Sherman County 2 index well and Wichita County 2 index well, respectively). Integrated pressure transducer-datalogger units were placed in both wells on February 9, 2022. Telemetry equipment was added to the Sherman County 2 index well on April 12, 2022, and to the Wichita County 2 index well on April 13, 2022. Real-time data from these wells are now accessible on the KGS website.

In the late summer and fall of 2022, we used funding from the USGS (National Ground-Water Monitoring Network) and this program to drill two well nests in GMD3 (Ulysses and Satanta sites). Each nest consists of one well near the bottom of the HPA and one well in the underlying Dakota aquifer. Integrated pressure transducer-datalogger units were placed in both wells at the Ulysses site in western Grant County on March 8, 2023, and at the Satanta site in southwest Haskell County the following day. Telemetry equipment was added at both sites on March 22, 2023. Real-time data from these wells are now accessible on the KGS website.

Figure 1 shows the current state of the index well network. There are now 29 wells in the network with telemetry equipment and real-time data access from the KGS website and 6 wells without telemetry equipment (data downloaded approximately quarterly and displayed on the KGS website). The vast majority of these wells have been added to the annual water-level measurement network and are measured as part of the annual program. In addition, monitoring without telemetry equipment continues at three expansion wells in GMD1.

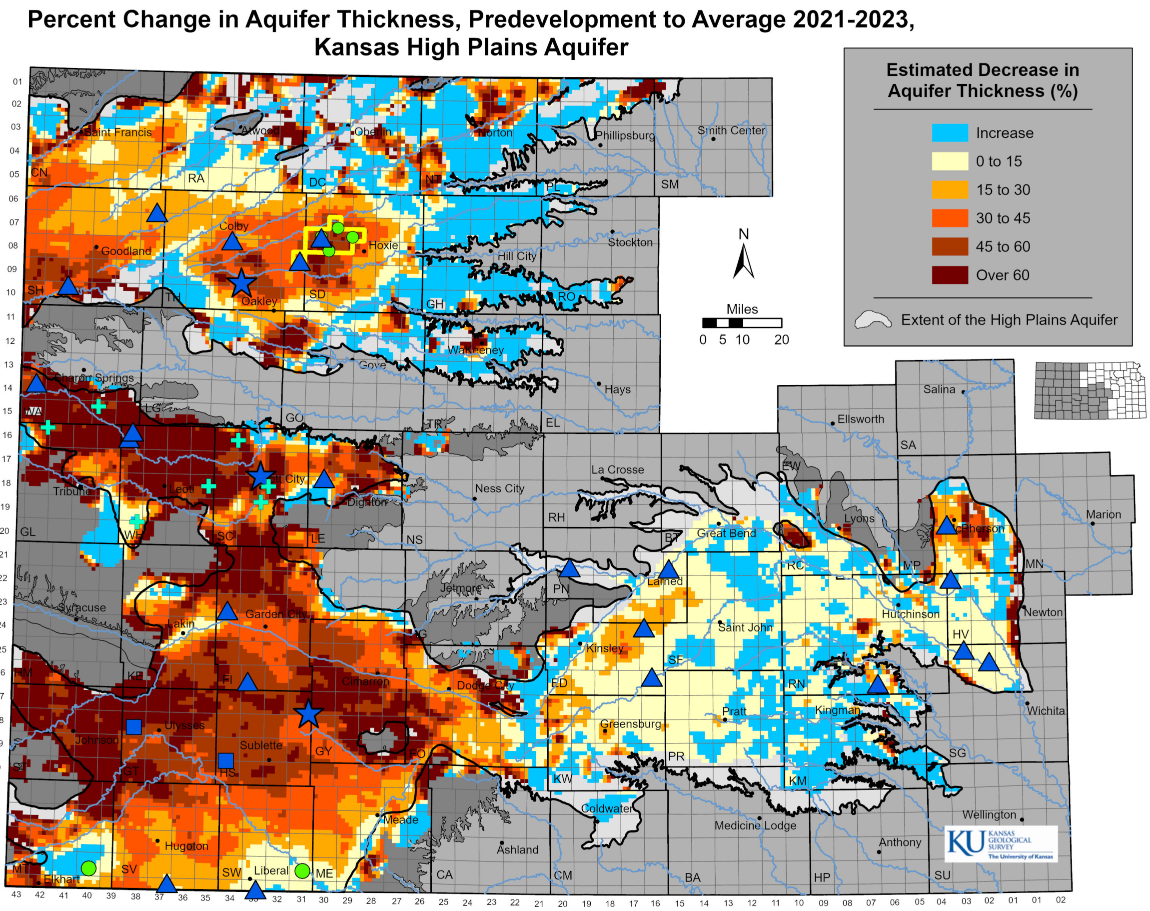


Figure 1—The Kansas portion of the High Plains aquifer, with aquifer and county boundaries shown. Each colored pixel represents one section (1 mi^2), coded for the degree of groundwater depletion from the beginning of large-scale development to the average of conditions in 2021–2023. The blue stars indicate the locations of the original three index well sites, the blue triangles indicate additional telemetry-equipped wells, the blue squares are the telemetry-equipped two-well nests (one well in the HPA and one in the Dakota aquifer), the green circles are the index wells without telemetry equipment for which data are downloaded quarterly, and the yellow polygon indicates the Sheridan-6 Local Enhanced Management Area. The plus signs are seven expansion wells that have been or are being continuously monitored within GMD1.

3 Overview of Index Well Sites and Monitoring Data

This section provides a brief discussion of the hydrographs from the 35 index wells and additional GMD1 expansion wells currently in operation. The duration of monitoring ranges from about 16 years of hourly measurements at the three original index wells to less than three months at the two recently added well nests. Although pumping occurs sporadically throughout the year, the major drawdown in water level in all of the wells occurs during the summer pumping season when the aquifer is stressed significantly for an extended period. For this study, the pumping season is defined as the period from the first sustained drawdown during the growing season (often, but not always, following the maximum recovered water level) to the first major increase in water level near the end of the growing season. The recovery season (period) is defined as the time between pumping seasons. Since water levels continue to increase throughout the recovery period at most of the index wells, the difference between water levels measured during the recovery period from one year to the next only provides a measure of the year-to-year change in still-recovering water levels. This year-to-year change in recovering water levels must be used cautiously by managers because it can be affected by a variety of factors that are unrelated to aquifer trends, such as the year-to-year variability in the time between the end of the irrigation season and the annual measurement. More importantly, it *does not* involve the final recovered water level, the elevation to which the water level would rise if the recovery were not interrupted by the next pumping season. Efforts to estimate this final recovered water level, which would provide a reliable basis for managers to assess the effect of changes in water use, through various extrapolation procedures have proven difficult because of the variety of mechanisms that can affect the recovery process (Stotler et al., 2011).

In the following subsections, the hydrograph and characteristics of each well are discussed. The wells are organized by the GMD in which they are located. In the interest of brevity, except for the wells that were added to the program in the late summer and fall of 2022, discussion of each well will be limited to one page. Further information can be found in previous reports and on the KGS website. In reports before 2017, two tables were presented for most wells: one provided information about the well hydrograph and the local water use, and the other provided comparisons between the manual annual water-level measurements and the transducer measurements. Those tables with data from all years of index well operation are now online at www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml.

3.1 GMD1 Index Wells

Five index wells are located in GMD1 (fig. 2). The Scott well was one of the original index wells drilled in 2007, whereas the Lane, Wallace, and Wichita County wells were drilled in the spring of 2016. The Wichita County 2 well was added to the network in early 2022 because the Wichita County index well showed little response to nearby pumping. Table 1 summarizes the characteristics of these five wells. Further details concerning these wells are given in the 2016 and 2021 annual reports (Butler, Whittemore et al., 2017; Butler et al., 2022) and the online appendices for this report (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml). Section 3.6.1 discusses the GMD1 expansion wells.

Table 1—Characteristics of the GMD1 index well sites (water use is for irrigation unless noted otherwise).

Site	2023 WL elev. (ft)[a]	2023 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2021, 2022 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Lane	2,767.8	33.8	118	105–115	467, 749	1,148, 1,447	3,396[b], 4,157[b]
Scott	2,824.3[c]	80.1	223	215–225	665, 883	2,582[d], 3,313[d]	13,071[e], 16,966[e]
Wallace	3,554.2	114.2	394	375–385	932[f], 1,253[f]	5,108[f], 7,346[f]	15,704[g], 21,117[g]
Wichita	3,287.2	29.2	190	175–185	289, 340	2,096, 2,592	7,894[h], 9,521[h]
Wichita 2	3,275.5	37.5	221	189–226	894, 1,243	3,192, 3,943	7,473[h], 9,104[h]

[a] 2023 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html). Wichita 2 is not an annually measured index well; 2023 water-level measurement estimated from sensor data on 01/5/2023 from 0800 to 1700.

[b] Includes 53 ac-ft (2021) and 66 ac-ft (2022) of municipal water and 8 ac-ft (2021) and 2 ac-ft (2022) of non-irrigation stock water.

[c] Annual measurement (2,825.9) in error; 2023 water-level measurement estimated from sensor data on 01/4/2023 from 0800 to 1700.

[d] Includes 5 ac-ft (2021) and 1 ac-ft (2022) of non-irrigation stock water.

[e] Includes 5 ac-ft (2021) of domestic water, 4 ac-ft (2021) and 6 ac-ft (2022) of industrial water, 1,029 ac-ft (2021) and 1,125 ac-ft (2022) of municipal water, and 439 ac-ft (2021) and 381 ac-ft (2022) of non-irrigation stock water.

[f] Includes 69 ac-ft (2021) and 62 ac-ft (2022) of municipal water.

[g] Includes 69 ac-ft (2021) and 62 ac-ft (2022) of municipal water and 9 ac-ft (2021) and 8 ac-ft (2022) of non-irrigation stock water.

[h] Includes 85 ac-ft (2021) and 92 ac-ft (2022) of non-irrigation stock water.

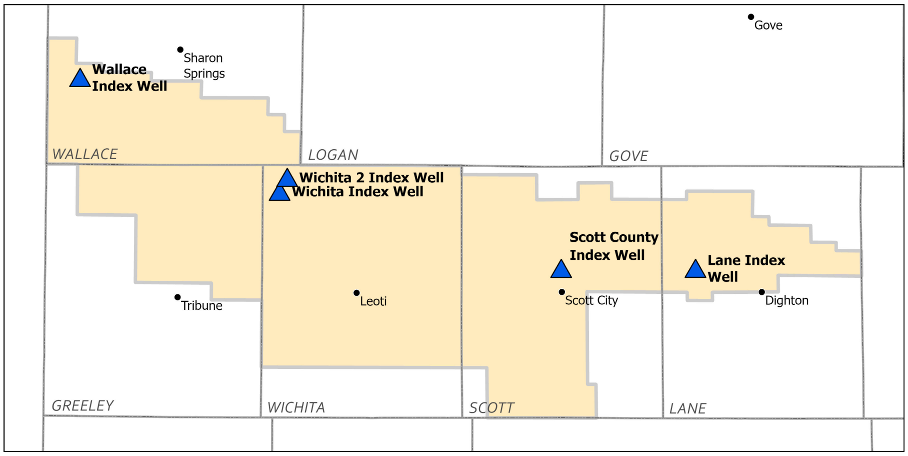


Figure 2—Map of index wells in GMD1; data from these wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

3.1.1 Lane County Index Well

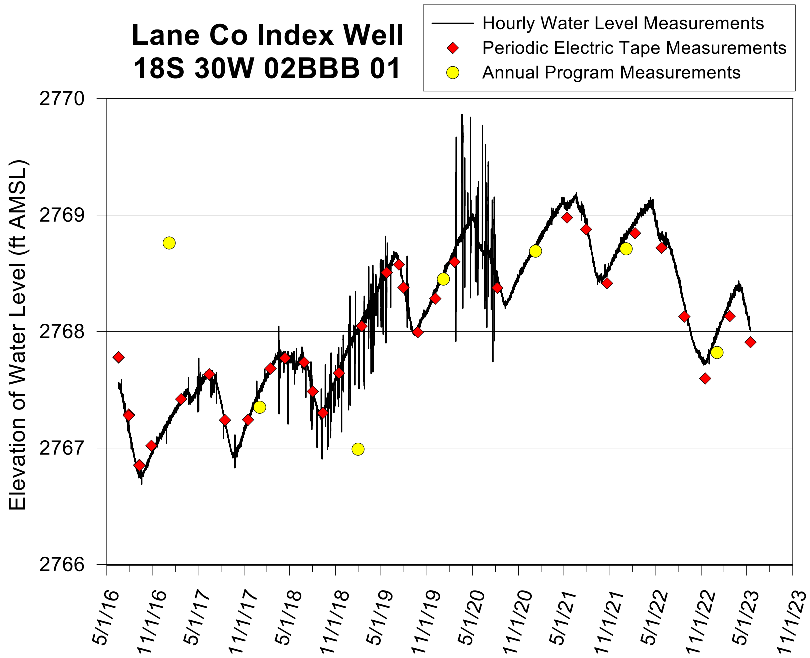


Figure 3—Lane County index well hydrograph—total data run to 5/16/23. A water-level elevation of 2,767 ft corresponds to a depth to water of 85 ft below land surface (lsf). The top of the screen is 105 ft below lsf (elevation of 2,747 ft), and the bottom of the aquifer is 118 ft below lsf (elevation of 2,734 ft). The screen terminates 3 ft above the bottom of the aquifer. The 2017 and 2019 annual water-level measurements appear to be in error. The agreement between electric-tape measurements and the transducer is beginning to lessen, indicating that the transducer likely needs to be recalibrated.

Major Points

- Very small amplitude fluctuations superimposed on the water levels are likely an indication of a relatively shallow unconfined aquifer overlain by a vadose zone with high air permeability.
- The influence of individual nearby pumping wells is not discernible; the water-level response appears to be a response to regional, more distant pumping, rather than a response to pumping at nearby wells as at most of the index wells (i.e., response is more integrated in nature).
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The minimum water level for 2022 was 0.7 ft below that of 2021, the first year-on-year decrease that has occurred during monitoring at the Lane County well.
- Many short-duration spikes appear on the hydrograph until mid-summer 2020; we suspect the origin of the spikes is related to air expansion and contraction in the desiccant tube of the gauge pressure sensor (Cain et al., 2004), which was located by the telemetry box and exposed to sunlight. On August 8, 2020, we replaced the telemetry system with a different vendor's system that did not expose the tubing to sunlight and the spikes disappeared.

3.1.2 Scott County Index Well

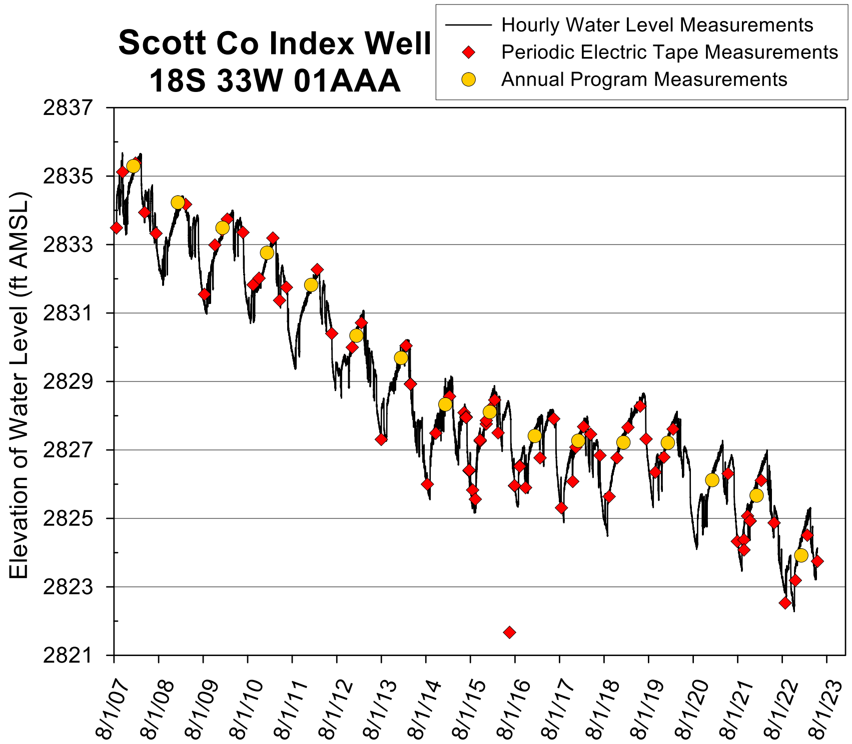


Figure 4—Scott County index well hydrograph—total data run to 5/16/23. A water-level elevation of 2,829 ft corresponds to a depth to water of 138.2 ft below lsf. The top of the screen is 215 ft below lsf (elevation of 2,752.2 ft), and the bottom of the aquifer is 223 ft below lsf (elevation of 2,744.2 ft). The screen terminates 2 ft below the bottom of the aquifer. Transducer data have been adjusted for change in position as described in a previous annual report (Butler, Whittemore, Reboulet et al., 2016).

Major Points

- The hydrograph form, the relatively small change and rate of change in water level during each pumping and recovery season (despite at least two high-capacity pumping wells within approximately a half mile of the index well), and the fluctuations superimposed on the water levels are all indications of an unconfined aquifer.
- The effect of individual pumping wells is discernible, indicating that one or more pumping wells are in relatively close proximity to and in good hydraulic connection with the index well.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The maximum water level has been below that of the preceding year for every year except 2019. The minimum water level for 2022 was the lowest of the monitoring period and 1.2 ft below that for 2021.
- Transducer readings are in good agreement with manual measurements except one electric-tape measurement that appears to be a transcription error.

3.1.3 Wallace County Index Well

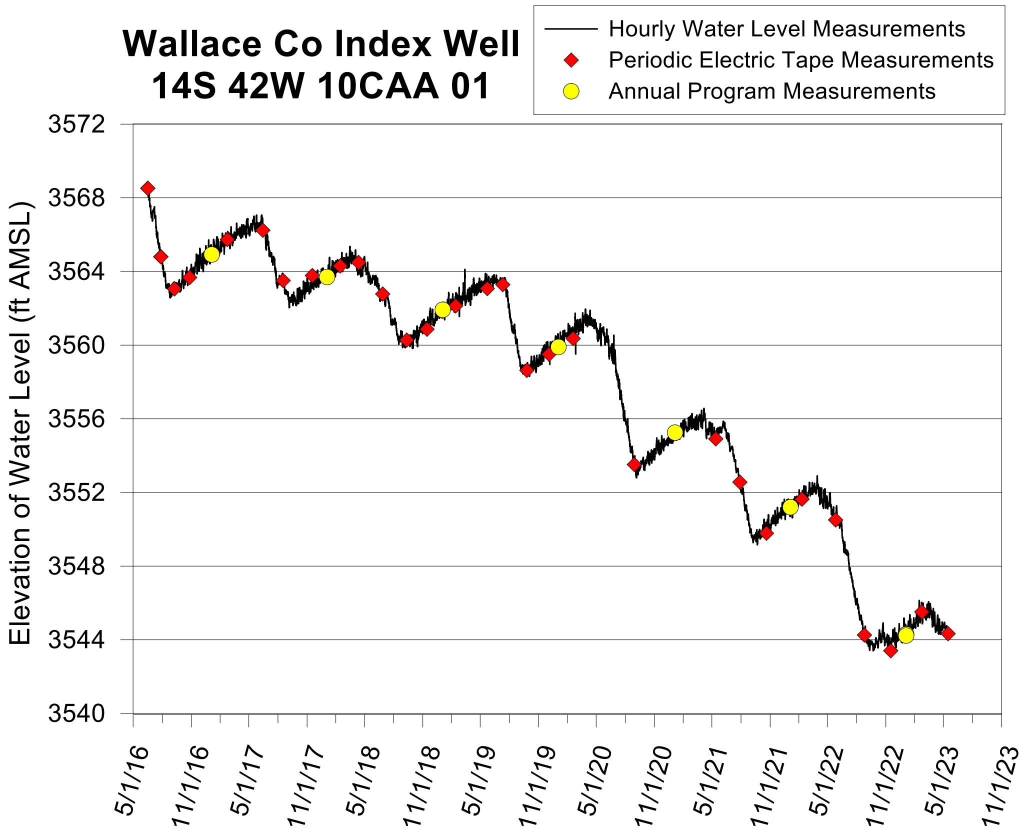


Figure 5—Wallace County index well hydrograph—total data run to 5/16/23. A water-level elevation of 3,544 ft corresponds to a depth to water of 284 ft below lsf. The top of the screen is 375 ft below lsf (elevation of 3,453 ft), and the bottom of the aquifer is 394 ft below lsf (elevation of 3,434 ft). The screen terminates 9 ft above the bottom of the aquifer.

Major Points

- The large amplitude fluctuations superimposed on the water levels, particularly evident during the recovery period, are an indication of unconfined conditions with a relatively deep water table.
- The effect of individual pumping wells is discernible, indicating that one or more pumping wells are in relatively close proximity to and in good hydraulic connection with the index well.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- Each year, the maximum and minimum water levels are below that of the preceding year, creating a downward stair-stepping pattern. The 2022 drought resulted in the 2022 minimum water level being 5.8 ft below that of 2021. The recovery over the winter of 2022-2023 was the shortest and the amount of recovery was the smallest during the monitoring period.
- Transducer readings are in good agreement with manual measurements. Similar to the Lane index well, many short-duration spikes appear on the hydrograph until mid-summer 2020. On August 29, 2020, we replaced the telemetry system with a different vendor's system and the spikes disappeared.

3.1.4 Wichita County Index Well

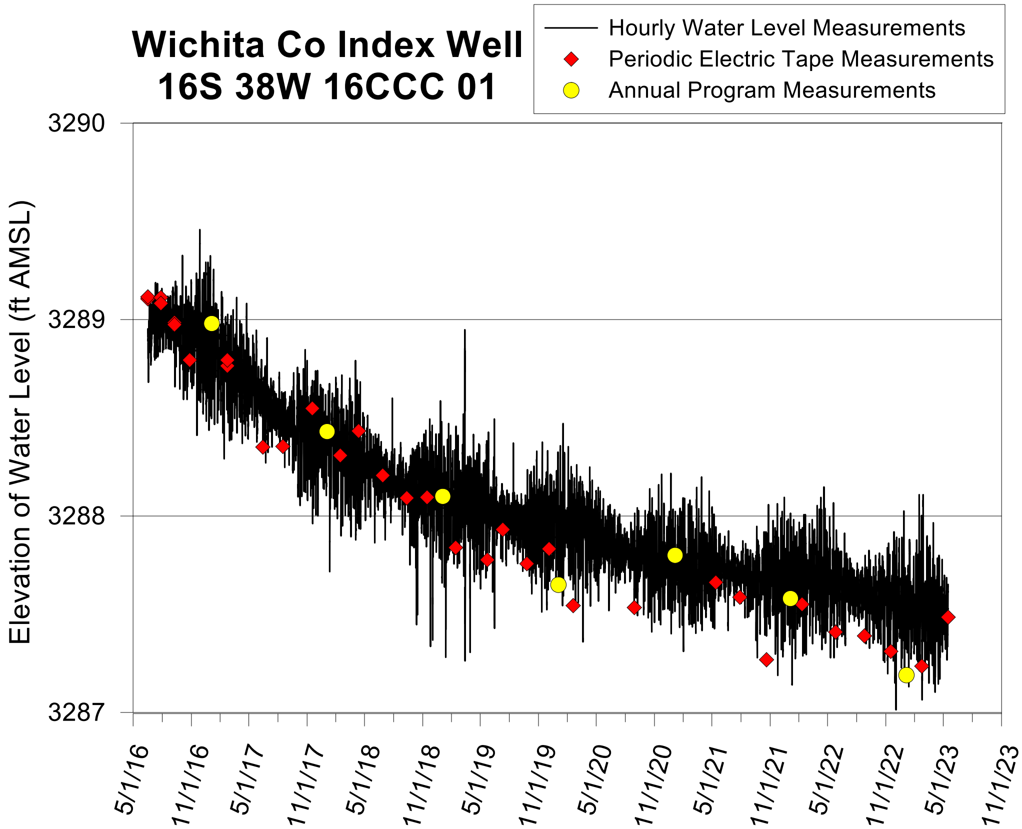


Figure 6—Wichita County index well hydrograph—total data run to 5/16/23. A water-level elevation of 3,288 ft corresponds to a depth to water of 160 ft below lsf. The top of the screen is 175 ft below lsf (elevation of 3,273 ft), and the bottom of the aquifer is 190 ft below lsf (elevation of 3,258 ft). The screen terminates 5 ft above the bottom of the aquifer.

Major Points

- The amplitude of the fluctuations superimposed on the water levels are an indication of unconfined conditions; the seasonal variations in the amplitude are produced by seasonal changes in the range over which barometric pressure can vary (smaller range during the summer [Butler, Knobbe et al., 2021]).
- It is difficult to discern individual pumping and recovery seasons; cannot discern effect of individual wells cutting on and off.
- Water levels continue to drop throughout the monitoring period.
- Transducer readings are in reasonable agreement with manual measurements. Similar to the Lane index well, short-duration spikes appear on the hydrograph until mid-summer 2020. On August 29, 2020, we replaced the telemetry system with a different vendor’s system and the spikes disappeared.

3.1.5 Wichita County 2 Index Well

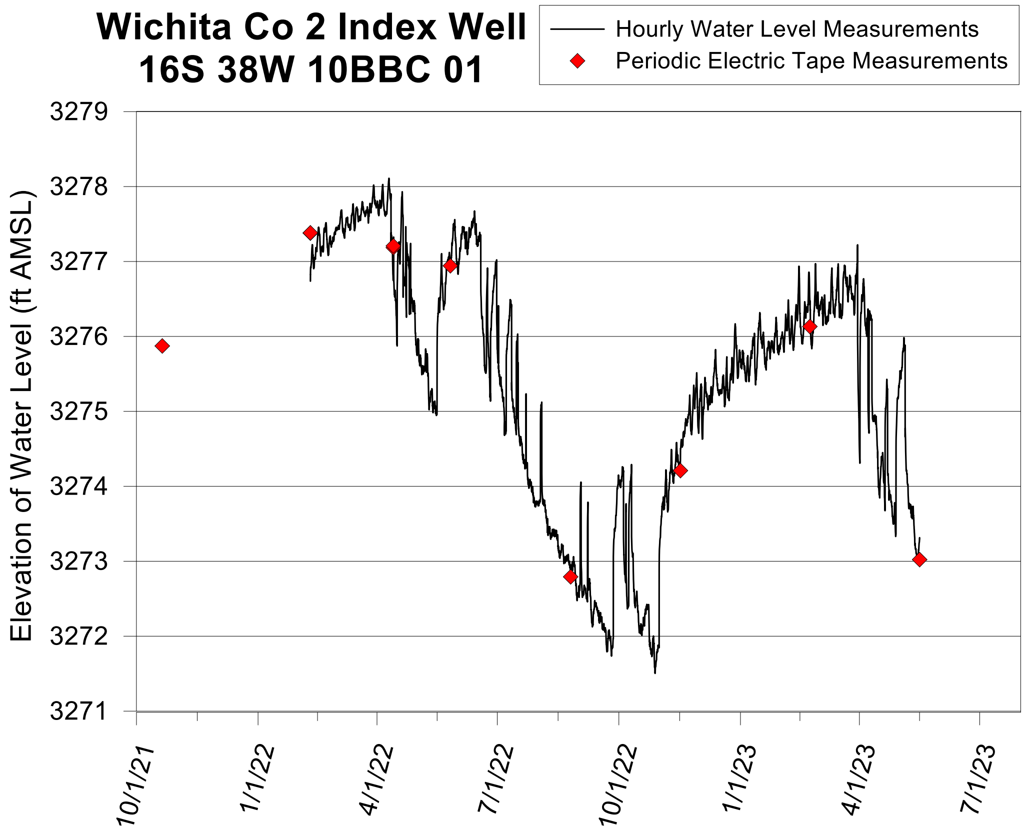


Figure 7—Wichita County 2 index well hydrograph—total data run to 5/16/23. A water-level elevation of 3,277 ft corresponds to a depth to water of 182 ft below lsf. The top of the screen is 189 ft below lsf (elevation of 3,270 ft), and the screen extends to the bottom of the well. The aquifer bottom is estimated to be 221 ft below lsf (elevation of 3,238 ft); the well bottom is 226.2 ft below lsf.

Major Points

- The hydrograph form during the irrigation season and the relatively large fluctuations superimposed on the water levels, particularly evident during the recovery period, are an indication of unconfined conditions.
- The effect of individual pumping wells is discernible, indicating that one or more of the nearby pumping wells are in good hydraulic connection with the index well.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- Despite the relatively close proximity (1.9 miles) to the Wichita County index well, the hydrographs of the two wells are dramatically different, indicating aquifer conditions change greatly over that distance.
- Transducer readings are in good agreement with manual measurements.

3.2 GMD2 Index Wells

Five index wells are located in GMD2 (fig. 8); the most recent well (Bentley) was brought into the network in September 2020. Table 2 summarizes the characteristics of these wells. Further details concerning the Bentley well and the first four wells are given in the 2020 annual report (Butler, Whittemore et al., 2021) and the 2019 annual report (Butler, Whittemore et al., 2020), respectively. In addition, the online appendices for this report (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml) provide further details for all five wells.

Table 2—Characteristics of the GMD2 index well sites (water use is for irrigation unless noted otherwise).

Site	2023 WL elev. (ft)[a]	2023 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2021, 2022 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Harvey	1,410.2	161.2	206	198–208	690, 1,058	3,532[b], 4,927[b]	12,244[c], 16,838[c]
McPherson	1,399.3	89.3	184	139–183	1,452[d], 1,960[d]	6,155[e], 6,667[e]	11,924[f], 14,871[f]
Mount Hope	1,407.1	158.9	173	166–176	1,035, 1,269	2,988[g], 3,884[g]	21,401[h], 26,898[h]
Pretty Prairie	1,545.2	47.2	71	61–71	679[i], 849[i]	2,532[j], 3,353[j]	8,654[j], 10,719[j]
Bentley	1,371.0	206.0	216	23–33	1,007, 1,323	3,289[k], 3,962[k]	24,759[l], 28,499[l]

[a] 2023 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html); Bentley estimated from sensor data on 1/9/23 from 0800 to 1700.

[b] Includes 224 ac-ft (2021) and 252 ac-ft (2022) of municipal water.

[c] Includes 224 ac-ft (2021) and 252 ac-ft (2022) of municipal water and 149 ac-ft (2021) and 153 ac-ft (2022) of non-irrigation recreation water.

[d] Includes 1,286 ac-ft (2021) and 1,729 ac-ft (2022) of municipal water.

[e] Includes 2,801 ac-ft (2021) and 2,874 ac-ft (2022) of municipal water, 2,350 ac-ft (2021) and 2,403 ac-ft (2022) of industrial water, and 1 ac-ft (2021 and 2022) of non-irrigation stock water.

[f] Includes 3,059 ac-ft (2021) and 3,292 ac-ft (2022) of municipal water, 2,403 ac-ft (2021) and 2,489 ac-ft (2022) of industrial water, 1 ac-ft (2021 and 2022) of non-irrigation stock water, 47 ac-ft (2021) and 139 ac-ft (2022) of non-irrigation recreation water, and 601 ac-ft (2021) and 1,072 ac-ft (2022) of other water (2021).

[g] Includes 15 ac-ft (2021) and 32 ac-ft (2022) of non-irrigation recreation water.

[h] Includes 4,911 ac-ft (2021) and 5,175 ac-ft (2022) of municipal water, 12 ac-ft (2021) and 11 ac-ft (2022) of domestic water, 4 ac-ft (2021) and 6 ac-ft (2022) of industrial water, 80 ac-ft (2021 and 2022) of other water, and 414 ac-ft (2021) and 517 ac-ft (2022) of non-irrigation recreation water.

[i] Includes 2 ac-ft (2021) and 9 ac-ft (2022) of municipal water.

[j] Includes 78 ac-ft (2021) and 86 ac-ft (2022) of municipal water.

[k] Includes 265 ac-ft (2021) and 103 ac-ft (2022) of municipal water.

[l] Includes 10,542 ac-ft (2021) and 10,540 ac-ft (2022) of municipal water and 1,005 ac-ft (2021) and 801 ac-ft (2022) of industrial water.

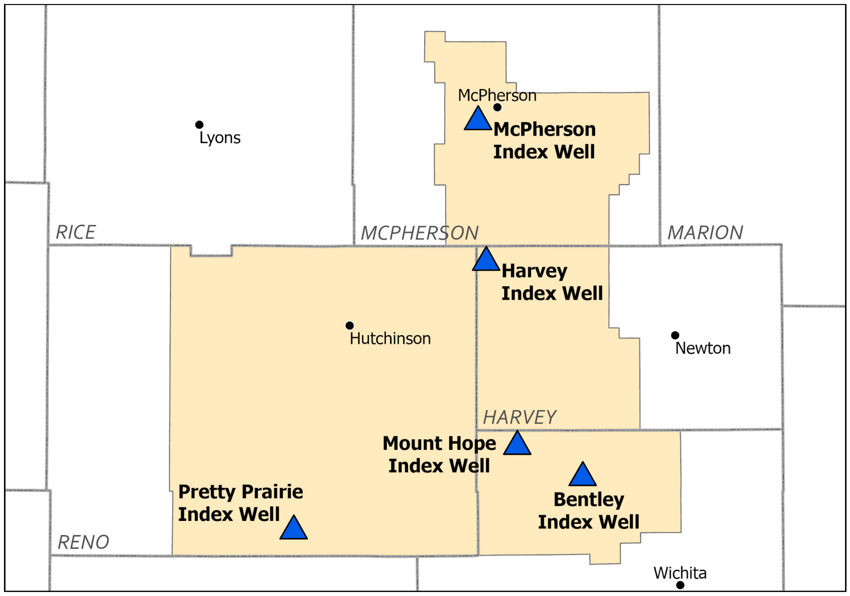


Figure 8—Map of index wells in GMD2; data from these wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_ program/index.shtml).

3.2.1 Bentley Index Well

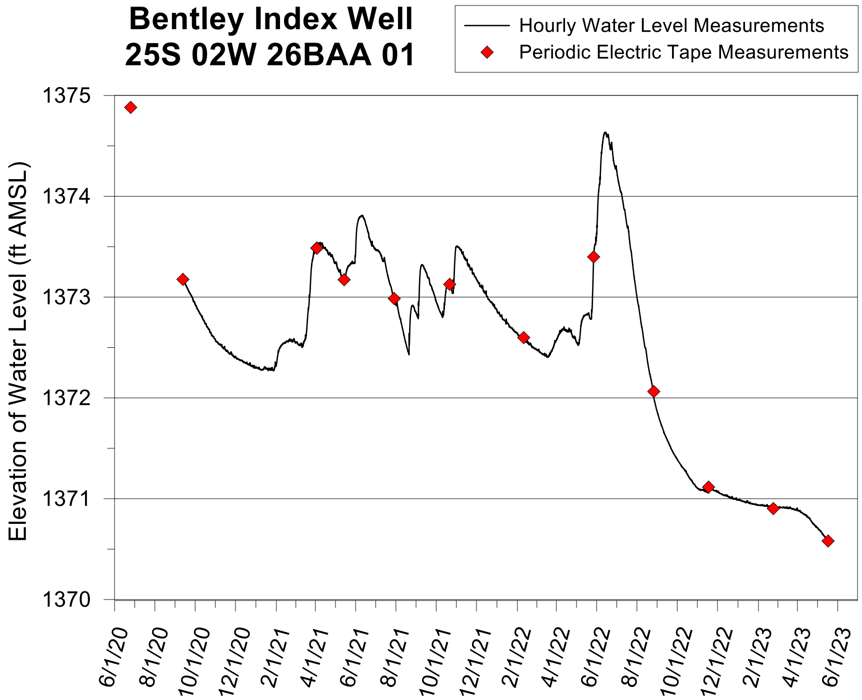


Figure 9—Bentley index well hydrograph—total data run to 5/17/23. A water-level elevation of 1,373 ft corresponds to a depth to water of 8.0 ft below lsf. The top of the 10 ft screen is 23 ft below lsf (elevation of 1,358 ft). The bottom of the aquifer is approximately 216 ft below lsf (elevation of 1,165 ft), and the bottom of the well is 33.0 ft below lsf (elevation of 1,348.0 ft).

Major Points

- The hydrograph shows a small response to barometric pressure fluctuations as would be expected for shallow unconfined conditions.
- Large rapid rises are likely produced by stage changes in the nearby Arkansas River and precipitation recharge.
- The large decline in the latter part of 2022 is primarily related to the substantial decrease in river flow due to the drought.
- There is little indication of nearby pumping activity, which is likely due to the well being screened above the screened interval of the many nearby pumping wells.
- Transducer readings are in good agreement with manual measurements.

3.2.2 Harvey County Index Well

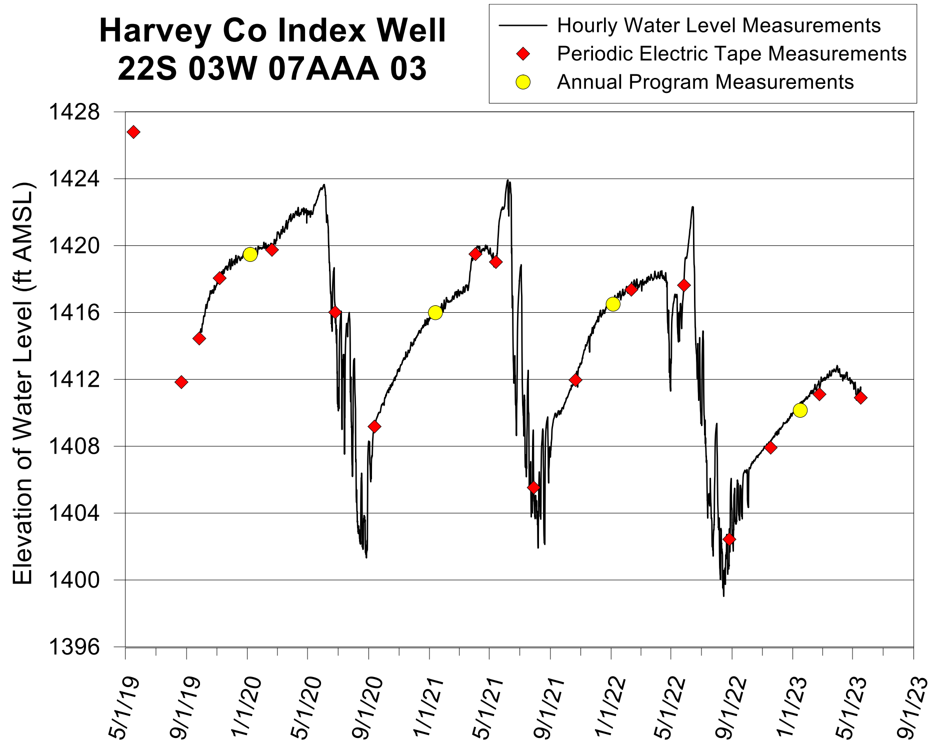


Figure 10—Harvey County index well hydrograph—total data run to 5/17/23. A water-level elevation of 1,416 ft corresponds to a depth to water of 39 ft below lsf. The top of the 10 ft screen is 198 ft below lsf (elevation of 1,257 ft), and the bottom of the aquifer is 206 ft below lsf (elevation of 1,249 ft).

Major Points

- The hydrograph form (response to nearby pumping) indicates confined conditions.
- After the end of the irrigation season, water levels continue to recover until the start of the next season.
- Abrupt rises in water level during the recovery period are likely produced by precipitation.
- The agreement between manual measurements and the transducer is beginning to lessen, indicating that the transducer likely needs to be recalibrated.

3.2.3 McPherson County Index Well

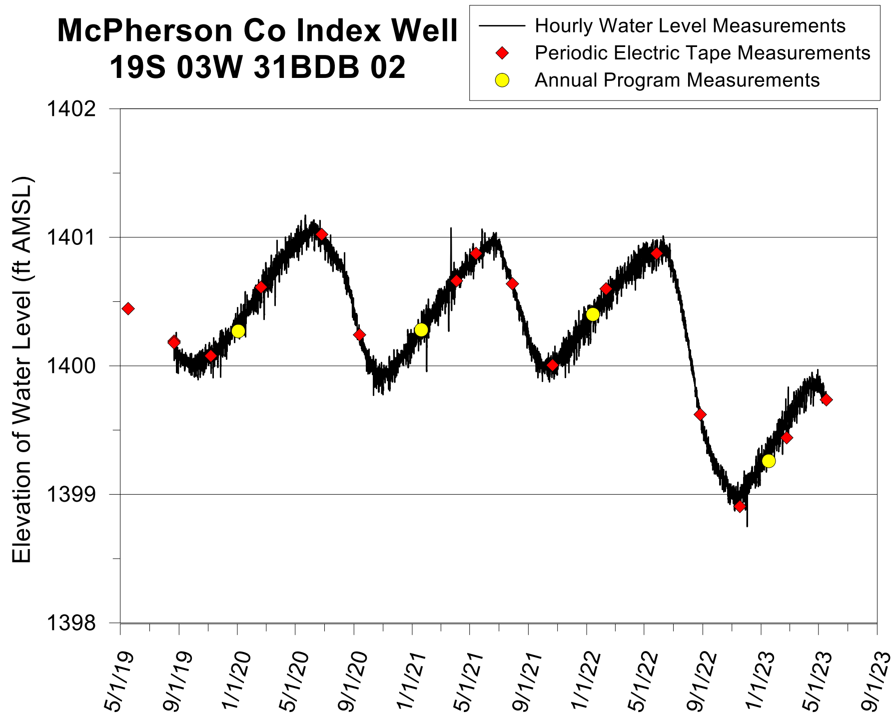


Figure 11—McPherson County index well hydrograph—total data run to 5/17/23. A water-level elevation of 1,400 ft corresponds to a depth to water of 94 ft below lsf. The top of the 44 ft screen is 139 ft below lsf (elevation of 1,355 ft), and the bottom of the screen is 183 ft below lsf (elevation of 1,311 ft). The bottom of the aquifer is 1 ft below the bottom of the screen (1,310 ft).

Major Points

- The relatively small amplitude fluctuations superimposed on the water levels hint at confined conditions.
- The impact of individual wells turning on and off is difficult to discern.
- After the end of the irrigation season, water levels continue to recover until the start of the next irrigation season.
- Transducer readings are in good agreement with manual measurements.
- The lack of water-level rises similar to those seen in the other GMD2 index wells in late March 2021 and late May 2022 indicates that overlying clay layers are shielding the screened interval from short-term effects of recharge.
- The 2022 minimum water level was close to a foot lower than the previous minimum water levels observed during the monitoring period.

3.2.4 Mount Hope Index Well

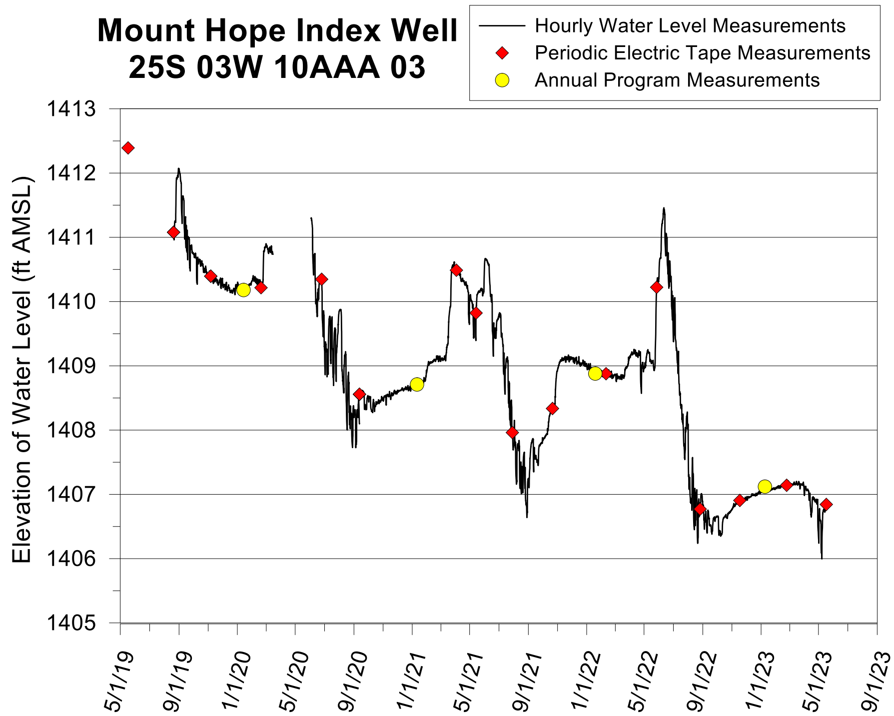


Figure 12—Mount Hope index well hydrograph—total data run to 5/17/23. A water-level elevation of 1,410 ft corresponds to a depth to water of 11.4 ft below lsf. The top of the 10 ft screen is 163 ft below lsf (elevation of 1,258.4 ft), and the bottom of the aquifer is 173 ft below lsf (elevation of 1,248.4 ft). Sensor failure produced the break in monitoring from 3/15/20 to 6/3/20.

Major Points

- The abrupt rise in water level shortly after instrumentation was installed in the well and the decline after that are likely produced by stage changes in the nearby Arkansas River. Other abrupt rises and falls appear to be a combination of stage changes in the Arkansas River and recharge from precipitation and flow in the nearby creek about 0.3 mi to the southwest.
- The effect of individual wells turning on and off is clearly visible on the hydrograph, indicating pumping wells in good hydraulic connection with the index well.
- The hydrograph from late spring 2022 to late spring 2023 is dramatically different from that of the previous years as a result of drought conditions.
- Transducer readings are in good agreement with manual measurements.

3.2.5 Pretty Prairie Index Well

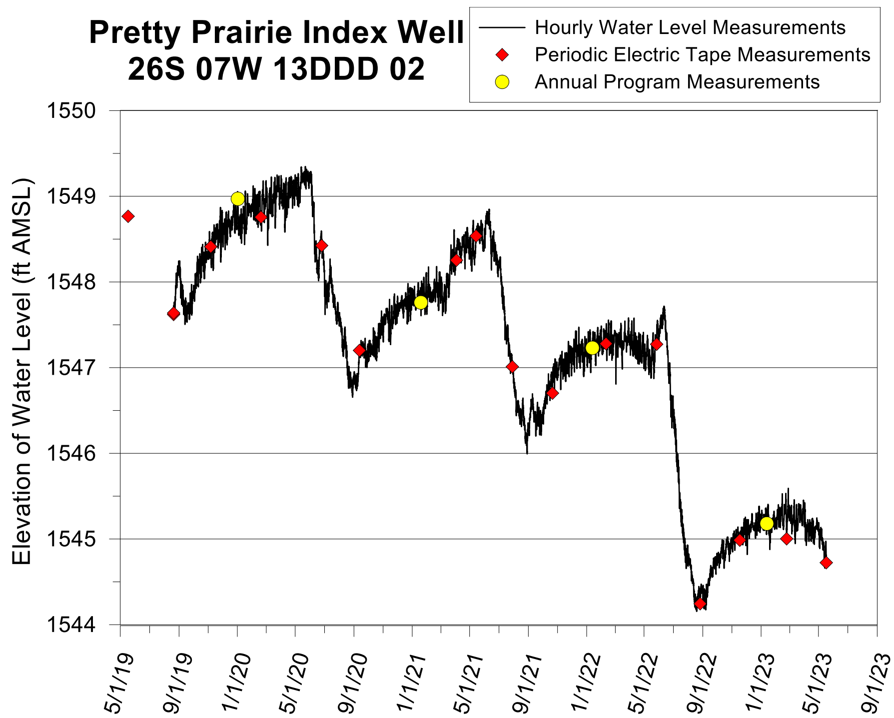


Figure 13—Pretty Prairie index well hydrograph—total data run to 5/17/23. A water-level elevation of 1,548 ft corresponds to a depth to water of 21 ft below lsf. The top of the 10 ft screen is 61 ft below lsf (elevation of 1,508 ft), and the bottom of the screen and aquifer is 71 ft below lsf (elevation of 1,498 ft).

Major Points

- The relatively large amplitude fluctuations superimposed on the water levels indicate unconfined conditions.
- The effect of individual wells turning on and off is visible on the hydrograph.
- After the end of the irrigation season, water levels continue to recover until stabilizing in January; water level rises after that time appear to be driven by precipitation.
- Transducer readings are in good agreement with manual measurements.

3.3 GMD3 Index Wells

Twelve index wells are located in GMD3 (fig. 14). The Haskell index well was one of the original 2007 index wells; monitoring began at the Cimarron, Hugoton, Liberal, and Rolla well sites in 2012–2013, at the Willis Technology Farm index well in the summer of 2016, at the Kearny-Finney County index well in the summer of 2017, and at the Satanta and Ulysses well nests in late winter of 2023. Table 3 summarizes characteristics of these 12 wells. Further details concerning these wells are given in the 2016 annual report (Butler, Whittemore et al., 2017), later in this section, and the online appendices for this report (www.kgs.ku.edu/HighPlains/OHP/index_program/ index.shtml).

Table 3—Characteristics of the GMD3 index well sites (water use is for irrigation unless noted otherwise).

Site	2023 WL elev. (ft)[a]	2023 saturated thickness (ft)	Bedrock depth (ft below land surface)[b]	Screened interval (ft below land surface)[b]	2021, 2022 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Cimarron 210	2,473.55	289.58	345	200–210	55, 81	55, 81	9,904[c], 10,367[c]
Haskell	2,510.63	105.76	433	420–430	570, 844	6,126[d], 7,647[d]	34,813[e], 43,346[e]
Hugoton 495	2,894.90	427.57	635	485–495	493, 642	2,878, 3,498	39,114[f], 42,484[f]
Kearny-Finney	2,773.75	172.73[g]	360[h]	70–266[h]	1,947, 2,727	5,945[i], 8,560[i]	36,852[j], 50,198[j]
Liberal 436	2,650.66	404.66	576	426–436	0, 1	1,250[k,l], 1,424[k,l]	30,304[m,n], 31,102[m,n]
Rolla 366	3,185.45	209.44	399	356–366	321[o], 251[o]	1,132[p], 1,441[p]	8,660[q], 10,342[q]
Satanta - HPA	2,586.27[r]	136.27[r]	525	515–525	195, 222	3,691, 4,931	23,156[s], 30,974[s]
Satanta – Dakota	2,,579.50[r]	224.50[r]	620	600–620			
Ulysses – HPA	2,955.90[r]	220.90[r]	445	425–445	1,304, 1,651	4,306[t], 4,133[t]	16,630[u], 16,815[u]
Ulysses – Dakota	2,809.56[r]	209.56[r]	580	560–580			
Willis Tech Farm	2,621.39	183.40	502	262–482	874, 1,003	5,397[v], 5,460[v]	36,390[w], 41,042[w]

[a] 2023 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html).

[b] Measurements for the Cimarron, Hugoton, Liberal, and Rolla wells from table 2 in McMahon (2001).

[c] Includes 23 ac-ft (2021) and 31 ac-ft (2022) of non-irrigation stock water.

[d] Includes 3 ac-ft (2021 and 2022) of industrial use water and 11 ac-ft (2021) and 9 ac-ft (2022) of municipal water.

[e] Includes 3 ac-ft (2021 and 2022) of industrial use water, 11 ac-ft (2021) and 9 ac-ft (2022) of municipal water, and 12 ac-ft (2021) and 15 ac-ft (2022) of stock water.

[f] Includes estimates of water use in Oklahoma based on "permitted" quantities, 17,989 ac-ft.

[g] Based on logs of nearby wells to bedrock.

[h] Measurements estimated from borehole camera log.

[i] Includes 25 ac-ft (2021) and 14 ac-ft (2022) of industrial water.

[j] Includes 166 ac-ft (2021) and 140 ac-ft (2022) of industrial water, 283 ac-ft (2021) and 256 ac-ft (2022) of municipal water, and 466 ac-ft (2021) and 441 ac-ft (2022) of non-irrigation stock water.

[k] Includes estimates of water use in Oklahoma based on "permitted" quantities, 675 ac-ft.

[l] Includes 456 ac-ft (2021) and 605 ac-ft (2022) of non-irrigation water for the city of Liberal.

[m] Includes estimates of water use in Oklahoma based on "permitted" quantities, 20,909 ac-ft.

[n] Includes 6,009 ac-ft (2021) and 6,301 ac-ft (2022) of non-irrigation water for city of Liberal.
[o] Includes 43 ac-ft (2021) and 22 ac-ft (2022) of non-irrigation stock water.
[p] Includes 126 ac-ft (2021) and 90 ac-ft (2022) of non-irrigation stock water.
[q] Includes 322 ac-ft (2021) and 264 ac-ft (2022) of non-irrigation stock water and 92 ac-ft (2021) and 102 ac-ft (2022) of municipal water.
[r] Sensors installed in wells 3/22/2023, water level at that time.
[s] Includes 262 ac-ft (2021) and 323 ac-ft (2022) of municipal water and 366 ac-ft (2021) and 319 ac-ft (2022) of non-irrigation stock water.
[t] Includes 6 ac-ft (2021 and 2022) of industrial water.
[u] Includes 24 ac-ft (2021) and 30 ac-ft (2022) of industrial water and 836 ac-ft (2021) and 760 ac-ft (2022) of municipal water.
[v] Includes 12 ac-ft (2021 and 2022) of non-irrigation stock water.
[w] Includes 12 ac-ft (2021 and 2022) of non-irrigation stock water and 521 ac-ft (2021) and 978 ac-ft (2022) of industrial water.

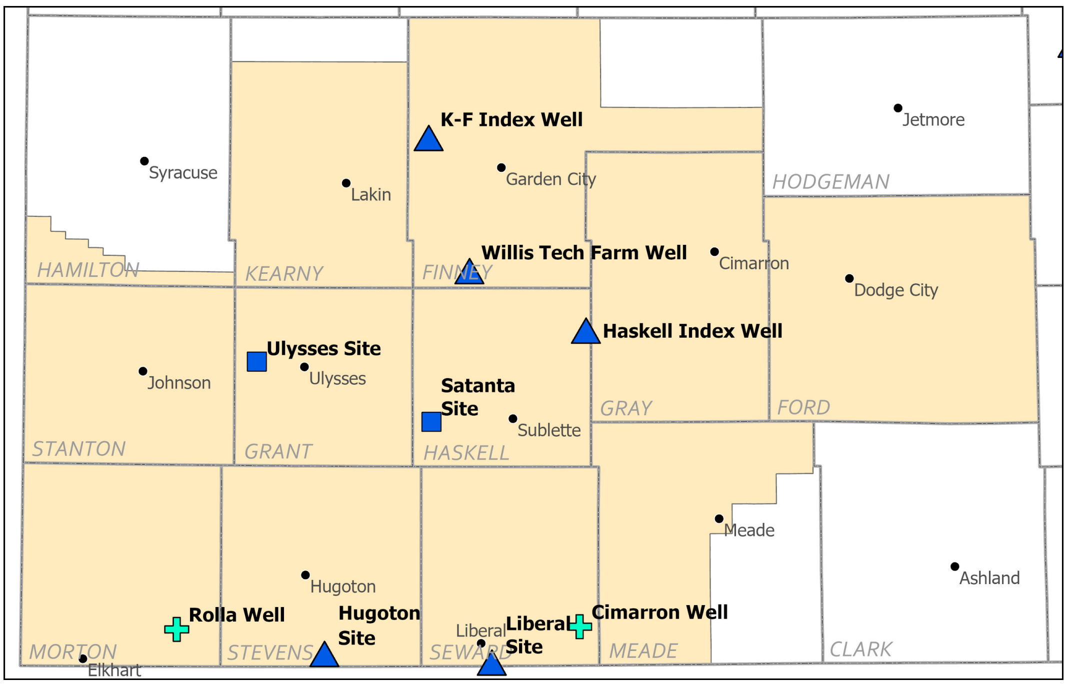


Figure 14—Map of index wells in GMD3. Triangles and squares designate wells with telemetry equipment, whereas plus signs designate wells without telemetry equipment. Data from wells with telemetry equipment can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml); data from wells without telemetry equipment are periodically downloaded (typically quarterly) and posted on the KGS website. The Ulysses and Satanta sites each have one well near the bottom of the HPA and one well in the underlying Dakota aquifer; both wells at each site have telemetry equipment. The Hugoton site has one well with telemetry equipment and one well without; the well with telemetry equipment is located in the main body of the HPA. K-F = Kearny-Finney.

3.3.1 Cimarron 210 Index Well

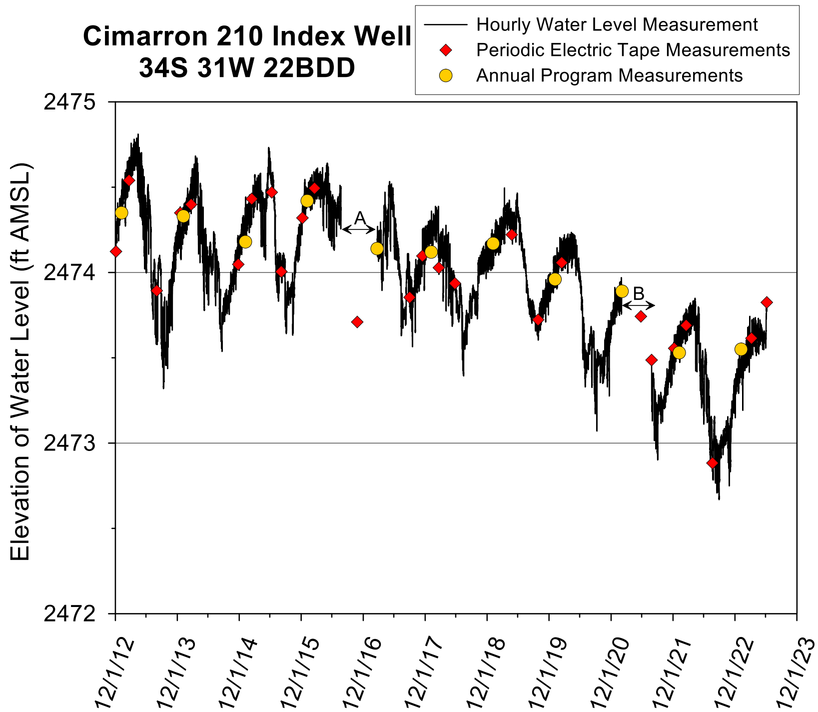


Figure 15—Cimarron 210 index well hydrograph—total data run to 6/6/23. A water-level elevation of 2,474 ft corresponds to a depth to water of 55 ft below lsf. The top of the 10 ft screen is 200 ft below lsf (elevation of 2,329 ft), and the bottom of the aquifer is 345 ft below lsf (elevation of 2,184 ft); A and B defined in text.

Major Points

- The hydrograph form and small response to pumping, despite the nearby (within 0.3 mi) irrigation well, indicate unconfined conditions.
- The relatively small (< 0.2 ft) fluctuations superimposed on the water levels, particularly evident during the recovery periods, indicate an unconfined aquifer with a relatively shallow depth to water.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- Sensor failure produced gaps (A [7/22/16–2/22/17] and B [2/3/21–7/27/21]) in hydrograph record.
- Water use within a 2 mi radius of the well is the lowest of any of the index wells.
- Water level has declined 2.4 ft since January 2000 (decline rate of 0.1 ft/yr); see 2016 annual report (Butler, Whittemore et al., 2017) for further details.
- Transducer readings are in good agreement with manual measurements.

3.3.2 Haskell County Index Well

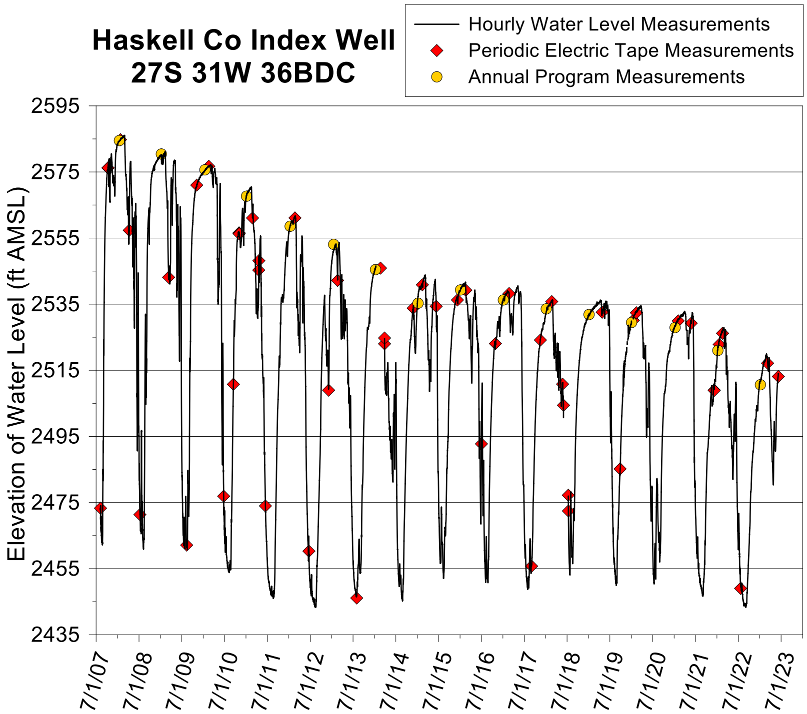


Figure 16—Haskell County index well hydrograph—total data run to 6/7/23. A water-level elevation of 2,455 ft corresponds to a depth to water of 382.8 ft below lsf. The top of the screen is 420 ft below lsf (elevation of 2,417.8 ft), and the bottom of the aquifer is 433 ft below lsf (elevation of 2,404.8 ft). The screen terminates 3 ft above the bottom of the aquifer. A sensor failure produced a break in monitoring from January to March 2014; a damaged cable produced a break in monitoring from early June to mid-July 2018; a malfunctioning sensor began producing many spurious values on 10/17/19 and was replaced on 1/16/20—only the sensor values deemed reasonable are plotted during that three-month period.

Major Points

- The hydrograph form and large response (80–120 ft) to pumping, despite the absence of nearby high-capacity wells (closest irrigation well about 0.5 mi away), indicate a confined aquifer.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- An increase in the minimum water-level elevation and large decrease in the rate of decline of the maximum recovered water level after 2013 were produced by court-ordered early (2013 and 2014) cessation of pumping at two nearby irrigation wells and complete (after 2014) cessation of pumping at those two wells and three additional nearby irrigation wells. Recent increases in the rate of decline of both the maximum recovered water level and the minimum water level were likely produced by more pumping in response to drier conditions than in the preceding 2015–2019 period.
- The 2022 minimum water level was the lowest since the start of monitoring (2007) at the Haskell index well.
- Transducer readings are in reasonable agreement with manual measurements.

3.3.3 Hugoton Site

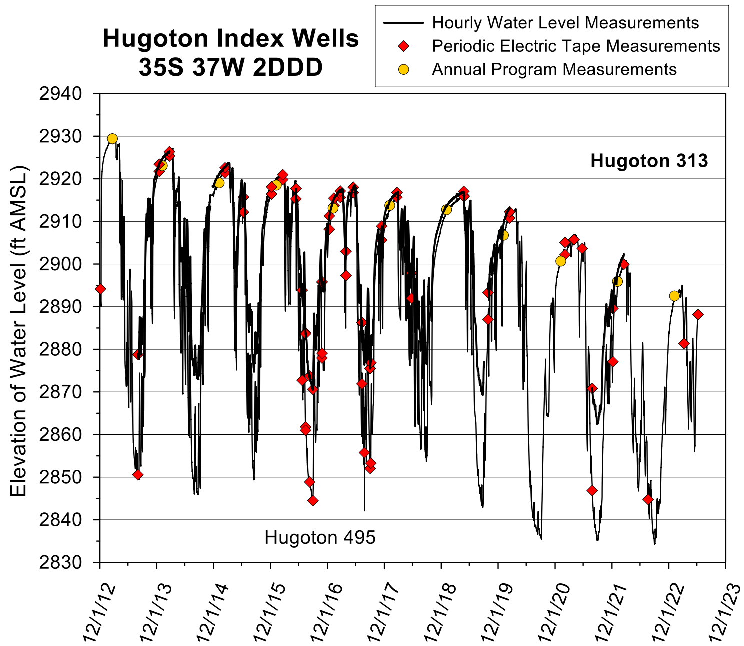


Figure 17—Hydrographs of Hugoton index wells—total data run to 6/6/23 for Hugoton 495 and 2/15/22 for Hugoton 313. A water-level elevation of 2,900 ft corresponds to a depth to water of 200 ft below lsf. For the Hugoton 495 well, the top of the 10 ft screen is 485 ft below lsf (elevation of 2,615 ft). For the Hugoton 313 well, the top of the 10 ft screen is 303 ft below lsf (elevation of 2,797 ft). Bottom of the aquifer is 635 ft below lsf (elevation of 2,465 ft). Three-hour downward spike (13–15 ft drop) on 7/26/17 in the Hugoton 495 well is associated with movement of the transducer in the well and is considered spurious. Sensor failed in Hugoton 313 on 5/19/20 but, because of pandemic-limited travel, the failure was not recognized until 2/2/21. Sensor was replaced on 7/27/21 and failed again on 2/15/22; sensor will be replaced in the latter half of 2023.

Major Points

- Two wells are monitored in a four-well nest.
- Large rapid drops and rises of water level following commencement and cessation of pumping, respectively, are indicative of confined conditions in both monitored intervals.
- Hydrographs indicate both intervals are affected by the same pumping stresses; the larger response in Hugoton 495 shows that that interval is more heavily stressed, while the elevation difference between the water levels indicates that pumping has induced downward flow from the shallower interval.
- After the end of the irrigation season, water levels continue to recover until the start of the next season at both wells (water levels never stabilize).
- The water level in Hugoton 495 has declined 78.5 ft since January 2000 (decline rate of 3.4 ft/yr); see 2016 annual report (Butler, Whittemore et al., 2017) for further details.
- The 2022 minimum water level was the lowest since the start of monitoring (2012) at Hugoton 495.
- Transducer readings are in good agreement with manual measurements.

3.3.4 Kearny-Finney Index Well

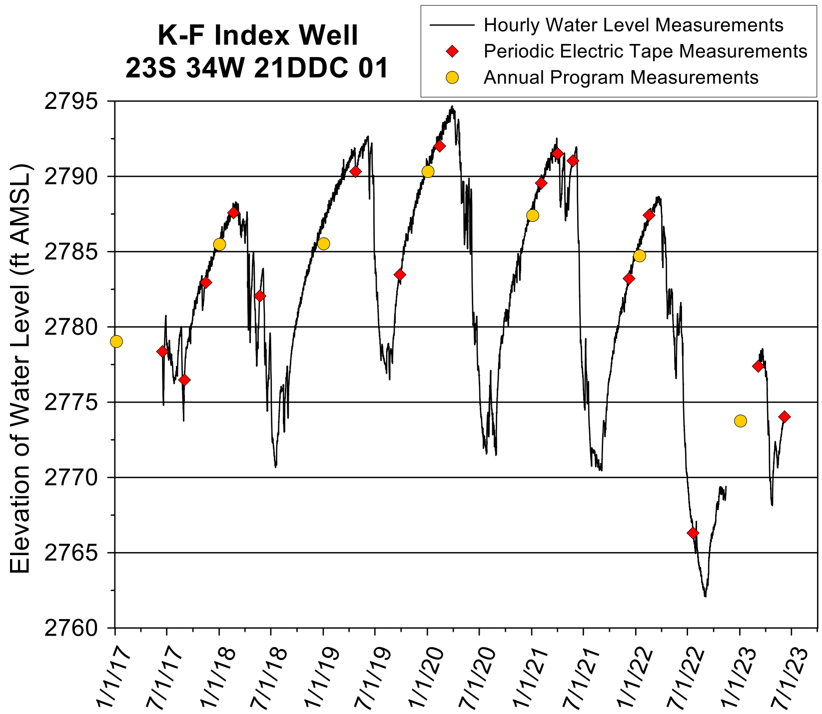


Figure 18—Kearny-Finney (K-F) index well hydrograph—total data run to 6/6/23. A water-level elevation of 2,785 ft corresponds to a depth to water of 176 ft below lsf. Nominal bottom of well is 300 ft below lsf (elevation of 2,661 ft), but the well is currently filled with sediments to 266 ft below lsf (elevation of 2,695 ft). Monitoring ceased on 11/13/22 after mice chewed through most of the sensor cable; cable was replaced and monitoring resumed on 3/6/23.

Major Points

- Relatively large amplitude fluctuations superimposed on the water levels are an indication of unconfined conditions.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The winter water-level elevation has dropped 64.5 ft since January 2008 (-4.3 ft/yr); the 2022 water-level decline (11.0 ft) was the largest since 2012.
- Minimum water-level elevation for 2022 was the lowest since the start of monitoring and approximately 8 ft lower than that of 2021; the apparent maximum recovered water level for 2023 was approximately 10 ft below the maximum recovered level for 2022.
- 2022 water use (1, 2, and 5 mi radii centered on well) was the highest of any of the index wells; virtually all of the pumping was for irrigation (100%, 99.8%, and 98.3%, respectively).
- Transducer readings are in relatively good agreement with electric-tape measurements; 2019 annual measurement appears to be in error.

3.3.5 Liberal Index Well

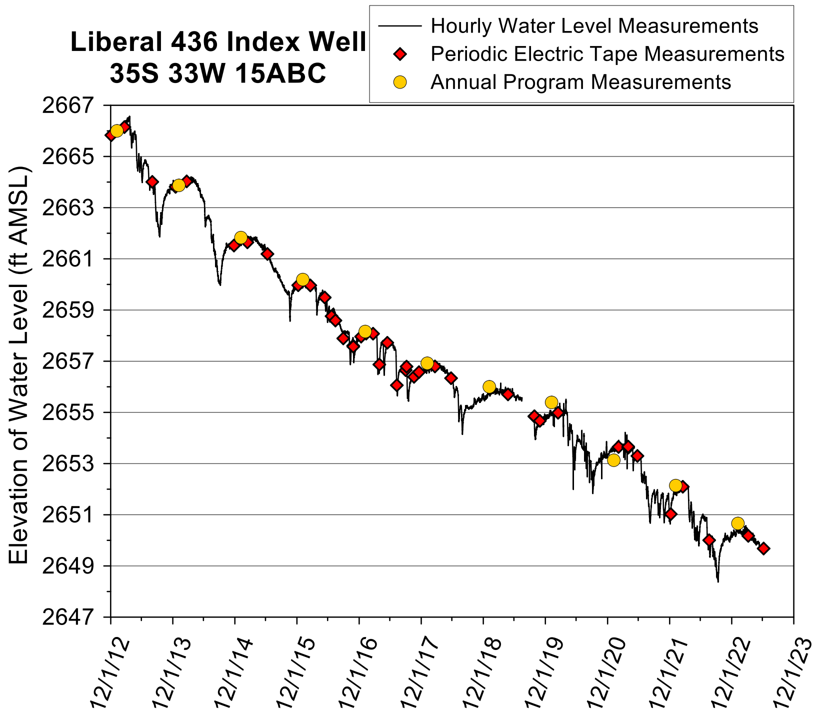


Figure 19—Hydrograph of Liberal 436 index well—total data run to 6/6/23. A water-level elevation of 2,651 ft corresponds to a depth to water of 170 ft below lsf. The top of the 10 ft screen is 426 ft below lsf (elevation of 2,395 ft). Sensor failed on July 6, 2019; a new sensor was installed on September 27, 2019.

Major Points

- One well is monitored in a four-well nest. Formerly, Liberal 160 well was also monitored but that stopped 12/26/18 as the monitoring provided very limited information.
- The hydrograph form and the relatively small (< 0.35 ft) amplitude fluctuations superimposed on water levels indicate confined conditions.
- After the end of the irrigation season, water levels recover to a near-stable value that is generally well below the level at the start of the pumping season; this pattern is an indication of limited lateral flow to the well (see Butler, Knobbe et al., 2021).
- The water level in Liberal 436 has declined 32.3 ft since January 2000 (decline rate of 1.4 ft/yr).
- Transducer readings are in good agreement with electric tape measurements, but annual program measurements recently appear to have greater error.

3.3.6 Rolla Index Well

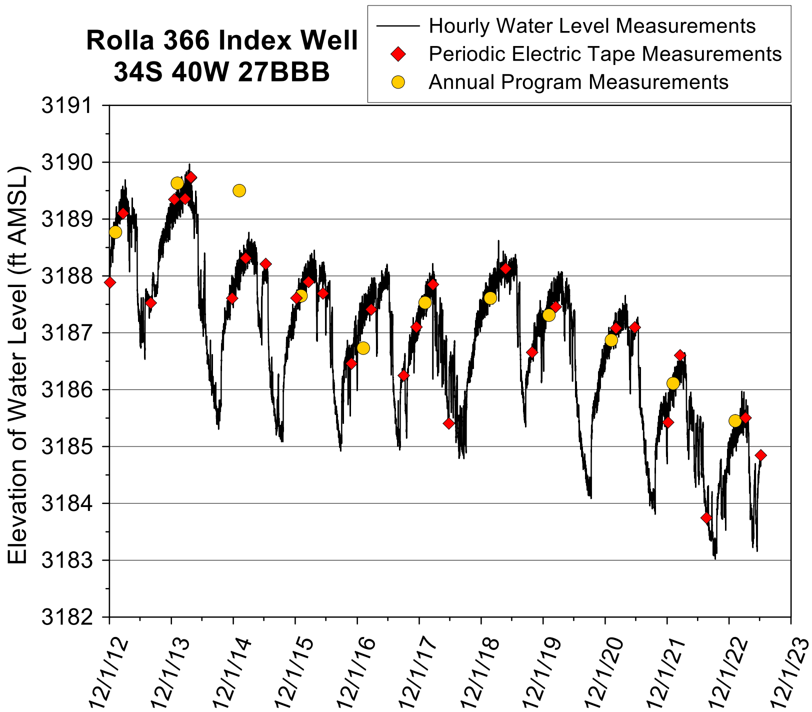


Figure 20—Rolla 366 index well hydrograph—total data run to 6/6/23. A water-level elevation of 3,188 ft corresponds to a depth to water of 187 ft below lsf. The top of the 10 ft screen is 356 ft below lsf (elevation of 3,019 ft), and the bottom of the aquifer is 399 ft below lsf (elevation of 2,976 ft). Note the suspect 2015 and 2017 annual program measurements.

Major Points

- The hydrograph form and the relatively large (up to 0.7 ft) amplitude fluctuations superimposed on water levels indicate unconfined conditions.
- The effect of individual wells turning on and off is clearly visible on the hydrograph, indicating that pumping wells are in relatively close proximity to and in good hydraulic connection with the index well.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The minimum water-level elevation in 2022 and the apparent maximum water level in 2023 were the lowest since monitoring began in late 2012.
- The water level has declined 11.6 ft since January 2000 (decline rate of 0.50 ft/yr).
- Transducer readings are in good agreement with electric-tape measurements but poorer agreement with some of the annual measurements.

3.3.7 Satanta Site

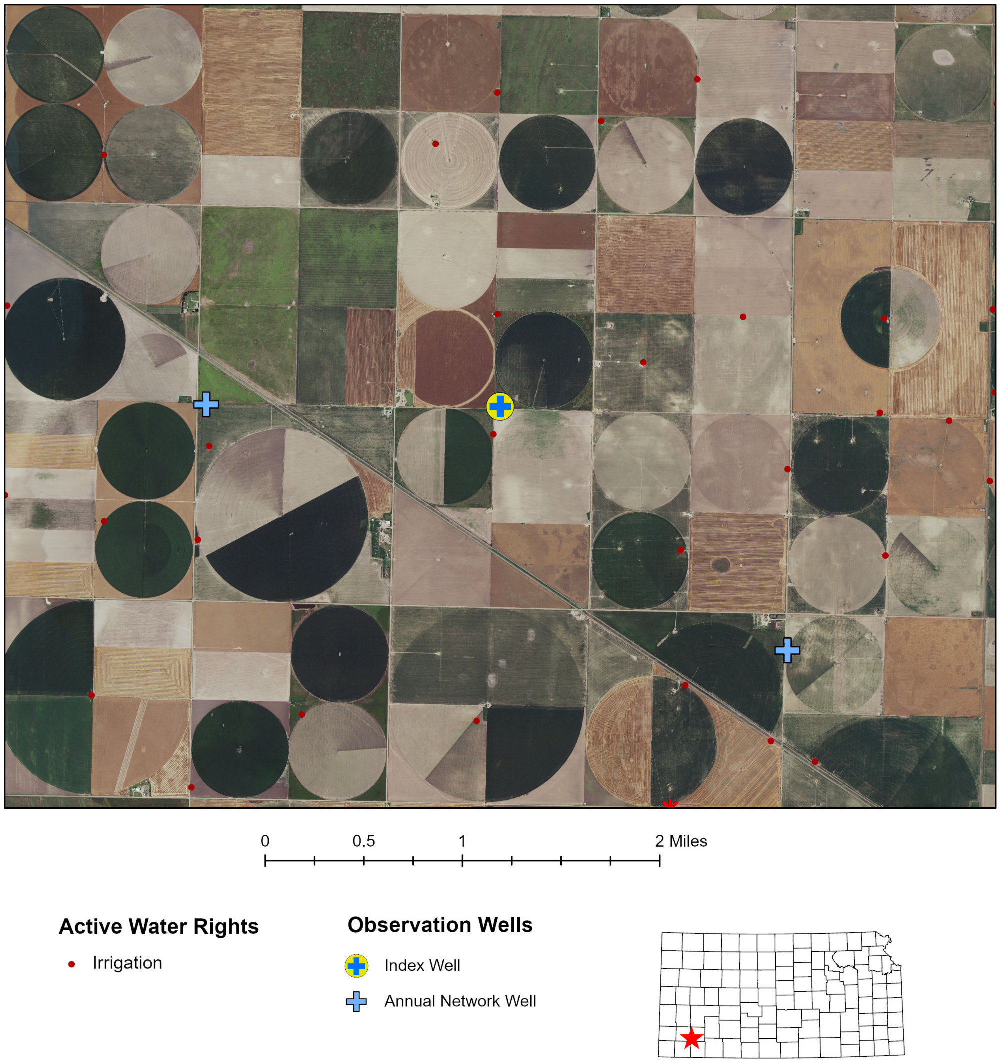


Figure 21—Aerial view of the Satanta well nest site (center of figure) and nearby annual wells and points of diversion.

Figure 21 is an aerial view of the Satanta well nest site (T. 29 S., R. 34 W., 33 DCC 01) at a scale that shows the site of the index well nest, two additional annual program wells, and the nearby wells with active water rights. The nest consists of two PVC wells in a 12.25 in. borehole; one well is screened at the base of the HPA and the other is screened near the bottom of the upper Dakota formation. A bentonite seal was placed in the annulus to isolate the wells from each other.

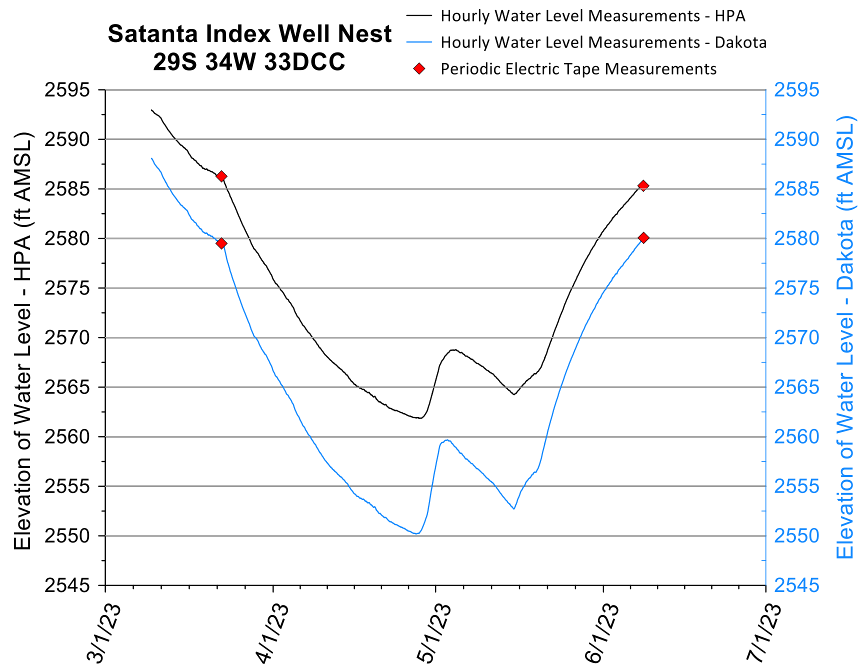


Figure 22—Satanta site hydrographs—total data run to 6/8/23. A water-level elevation of 2,580 ft corresponds to a depth to water of 400 ft below lsf. The top of the 20 ft screen in the HPA is 500 ft below lsf (elevation of 2,480 ft), and the top of the 20 ft screen in the Dakota is 600 ft below lsf (elevation of 2,380 ft). The bottom of the HPA is estimated to be at 520 ft below lsf (elevation of 2,460 ft); a 20-ft bentonite seal was placed in the annular space at 530–550 ft (just below the HPA-Dakota boundary). The well log indicates that the screened intervals in the HPA (sandy clay) and the Dakota (yellowish clay) are in lower permeability sediment.

Major Points

- The HPA and Dakota hydrographs are approximately parallel with one another, with the Dakota appearing to have larger drawdown in response to nearby pumping. All indications are that the bentonite seal has isolated the two screened intervals. Nearby pumping wells are likely screened in both aquifers.
- Further monitoring is needed to assess hydraulic conditions in the two screened intervals and the impact of nearby pumping wells.
- Transducer readings are in good agreement with manual measurements.
- The water pumped from the HPA well on September 14, 2022, was fresh; total dissolved solids (TDS) concentration in samples collected at two different pumping times was 691 mg/L (both times) and chloride and sulfate concentrations were 104–109 mg/L and 203 mg/L (both times), respectively. The water pumped from the Dakota well was slightly saline; TDS concentrations were 1,442–1,572 mg/L, and the chloride and sulfate concentrations were 530–640 mg/L and 207–216 mg/L, respectively.

3.3.8 Ulysses Site

Figure 23—Aerial view of the Ulysses well nest site (center of figure) and nearby annual well and points of diversion.

Figure 23 is an aerial view of the Ulysses well nest site (T. 28 S., R. 38 W., 21 DDD) at a scale that shows the site of the index well nest, an annual program well, and the nearby wells with active water rights. The nest consists of two PVC wells in a 12.25 in. borehole; one well is screened at the base of the HPA and the other is screened near the bottom of the upper Dakota formation. A bentonite seal was placed in the annulus to isolate the wells from each other.

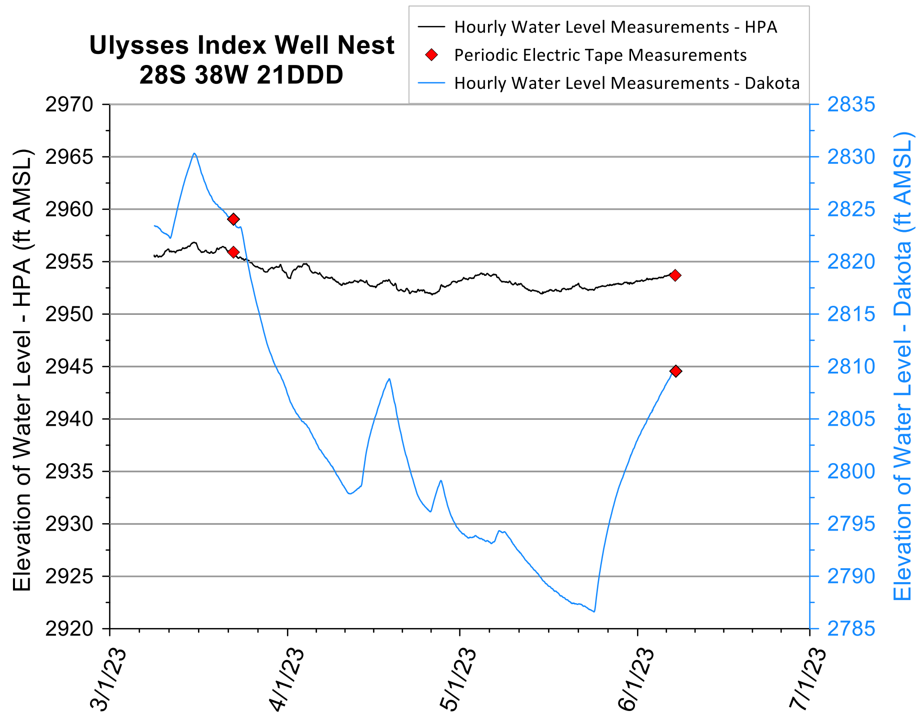


Figure 24—Ulysses site hydrographs—total data run to 6/7/23. For the HPA well, a water-level elevation of 2,955 ft corresponds to a depth to water of 225 ft below lsf. For the Dakota well, a water-level elevation of 2,800 ft corresponds to a depth to water of 380 ft below lsf. The top of the 20 ft screen in the HPA is 425 ft below lsf (elevation of 2,755 ft), and the top of the 20 ft screen in the Dakota is 560 ft below lsf (elevation of 2,620 ft). The bottom of the HPA is estimated to be at 440 ft below lsf (elevation of 2,740 ft); a 14-ft bentonite seal was placed in the annular space at 450–464 ft just below the HPA-Dakota boundary. The well log indicates that the screened intervals in both the HPA (fine to medium sand) and the Dakota (sandstone) appear to be in relatively good aquifer material.

Major Points

- The HPA and Dakota hydrographs have little resemblance to each other, with the Dakota well appearing to have much larger drawdown in response to nearby pumping. All indications are that the bentonite seal has isolated the two screened intervals.
- Further monitoring is needed to assess hydraulic conditions in the two screened intervals and the impact of nearby pumping wells.
- Transducer readings are in good agreement with manual measurements.
- The water pumped from the HPA well on November 12, 2022, was fresh (but nearly slightly saline); TDS concentrations collected at three different pumping times were 861–1,009 mg/L, and chloride and sulfate concentrations were 412–525 mg/L and 253–277 mg/L, respectively. The water pumped from the Dakota well was slightly saline; TDS concentrations collected at three different pumping times were 1,289–1,892 mg/L, and the chloride and sulfate concentrations were 794–1,249 mg/L and 182–206 mg/L, respectively. Concentrations decreased in consecutive samples from the Dakota well, suggesting that fresher water might have been drawn downward from the HPA as also indicated by the hydrograph during the irrigation pumping season.

3.3.9 Willis Water Technology Farm Index Well

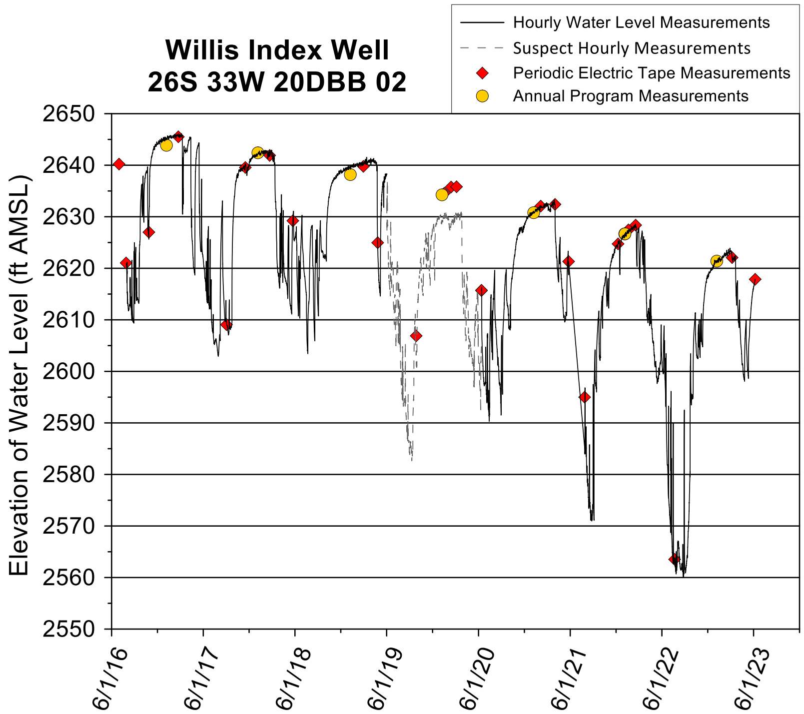


Figure 25—Willis Water Technology Farm index well hydrograph—total data run to 6/7/23. A water-level elevation of 2,620 ft corresponds to a depth to water of 320 ft below lsf. The top of the 220 ft screen is 262 ft below lsf (elevation of 2,678 ft), and the bottom of the aquifer is 502 ft below lsf (elevation of 2,438 ft). The first electric-tape measurement was taken before continuous monitoring began. The lack of agreement between manual and transducer measurements from September 2019 to June 2020 is a result of a miscalibrated transducer (dashed line indicates transducer data during this period). Telemetry ceased operating on 2/9/21 due to cable damage; repaired cable was installed on 7/27/21.

Major Points

- The relatively large amplitude fluctuations superimposed on the water levels, particularly evident during the latter stages of the recovery period, indicate unconfined conditions.
- The effect of individual wells turning on and off is clearly visible on the hydrograph, indicating pumping wells are in relatively close proximity to and in good hydraulic connection with the index well.
- Each year, the maximum water level is below that of the preceding year, creating a downward stair-stepping pattern. Some years, water levels recover to a near stable value, while in other years, the recovery continues until the start of the next irrigation season. Water level has fallen approximately 21.0 ft since January 2018, a rate of decline of approximately 4.2 ft/year. The minimum water level for 2022 was the lowest since the start of monitoring.
- Transducer readings are in good agreement with manual measurements except for the 2017 and 2019 annual measurements and from 2/19 to 6/20 (dashed record).

3.4 GMD4 Index Wells

Nine index wells are located in GMD4, six of which have telemetry equipment that allows real-time viewing of data (fig. 26). The Thomas index well was one of the original 2007 index wells and had telemetry capabilities from the start. Monitoring with telemetry began at the Colby, Seegmiller Sheridan-6 (SD-6) LEMA, Sherman, Steiger SD-6 LEMA, and Sherman 2 index wells in 2015, 2016, 2017, 2021, and 2022, respectively. Table 4 summarizes characteristics of these nine wells. Further details concerning these wells are given in the 2016 and 2021 annual reports (Butler, Whittemore et al., 2017; Butler et al., 2022) and the online appendices for this report (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

Table 4—Characteristics of the GMD4 index well sites (water use is for irrigation unless noted otherwise).

Site	2023 WL elev. (ft)[a]	2023 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2021, 2022 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Colby	3,022.2	95.4[b]	250–300	156–175	597[c], 642[c]	2,077[d], 2,524[d]	11,318[e], 14,197[e]
SD-6 Baalman	2,708.6	73.6	262	260–270	531, 851	2,126, 3,242	13,590[f], 20,662[f]
SD-6 Beckman[g,h]	2,676.7[g]				943, 1,077	3,170[i], 4,346[i]	13,730[j], 18,998[j]
SD-6 Moss[g]	2,622.3[g]	49.3	243	205–245	271, 565	2,324, 3,711	14,499[k], 19,919[k]
SD-6 Seegmiller	2,736.6	68.6	265	225–265	665, 1,068	2,710, 4,606	14,875[l], 22,891[l]
SD-6 Steiger	2,847.0	59.0	177	145–185	213, 371	1,143[m], 1,423[m]	9,338[n], 13,882[n]
Sherman	3,609.9	138.9	323	310–320	1,862, 1,836	3,567, 4,026	12,623[o], 14,416[o]
Sherman 2[g]	3364.7[g]	115.7	275	240–280	209, 323	1,969, 2,218	11,015[p], 13,468[p]
Thomas	2,968.2	64.8	284	274–284	1,049, 1,393	2,790, 3,625	12,223, 16,967

[a] 2023 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html).

[b] Based on bedrock depth of 250 ft below lsf.

[c] Includes 312 ac-ft of municipal water (2021); and 328 ac-ft of municipal water (2022).

[d] Includes 1,252 ac-ft (2021) and 1,422 ac-ft (2022) of municipal water and 221 ac-ft (2021) and 242 ac-ft (2022) of other water.

[e] Includes 1,407 ac-ft (2021) and 1,578 ac-ft (2022) of municipal water, 221 ac-ft (2021) and 242 ac-ft (2022) of other water, 1 ac-ft (2021 and 2022) of industrial water, and 29 ac-ft (2021) and 32 ac-ft (2022) of non-irrigation stock water.

[f] Includes 757 ac-ft (2021) and 784 ac-ft (2022) of non-irrigation stock water.

[g] Not an annually measured index well; 2023 water-level measurements estimated from sensor data on 01/4/2023 from 0800 to 1700 at Beckman, Moss, and Sherman 2.

[h] Well construction information not available.

[i] Includes 295 ac-ft (2021) and 405 ac-ft (2022) of non-irrigation stock water.

[j] Includes 670 ac-ft (2021) and 726 ac-ft (2022) of non-irrigation stock water.

[k] Includes 589 ac-ft (2021) and 614 ac-ft (2022) of non-irrigation stock water, 1 ac-ft (2021) and 2 ac-ft (2022) of industrial water, and 336 ac-ft (2021) and 385 ac-ft (2022) of municipal water.

[l] Includes 670 ac-ft (2021) and 726 ac-ft (2022) of non-irrigation stock water.

[m] Includes 30 ac-ft (2021) and 34 ac-ft (2022) of non-irrigation stock water.

[n] Includes 50 ac-ft (2021) and 55 ac-ft (2022) of non-irrigation stock water and 5 ac-ft (2022) of recreational water.
[o] Includes 104 ac-ft (2021) and 103 ac-ft (2022) of recreational water.
[p] Includes 100 ac-ft (2021) and 160 ac-ft (2022) of non-irrigation stock water.

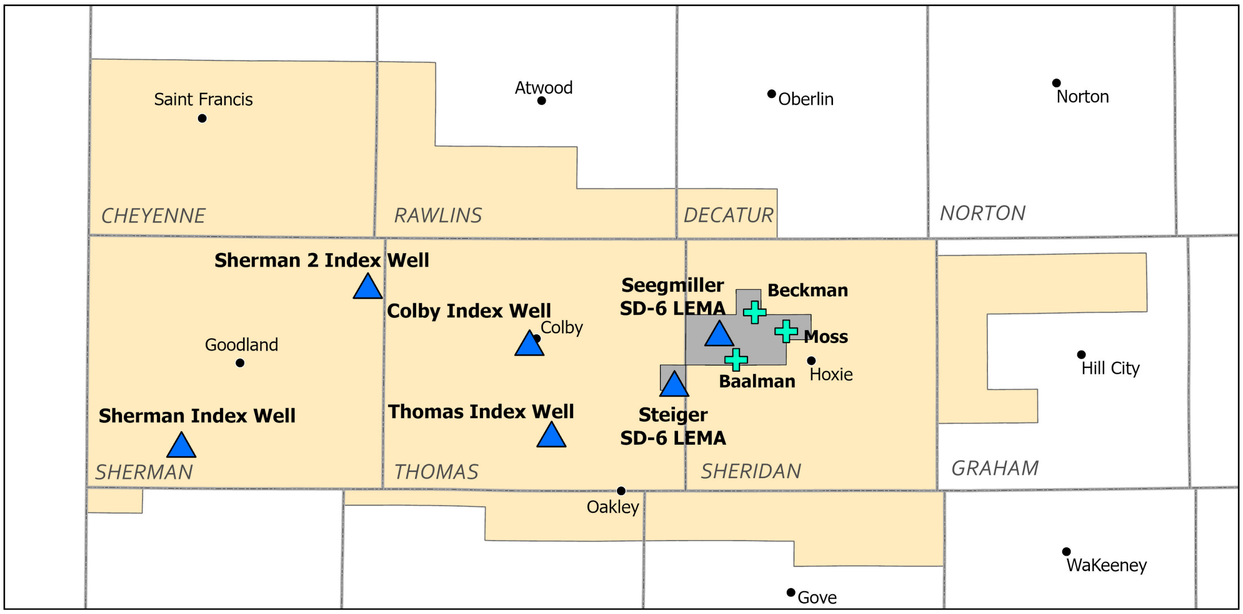


Figure 26—Map of index wells in GMD4. Triangles designate wells with telemetry equipment, and plus signs designate wells without telemetry equipment. Data from wells with telemetry equipment can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml); data from wells without telemetry equipment are periodically downloaded (typically quarterly) and posted on the KGS website. Shaded area is the Sheridan-6 LEMA.

3.4.1 Colby Index Well

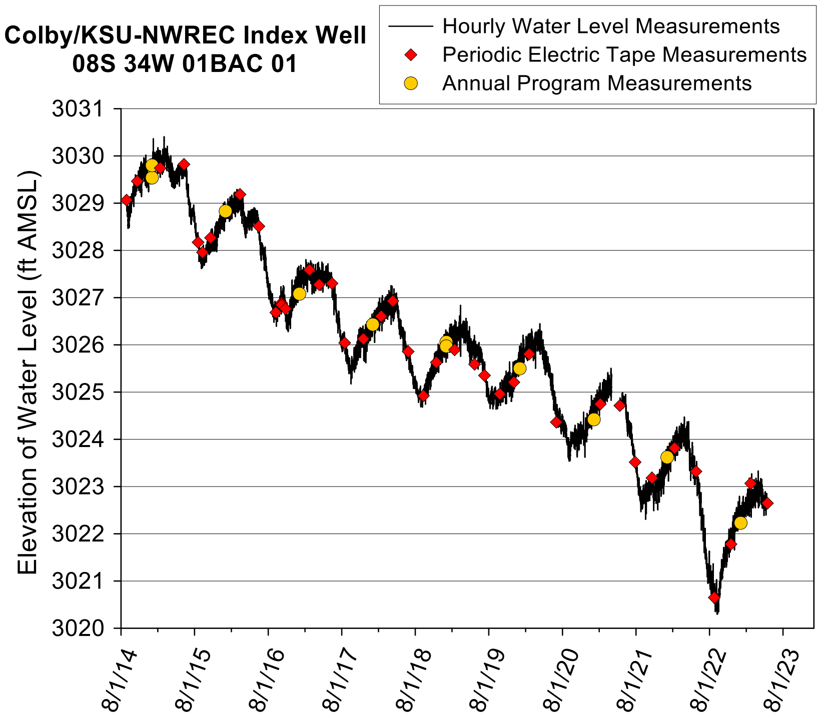


Figure 27—Colby index well hydrograph—total data run to 5/15/23. A water-level elevation of 3,024 ft corresponds to a depth to water of 153 ft below lsf. Total depth of the well is 175 ft below lsf (elevation of 3,002 ft). The screened interval extends from 156 to 175 ft below lsf. The base of the aquifer is estimated to be 250–300 ft below lsf (Butler, Whittemore et al., 2017). Sensor failed on 4/1/21 and was replaced on 5/12/21.

Major Points

- The relatively large amplitude fluctuations superimposed on the water-level record indicate unconfined conditions.
- After the end of the irrigation season, water levels continue to recover until the start of the next season; apparent stabilization of water levels in late winter and early spring of 2017 appears to be a product of nearby pumping.
- The maximum recovered water level has declined each year during the monitoring period, giving a distinct stair-step character to the hydrograph.
- Based on annual water-level measurements, the water level has declined approximately 0.9 ft/yr over the monitoring period (since January 2015) and a total of 39.3 ft since January 1948. The decline in 2022 was the largest during the monitoring period.
- Transducer readings are in good agreement with manual measurements.

3.4.2 SD-6 Baalman Index Well

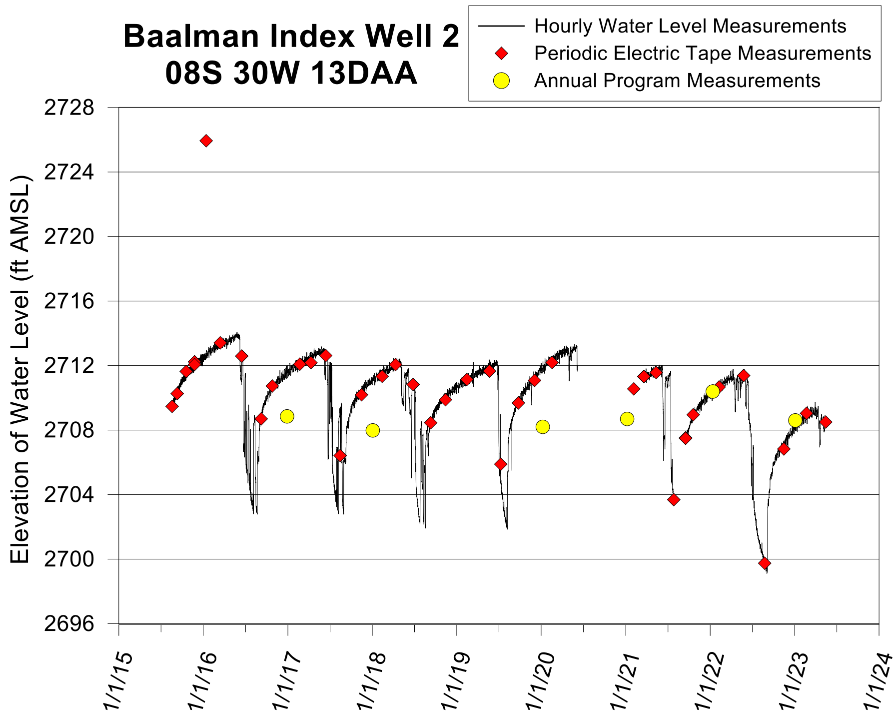


Figure 28—Baalman index well hydrograph—total data run to 5/15/23. A water-level elevation of 2,712 ft corresponds to a depth to water of 185 ft below lsf. The top of the 10 ft screen is 260 ft below lsf (elevation of 2,637 ft), and the bottom of the aquifer is 262 ft below lsf (elevation of 2,635 ft). The difference between the electric-tape and transducer measurements in January 2016 was caused by a malfunctioning electric tape.

Major Points

- The hydrograph form and the relatively large amplitude fluctuations superimposed on the water levels, particularly evident during the recovery period, are an indication of unconfined conditions.
- The effect of individual wells turning on and off is clearly visible, indicating pumping wells are in relatively close proximity to and in good hydraulic connection with the index well.
- The maximum water level in 2022 was the lowest in the monitoring period and the minimum water level in 2022 was far lower than previous minima during the monitoring period.
- In 2022, the water use per irrigated acre in the vicinity of the Baalman index well (2 mi radius) was 1.07 ft (12.8 inches)/acre, the largest since the SD-6 LEMA was established. Since the establishment of the LEMA, the average annual water use per irrigated acre for this same area has been approximately 0.74 ft (8.9 inches)/acre.
- Sensor failed on 6/5/20 but, because of the pandemic and the lack of telemetry, the failure was not recognized until 2/4/21; a new sensor was installed on 3/20/21. Sensor was removed on 7/27/21 because of faulty cable. New sensor and cable installed on 9/16/21.
- Transducer readings are in good agreement with periodic electric-tape measurements, except for the January 2016 measurement, but in poor agreement with annual program measurements.

3.4.3 SD-6 Beckman Index Well

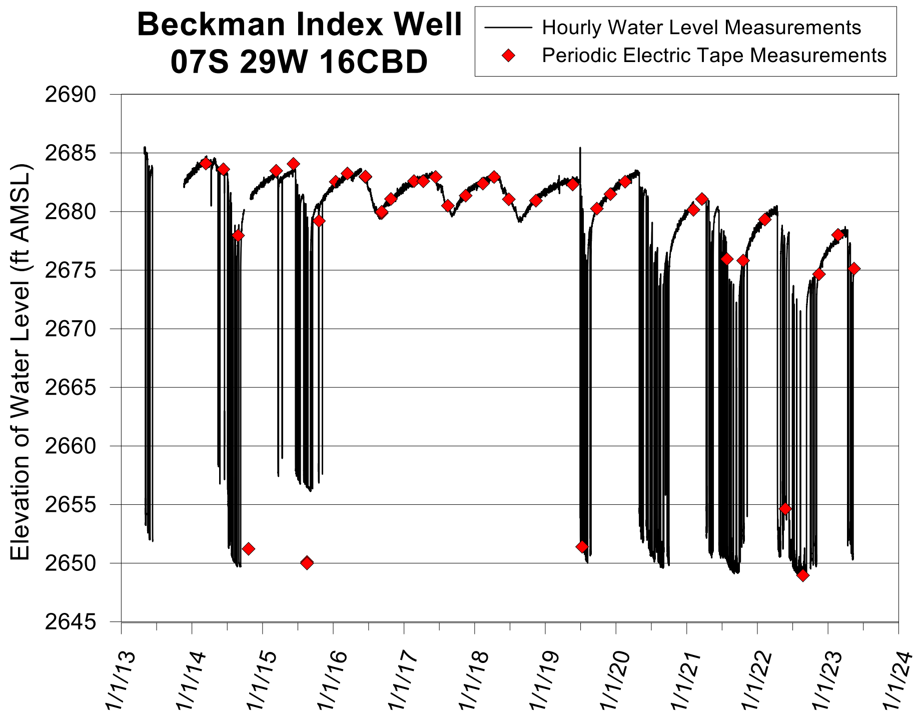


Figure 29—Beckman index well hydrograph—total data run to 5/15/23. A water-level elevation of 2,680 ft corresponds to a depth to water of 200.2 ft below lsf. The data gaps in 2013 and 2014 were caused by datalogger battery problems. The difference between the electric-tape measurement in the summer of 2015 and the hourly measurements from the transducer is thought to be caused by a change in transducer calibration specifications associated with the resumption of monitoring in late October 2014.

Major Points

- The irrigation well adjacent to the Beckman index well was pumped for the fourth time in the last four irrigation seasons and the seventh time since the establishment of the SD-6 LEMA.
- The hydrograph form and the relatively large amplitude fluctuations superimposed on the water levels, particularly evident during the recovery period, are an indication of unconfined conditions.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- In 2022, the water use per irrigated acre in the vicinity of the Beckman index well (2 mi radius) was 1.13 ft (13.6 inches)/acre, the largest since the SD-6 LEMA was established. Since the establishment of the LEMA, the average annual water use per irrigated acre for this same area has been approximately 0.77 ft (9.2 inches)/acre.
- Sensor failed on 2/4/21 and was replaced during site visit on 3/20/21.
- Transducer readings are in good agreement with manual measurements in the latter half of the monitoring period.

3.4.4 SD-6 Moss Index Well

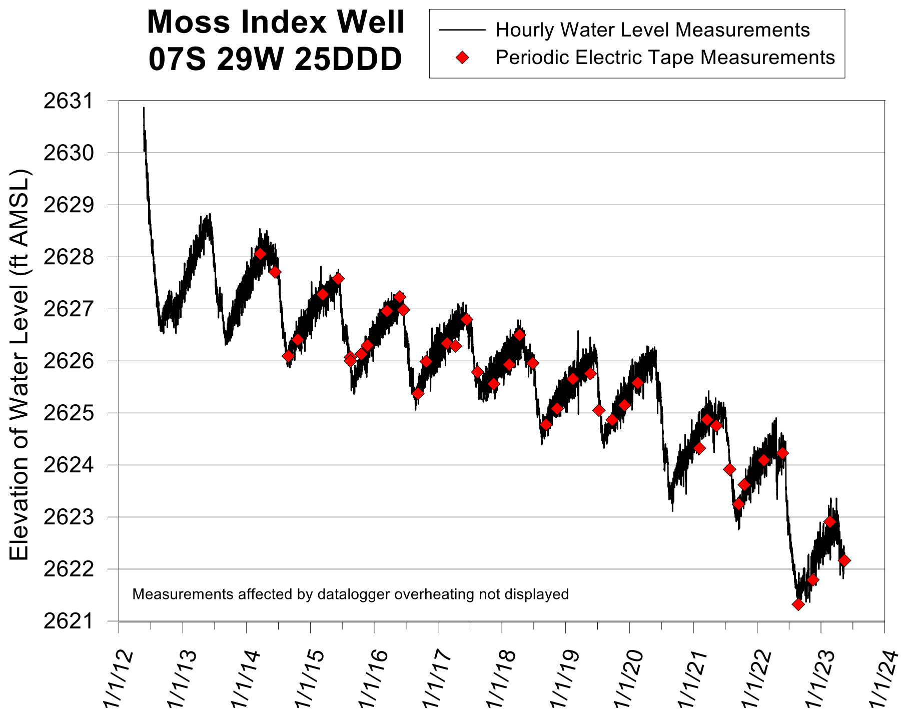


Figure 30—Moss index well hydrograph—total data run to 5/15/23. A water-level elevation of 2,625 ft corresponds to a depth to water of 191 ft below lsf. The top of the 40 ft screen is 205 ft below lsf (elevation of 2,611 ft), and the bottom of the aquifer is 243 ft below lsf (elevation of 2,573 ft).

Major Points

- The relatively large amplitude fluctuations superimposed on the water levels, particularly evident during the recovery period, are an indication of unconfined conditions.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The minimum water-level elevation has been above that of the preceding year once (2017, a wet year). Otherwise, the hydrograph displays a downward stepping pattern.
- In 2022, the water use per irrigated acre in the vicinity of the Moss index well (2 mi radius) was 1.29 ft (15.5 inches)/acre, the largest since the SD-6 LEMA was established. Since the establishment of the LEMA, the average annual water use per irrigated acre for this same area has been approximately 0.87 ft (10.4 inches)/acre.
- Transducer readings are in good agreement with manual measurements.

3.4.5 SD-6 Seegmiller Index Well

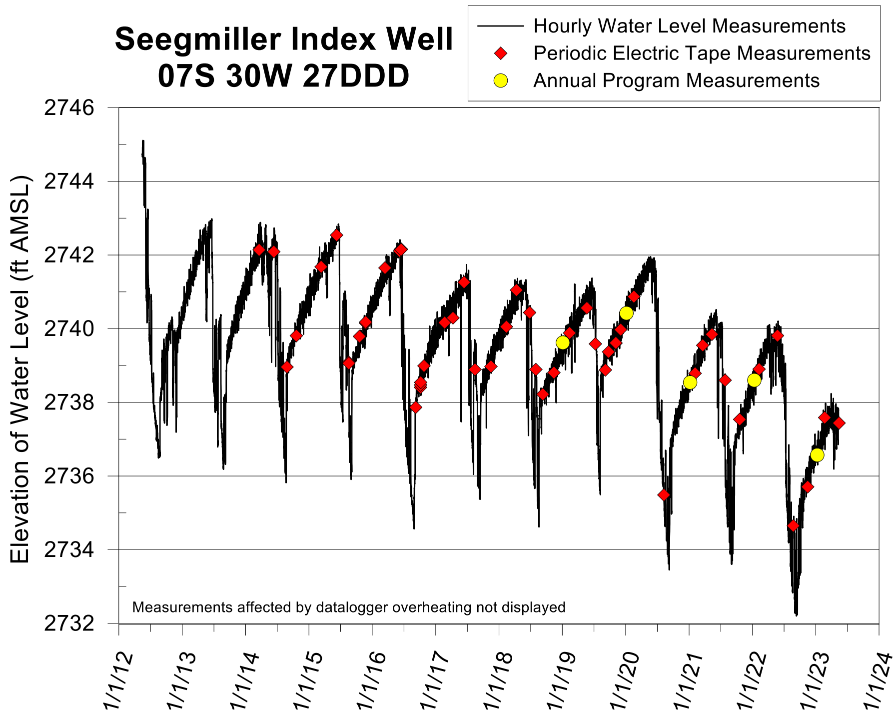


Figure 31—Seegmiller index well hydrograph—total data run to 5/15/23. A water-level elevation of 2,740 ft corresponds to a depth to water of 193 ft below lsf. The top of the 40 ft screen is 225 ft below lsf (elevation of 2,708 ft), and the bottom of the aquifer is 265 ft below lsf (elevation of 2,668 ft).

Major Points

- The hydrograph form and the relatively large amplitude fluctuations superimposed on the water levels, particularly evident during the recovery period, indicate unconfined conditions.
- The effect of individual wells turning on and off is clearly visible on the hydrograph, indicating pumping wells in relatively close proximity to and in good hydraulic connection with the index well.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The minimum water-level elevation for 2022 is 1.2 ft below that of 2020, which was the lowest observed during the monitoring period prior to 2022.
- In 2022, the water use per irrigated acre in the vicinity of the Seegmiller index well (2 mi radius) was 1.10 ft (13.2 inches)/acre, the largest since the SD-6 LEMA was established. Since the establishment of the LEMA, the average annual water use per irrigated acre for this same area has been approximately 0.77 ft (9.2 inches)/acre.
- Transducer readings are in good agreement with manual measurements.

3.4.6 SD-6 Steiger Index Well

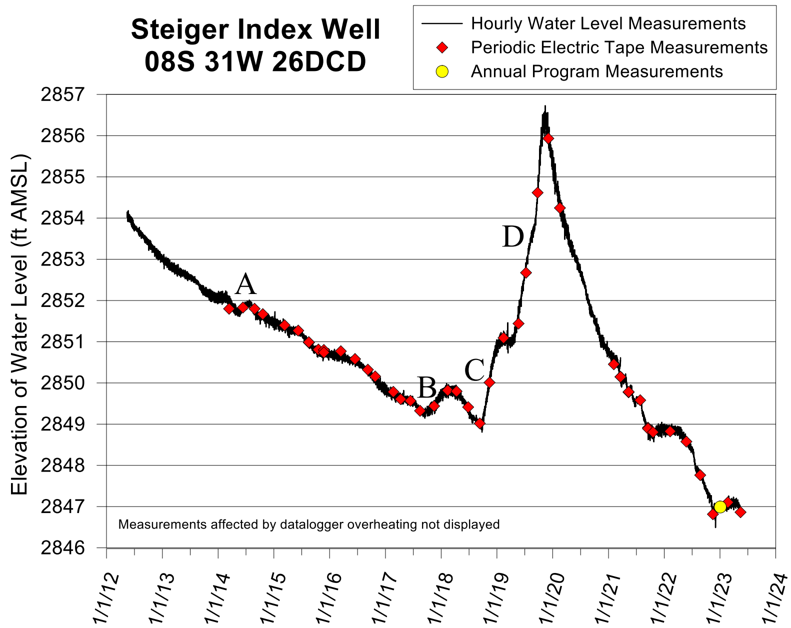


Figure 32—Steiger index well hydrograph—total data run to 5/15/23. A water-level elevation of 2,850 ft corresponds to a depth to water of 115 ft below lsf. The top of the 40 ft screen is 145 ft below lsf (elevation of 2,820 ft), and the bottom of the aquifer is 177 ft below lsf (elevation of 2,788 ft). A–D defined in text.

Major Points

- The fluctuations superimposed on the water levels are an indication of unconfined conditions but are of smaller magnitude than the other index wells in GMD4; this small magnitude typically indicates a relatively shallow depth to water.
- It is difficult to discern individual pumping seasons. The humps and troughs observed in the hydrograph at points marked A–D are likely related to a series of episodic recharge events and not pumping. The Steiger index well is located near an impoundment behind a small dam over an ephemeral stream channel; the impoundment appears to serve as a site of focused recharge.
- The effect of individual wells cutting on and off cannot be discerned.
- Except for a short decline early in the 2019 irrigation season, water levels rose continuously from the end of the 2018 pumping season to November 2019. This rise (>7.5 ft) is the only definitive example of episodic recharge that we have observed in the index wells in western Kansas. The sharp decline since the peak in November of 2019 indicates that the recharge was likely a localized event (i.e., water flows laterally to areas that did not receive the recharge) associated with the nearby impoundment (Butler, Knobbe et al., 2021). Comparison of the rise in water level with area rainfall indicates that the recharge pulse appears to have taken a little over a year to reach the water table.
- In 2022, the water use per irrigated acre in the vicinity of the Steiger index well (2 mi radius) was 1.21 ft (14.5 inches)/acre, the largest since the SD-6 LEMA was established. Since the establishment of the LEMA, the average annual water use per irrigated acre for this same area has been approximately 0.86 ft (10.3 inches)/acre.
- Transducer readings are in good agreement with manual measurements.

3.4.7 Sherman County Index Well

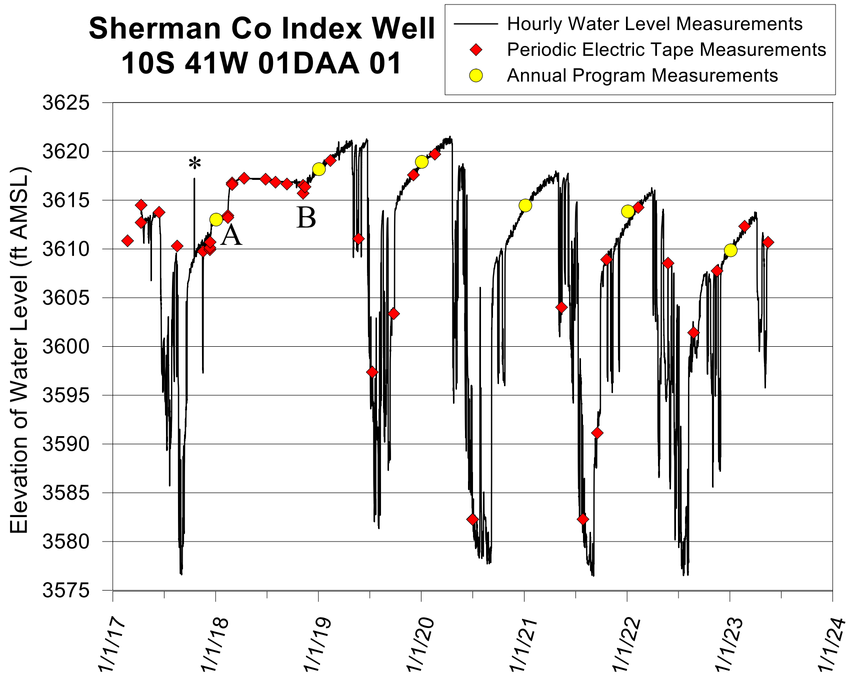


Figure 33—Sherman County index well hydrograph—total data run to 5/16/23. A water-level elevation of 3,615 ft corresponds to a depth to water of 179 ft below lsf. The top of the 10 ft screen is 310 ft below lsf (elevation of 3,484 ft), and the bottom of the aquifer is 323 ft below lsf (elevation of 3,471 ft). The well has a 10 ft sump that extends to 330 ft below lsf. The asterisk indicates a single spurious reading; A and B defined in text.

Major Points

- The hydrograph form and the relatively large amplitude fluctuations superimposed on the water levels, particularly evident during the recovery period, indicate unconfined conditions.
- The effect of individual wells turning on and off is clearly visible on the hydrograph, indicating pumping wells in relatively close proximity to and in good hydraulic connection with the index well.
- The well was not developed immediately after installation because of extreme cold. As a result, the screened interval gradually filled with fine-grained sediments. During the period from 2/13/18 (A on plot) to 11/7/18 (B on plot), the screened interval appears to have been in poor hydraulic connection with the aquifer. Well development on 11/7/18 (B) reestablished the hydraulic connections between the well and the aquifer (Butler, Knobbe et al., 2021).
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- Agreement between transducer readings and manual measurements varied over the monitoring period; agreement appears good after a new sensor was installed on 2/13/18 (A).

3.4.8 Sherman County 2 Index Well

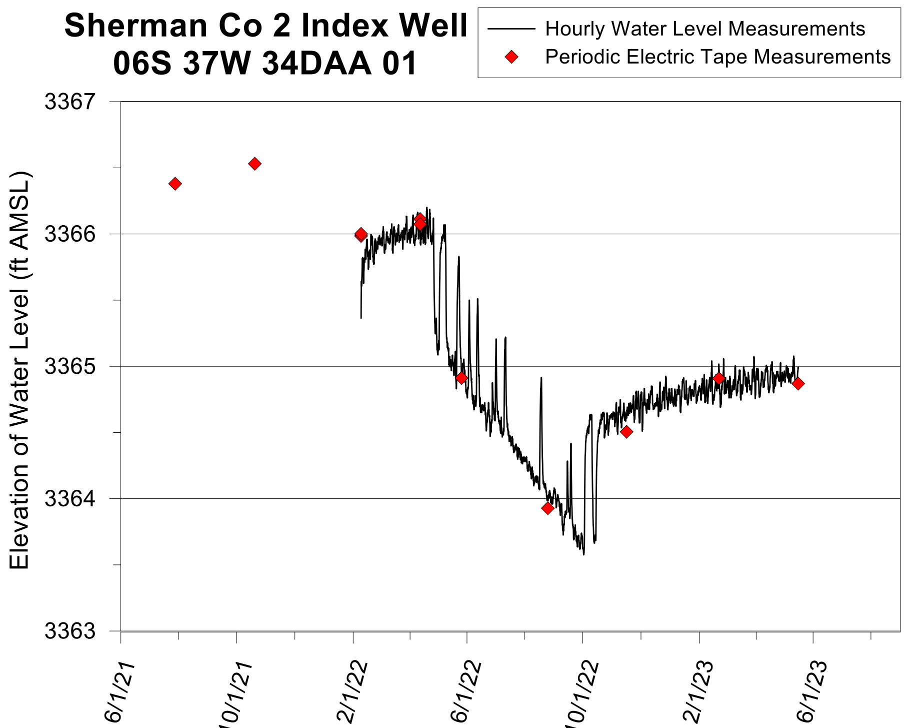


Figure 34—Sherman County 2 index well hydrograph—total data run to 5/16/23. A water-level elevation of 3,365 ft corresponds to a depth to water of 159 ft below lsf. The top of the 40 ft screen is 240 ft below lsf (elevation of 3,284 ft). The bottom of the aquifer is estimated to be 275 ft below lsf (elevation of 3,249 ft), and the bottom of the well is 276.3 ft below lsf (well appears to have 3.7 ft of material in the bottom – lower 5 ft of screen appear to be below the bottom of the aquifer).

Major Points

- The hydrograph form during the irrigation season and the relatively large fluctuations superimposed on the water levels, particularly evident during the recovery period, are an indication of unconfined conditions.
- The effect of individual pumping wells is discernible, indicating that one or more of the nearby pumping wells are in good hydraulic connection with the index well.
- The linear form of the water level decline during the 2022 irrigation season is an indication of a laterally bounded system (Butler, Stotler et al., 2013). This could be produced by aquifer heterogeneity or nearby pumping wells.
- Transducer readings are in good agreement with manual measurements from shortly after start of monitoring.

3.4.9 Thomas County Index Well

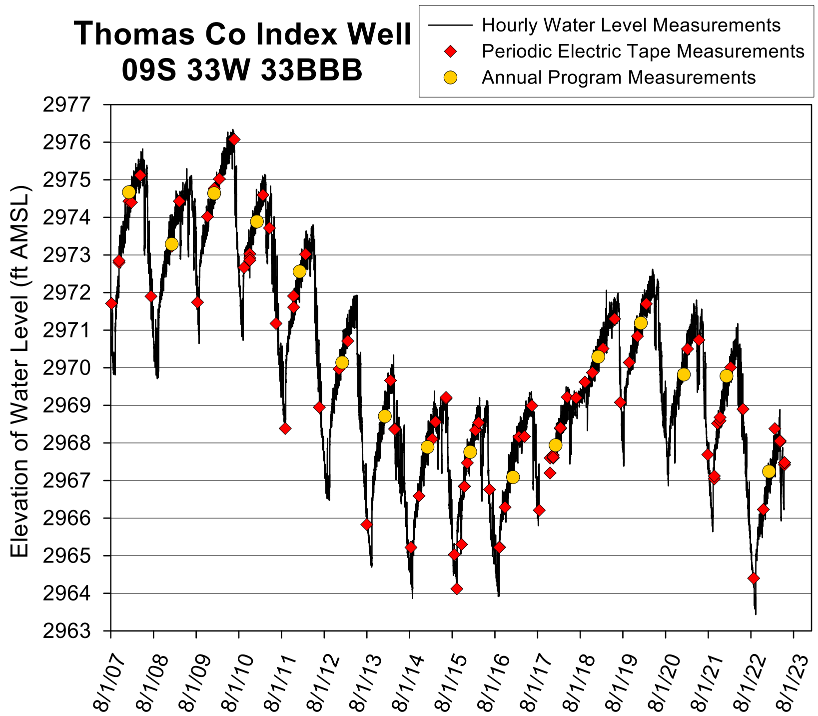


Figure 35—Thomas County index well hydrograph—total data run to 5/15/23. A water-level elevation of 2,967 ft corresponds to a depth to water of 220.6 ft below lsf. The top of the screen is 274 ft below lsf (elevation of 2,913.6 ft), and the bottom of the aquifer is 284 ft below lsf (elevation of 2,903.6 ft). The screen terminates at the bottom of the aquifer. No water-level data are available from 10/28/17 to 12/11/17 because of sensor failure.

Major Points

- The hydrograph form, the relatively small change and rate of change in water level during each pumping and recovery season (despite eight high-capacity pumping wells within a mile of the index well), and the relatively large amplitude fluctuations superimposed on water levels indicate unconfined conditions.
- The effect of individual wells turning on and off is clearly visible on the hydrograph, indicating pumping wells in relatively close proximity to and in good hydraulic connection with the index well.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The minimum water level in 2022 was 2.3 ft lower than that in 2021 and was the lowest since the start of monitoring (2007); previous lowest minimum was 0.5 ft higher (2014 and 2016).
- The 2018 water use (2-mi radius) was the lowest for the monitoring period because of cessation of pumping after a hail storm in late spring 2018 that destroyed the crops in the vicinity of the index well; the next lowest water use was 2019, which was 1.9 times greater than that in 2018.
- Transducer readings are in good agreement with manual measurements.

3.5 GMD5 Index Wells

Four index wells, all of which have telemetry equipment that allows real-time viewing of data, are located in GMD5 (fig. 36). Table 5 summarizes characteristics of these wells. Further details concerning the Belpre and Larned wells are given in the 2016 (Butler, Whittemore et al., 2017) and 2018 (Butler et al., 2019) annual reports, respectively, and information about the Rozel and Trousdale index wells is provided in the 2021 annual report (Butler et al., 2022). Further information about all wells is given in the online appendices for this report (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

Table 5—Characteristics of the GMD5 index well sites (water use is for irrigation unless noted otherwise).

Site	2023 WL elev. (ft)[a]	2023 saturated thickness (ft)	Bedrock depth (ft below land surface)	Screened interval (ft below land surface)	2021, 2022 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Belpre	2,041.61	135.9–161.6[b]	175–200[b]	89–109	803, 1,006	2,938, 3,677	17,618[c], 23,649[c]
Larned	1,942.40	58.08	71	66–71	354[d], 426[d]	3,189[e], 3,129[e]	18,091[f], 21,578[f]
Rozel	2,040.36	80.86	125.5[b]	40–59	412, 602	2,918, 4,194	11,014[g], 15,097[g]
Trousdale	2,047.87	103.08	140[b]	47–57	937, 1,143	3,655[h], 4,472[h]	21,701[i], 27,545[i]

[a] 2023 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html)

[b] Well not drilled to bedrock; depth to bedrock estimated from nearby well logs.

[c] Includes 12 ac-ft (2021) and 14 ac-ft (2022) of municipal water.

[d] Includes 17 ac-ft (2021) and 16 ac-ft (2022) of industrial water.

[e] Includes 17 ac-ft (2021) and 16 ac-ft (2022) of industrial water and 84 ac-ft (2021) and 132 ac-ft (2022) of non-irrigation stock water.

[f] Includes 17 ac-ft (2021) and 16 ac-ft (2022) of industrial water, 169 ac-ft (2021) and 274 ac-ft (2022) of non-irrigation stock water, and 402 ac-ft (2021) and 421 ac-ft (2022) of municipal water.

[g] Includes 55 ac-ft (2021) and 58 ac-ft (2022) of municipal water and 2 ac-ft (2021) and 5 ac-ft (2022) of non-irrigation stock water.

[h] Includes 8 ac-ft (2021 and 2022) of non-irrigation stock water.

[i] Includes 9 ac-ft (2021) and 10 ac-ft (2022) of non-irrigation stock water, 1 ac-ft (2022) of industrial water, and 5 ac-ft (2021) of recreation use water.

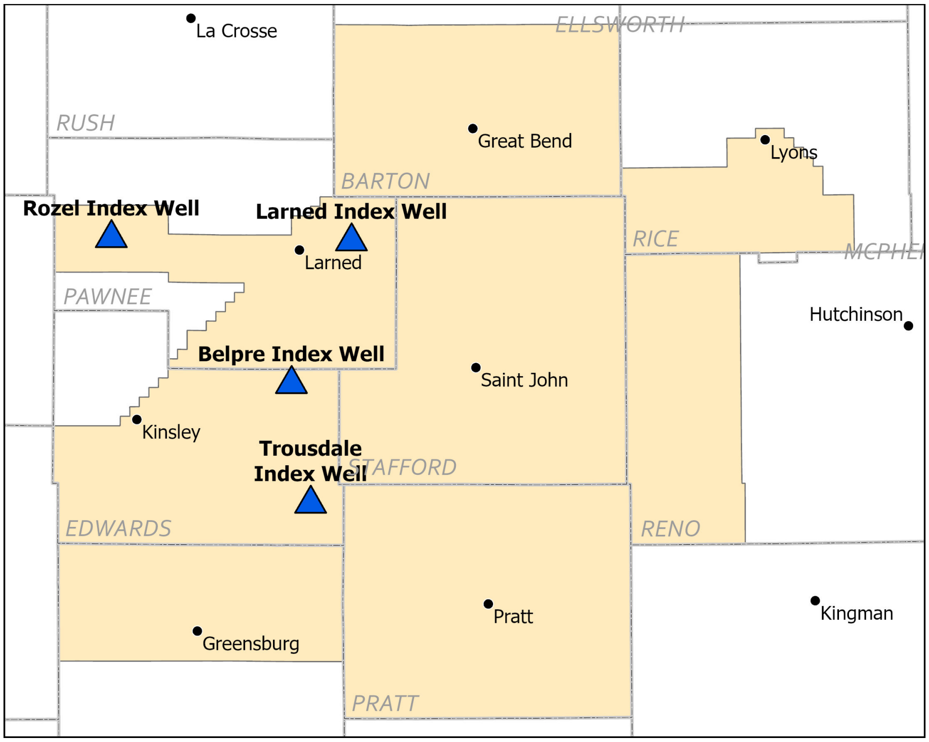


Figure 36—Map of index wells in GMD5 (blue triangles). Data from all four wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

3.5.1 Belpre Index Well

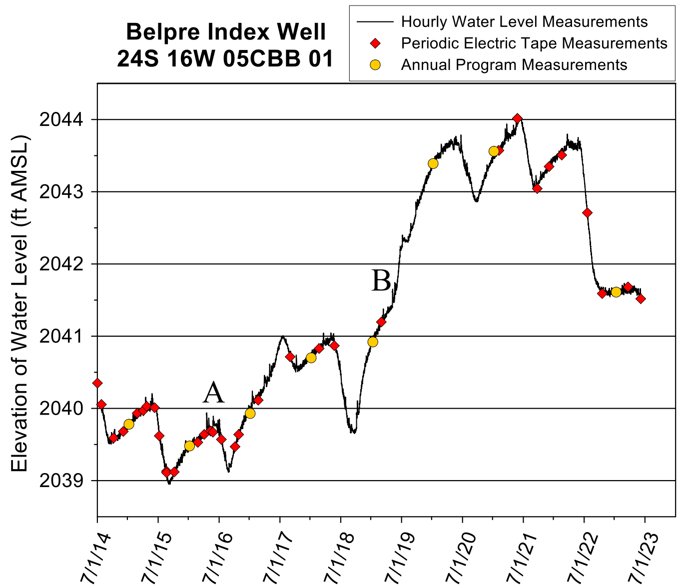


Figure 37—Belpre index well hydrograph—total data run to 6/5/23. A water-level elevation of 2,040 ft corresponds to a depth to water of 40 ft below lsf. The top of the 20 ft screen is 89 ft below lsf (elevation of 1,991 ft), and the bottom of the screen is 109 ft below lsf (elevation of 1,971 ft). The base of the aquifer is estimated to be 175–200 ft below lsf (elevation of 1,905–1,880 ft). A and B defined in text.

Major Points

- Small amplitude fluctuations superimposed on water levels indicate unconfined conditions with a relatively shallow depth to water.
- The effect of individual pumping wells cutting on and off is difficult to discern; the water-level response to pumping appears to be more integrated than at most of the index wells. Given the proximity of nearby pumping wells, this indicates that those wells are extracting water from intervals that are not in good hydraulic connection with the index well, which apparently is screened below the interval used by most of the irrigation wells in the area.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize). The rise was very small after the end of the 2022 irrigation season because of the drought conditions.
- The numerous upward spikes, such as marked by A, are local recharge events dissipated by lateral and vertical flow (Butler, Knobbe et al., 2021). Kinks in the plot, such as marked by B, were produced by regional recharge events from widespread precipitation.
- The maximum water level for 2022 was equal to the second highest on record and the minimum water level for 2022 was lower than the minima for the previous two years.
- The water level has declined 8.91 ft since January 1988 (decline rate of 0.25 ft/yr).
- Transducer readings are generally in good agreement with manual measurements.

3.5.2 Larned Index Well

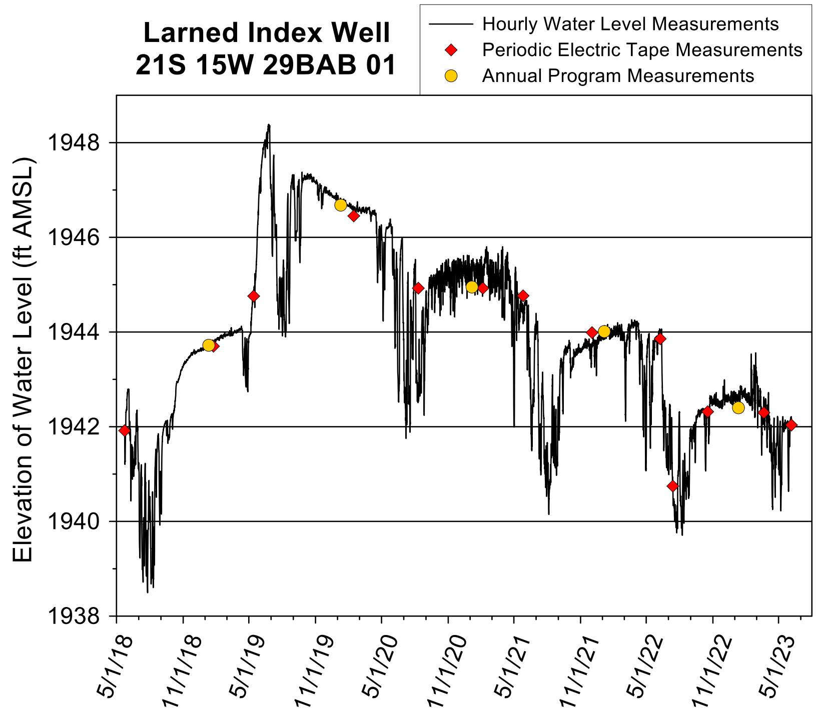


Figure 38—Larned index well hydrograph—total data run to 6/5/23. A water-level elevation of 1,944 ft corresponds to a depth to water of 11.3 ft below lsf. The top of the 5 ft screen is 66 ft below lsf (elevation of 1,889.3 ft), and the bottom of the screen, which is at the base of the aquifer, is 71 ft below lsf (elevation of 1,884.3 ft).

Major Points

- Hydrograph form and small amplitude fluctuations superimposed on water levels (until the fall of 2020) indicate confined conditions. Much larger amplitude fluctuations from 8/10/20 to 5/26/21 and from 2/13/23 to present are due to atmospheric pressure readings inadvertently being added to the water-level data. Data will be corrected shortly.
- The effect of individual wells turning on and off is clearly visible on the hydrograph, indicating pumping wells in good hydraulic connection with the index well.
- The rapid increase in water level in May and June 2019 was produced by large flow events in the nearby Arkansas River (maximum discharge reached 5,720 ft^3/s with a stage change greater than 9.9 ft at the end of May).
- After the end of the 2018 irrigation season, water levels continued to recover until the start of the next season. After the end of the 2019 irrigation season, water levels continued to decline until near the start of the 2020 irrigation season. Water levels appeared to stabilize after the 2020–2022 irrigation seasons, an indication of limited lateral flow to this portion of the aquifer. The 2022 recovery may also be affected by distant pumping in response to drought conditions.
- Transducer readings are in reasonable agreement with manual measurements.

3.5.3 Rozel Index Well

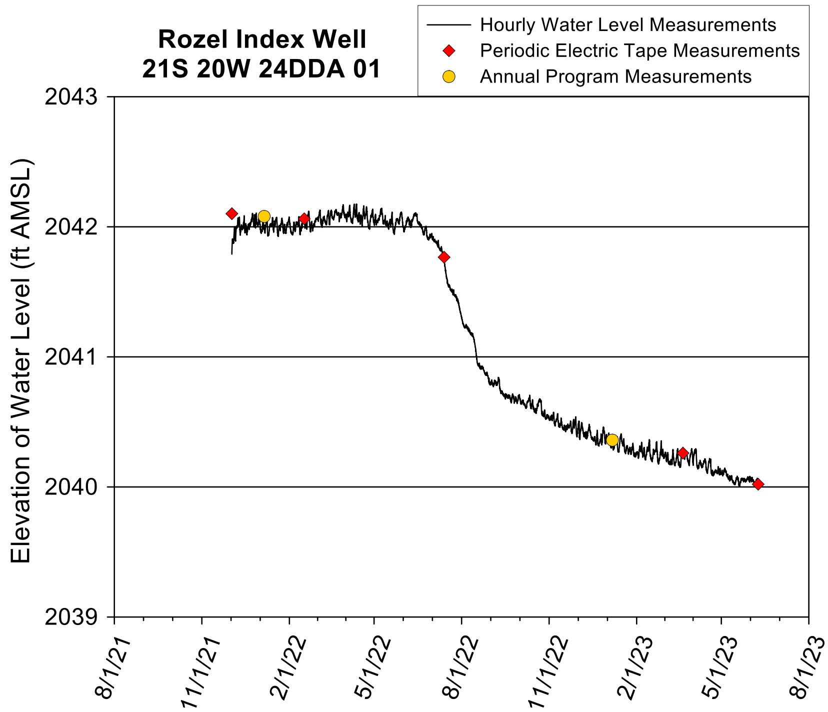


Figure 39—Rozel index well hydrograph—total data run to 6/8/23. A water-level elevation of 2,042 ft corresponds to a depth to water of 43 ft below lsf. There does not appear to have been a WWC5 form filed for this well so there are no well construction details. A camera survey found that the screen started at 40 ft below land surface and ended at a sand plug at 59 ft (elevation of 2,026 ft).

Major Points

- Further monitoring is needed to assess hydraulic conditions in the screened interval and the impact of nearby wells turning on and off.
- Water levels appear to stabilize after the 2021 irrigation season but not after the 2022 irrigation season.
- Transducer readings are in good agreement with manual measurements.

3.5.4 Trousdale Index Well

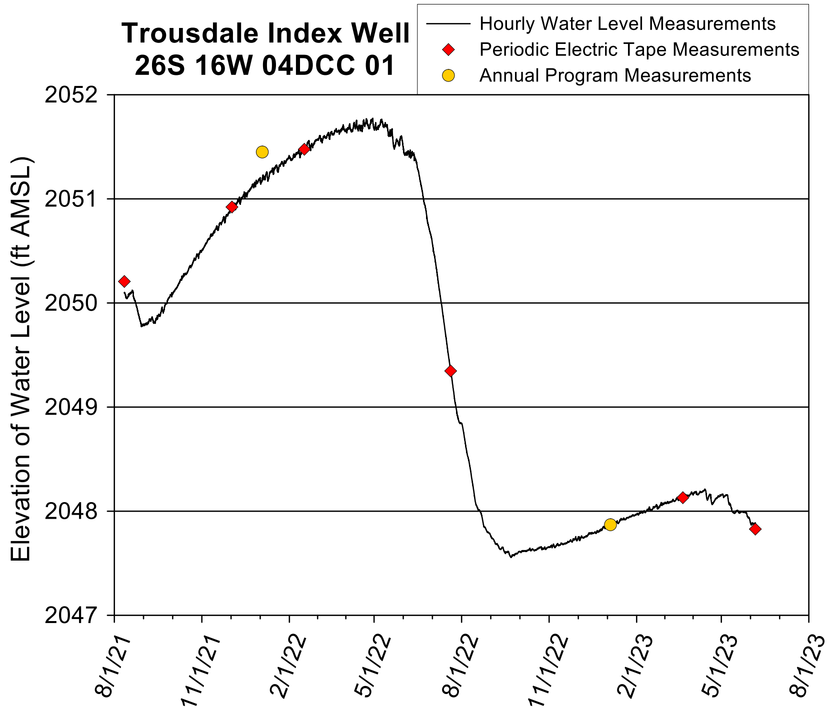


Figure 40—Trousdale index well hydrograph—total data run to 6/5/23. A water-level elevation of 2,051 ft corresponds to a depth to water of 33.8 ft below lsf. The top of the 10 ft screen is 47 ft below lsf (elevation of 2,037.8 ft). The bottom of the well is 57 ft below lsf (elevation of 2,027.8 ft); the base of the aquifer is at least 80 ft below the bottom of the well.

Major Points

- Further monitoring is needed to assess hydraulic conditions in the screened interval and the impact of nearby wells turning on and off.
- After the 2021 and 2022 irrigation seasons, water levels continued to increase until the start of the next irrigation season, but the rate of increase differed greatly. The difference in recovery rates is likely related to the 2022 and early 2023 drought conditions.
- Transducer readings are in good agreement with manual measurements except for the January 2022 annual program measurement.

3.6 Expansion Wells

3.6.1 GMD1 Expansion Wells

Seven expansion wells (SC-8 and wells 1 through 6) are now operating in GMD1 (table 6 and fig. 41). Monitoring at expansion well SC-8 (a former USGS recorder well) began in February 2012, monitoring at expansion wells 1 through 5 (existing wells; all but wells 4 and 5 were previously used for irrigation) began in late January 2017, and monitoring at expansion well 6 began in April 2018. The SC-8 well and wells 1–3 and 6 are part of the annual cooperative network program. Additional information about the expansion wells can be found in Butler, Whittemore et al. (2017). The expansion wells will not necessarily be permanently monitored; the GMD1 Board may move some or all of the sensors to other wells, if the need arises. In addition, continuous monitoring may be replaced by quarterly or annual measurements after sensors fail. We have had sensors fail at five of the seven sites. As a result, we now only continuously monitor expansion wells SC-8, 1, and 4. Expansion well 5 is measured quarterly and expansion wells 2 and 6 are measured annually. Hourly monitoring continued at expansion well 3 until mid-January 2023; the well is now measured quarterly. The barometer that had been a short distance below lsf at expansion well 3 has been moved to Wichita County 2 index well. More information about the expansion wells is given on the webpage for the GMD1 continuous monitoring wells expansion project (http://www.kgs.ku.edu/HighPlains/OHP/gmd_net/index.html).

Table 6—Characteristics of the GMD1 expansion well sites (water use is for irrigation unless noted otherwise).

Site	2023 WL elev. (ft)[a]	2023 saturated thickness (ft)[b]	Bedrock depth (estimated ft below land surface)[b]	Screened interval (ft below land surface)	2021, 2022 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
SC-8	2,846.8	83.8	174	c	468, 613	1,581, 2,312	9,503[d], 11,721[d]
Site 1	2,928.7	25.7	195	c	234[e], 266[e]	945[e], 1,063[e]	4,502[e], 5,265[e]
Site 2	3,053.2	42.2	160	c	0, 0	213, 281	2,202[f], 3,681[f]
Site 3	3,423.9	20.9	220	c	113, 407	1,203, 1,850	10,827[g], 14,149[g]
Site 4[h]	3,533.4	i	i	c	385, 562	2,428, 3,121	6,307[j], 7,968[j]
Site 5[h]	2,844.1	NA	158	c	243[k], 299[k]	2,069[l], 2,781[l]	9,530[m], 12,045[m]
Site 6	3,301.7	80.7	184	c	0, 0	246[n], 258[n]	1,291[o], 1,703[o]

[a] 2023 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html).

[b] Wells did not have WWC5 forms so values are estimated from nearby wells with WWC5 forms.

[c] Information on screened interval is not available for any of the wells.

[d] Includes 1,029 ac-ft (2021) and 1,125 ac-ft (2022) of municipal water, 4 ac-ft (2021) and 6 ac-ft (2022) of industrial water, 5 ac-ft (2021) of domestic water, and 311 ac-ft (2021) and 318 ac-ft (2022) of non-irrigation stock water.

[e] Includes 130 ac-ft, 217 ac-ft, and 402 ac-ft of non-irrigation stock water for 1 mi, 2 mi, and 5 mi circles, respectively (2021); and 88 ac-ft, 189 ac-ft, and 406 ac-ft of non-irrigation stock water for 1 mi, 2 mi, and 5 mi circles, respectively (2022).

[f] Includes 59 ac-ft (2021) and 69 ac-ft (2022) of non-irrigation stock water (2022).

[g] Includes 17 ac-ft (2021) and 22 ac-ft (2022) of municipal water and 63 ac-ft (2021) and 50 ac-ft (2022) of non-irrigation stock water.

[h] Not an annually measured index well; 2023 water-level measurements estimated from sensor data on 01/5/2023 from 0800 to 1700 at Site 4 and from 2/22/2023 manual measurement at Site 5.

[i] Lack of agreement among nearby WWC5 forms prevented estimation.

[j] Includes 640 ac-ft (2021) and 651 ac-ft (2022) of non-irrigation stock water.

[k] Includes 25 ac-ft (2021) and 13 ac-ft (2022) of non-irrigation stock water.

[l] Includes 425 ac-ft (2021) and 445 ac-ft (2022) of municipal water, 4 ac-ft (2021) and 6 ac-ft (2022) of industrial water, 5 ac-ft (2021) of domestic water, and 25 ac-ft (2021) and 13 ac-ft (2022) of non-irrigation stock water.

[m] Includes 4 ac-ft (2021) and 6 ac-ft (2022) of industrial water, 1,029 ac-ft (2021) and 1,125 ac-ft (2022) of municipal water, 5 ac-ft (2021) of domestic water, and 235 ac-ft (2021) and 203 ac-ft (2022) of non-irrigation stock water.

[n] Includes 228 ac-ft (2021) and 216 ac-ft (2022) of non-irrigation stock water.

[o] Includes 390 ac-ft (2021) and 366 ac-ft (2022) of non-irrigation stock water.

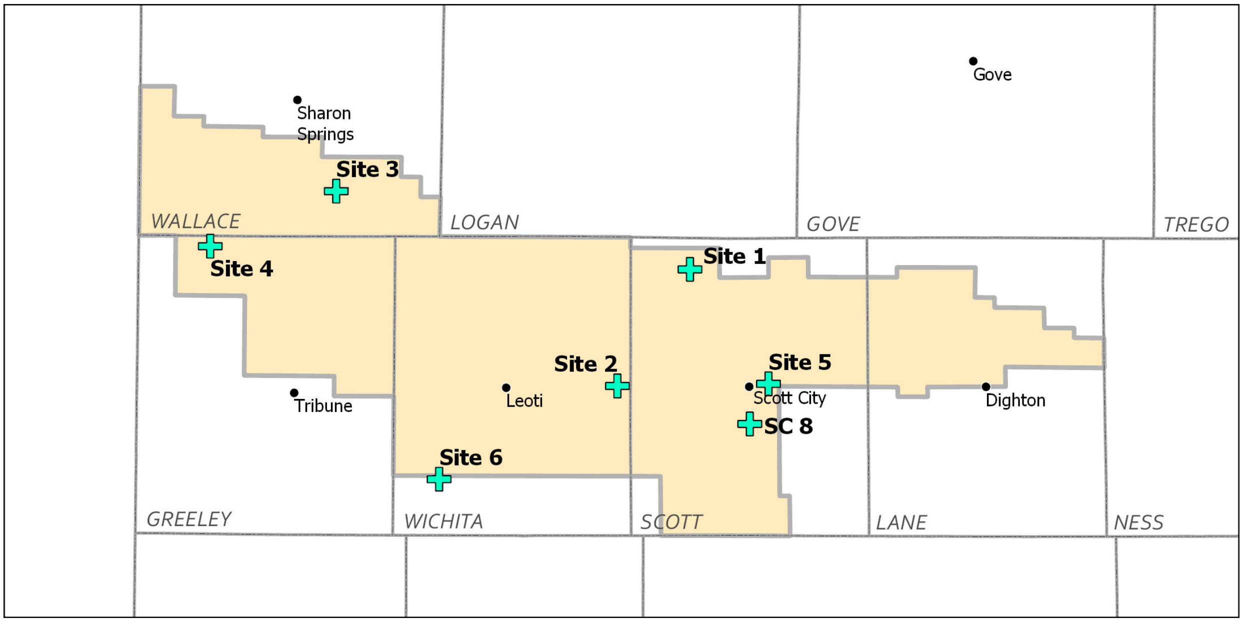


Figure 41—Map of GMD1 expansion wells.

3.6.1.1 SC-8 Site – Scott County

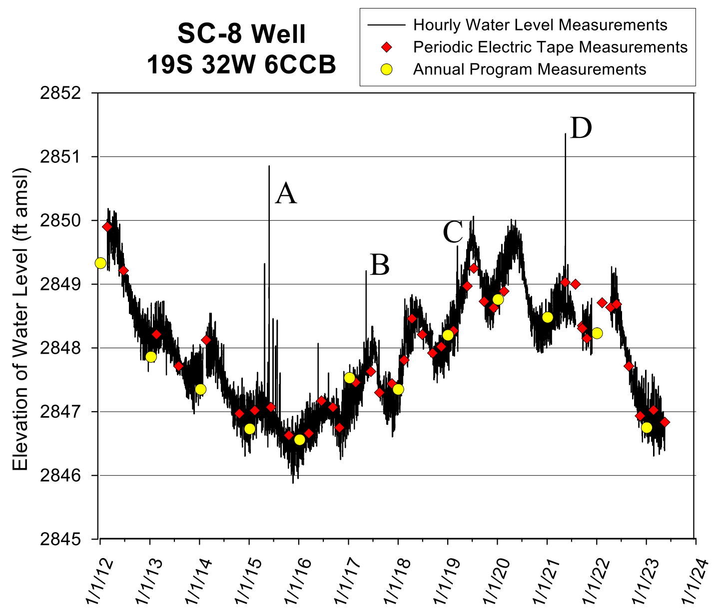


Figure 42—SC-8 well hydrograph—total data run to 5/16/23. A water-level elevation of 2,847 ft corresponds to a depth to water of 89 ft below lsf. Bottom of well is approximately 102 ft below lsf (elevation of 2,834 ft). Transducer measurements have been corrected from earlier reports for an incorrect offset parameter (Butler, Whittemore et al., 2017). Transducer measurements were corrected for a sudden 4.9 ft apparent drop in water level on 7/11/19 and a sudden 4.7 ft apparent rise in water level on 9/25/19. Monitoring temporarily suspended from 7/28/21 to 9/17/21 and 11/26/21 to 4/13/22 due to sensor failures. A–D defined in text.

Major Points

- The relatively large amplitude fluctuations superimposed on the water levels are an indication of unconfined conditions.
- The large number of upward spikes in the water level, such as the one marked by A, are associated with rainfall events and are likely produced by storm runoff flowing into the well; the added water is dissipated quickly through lateral flow to the aquifer (Butler, Whittemore et al., 2017). On August 15, 2017, (B), GMD1 staff sealed openings in the casing at the land surface; only one large spike that can be attributed to runoff flowing down the well has been recorded since that time (D). The spike on March 13, 2019, (C) was produced by a bomb cyclone (Butler, Knobbe et al., 2021).
- The overall rise in water level from late 2015 to 2020, the largest during the monitoring period, is explained by the well location in White Woman Basin, a closed surface drainage basin at the end of White Woman Creek. The period 2015–2019 was the wettest series of years since 2005, and flow from the creek into the basin provided recharge. The annual water-level change from 2022 to 2023 (-1.48 ft) was the largest since the start of monitoring.
- Transducer readings are generally in good agreement with manual measurements.

3.6.1.2 Expansion Site 1 – Scott County

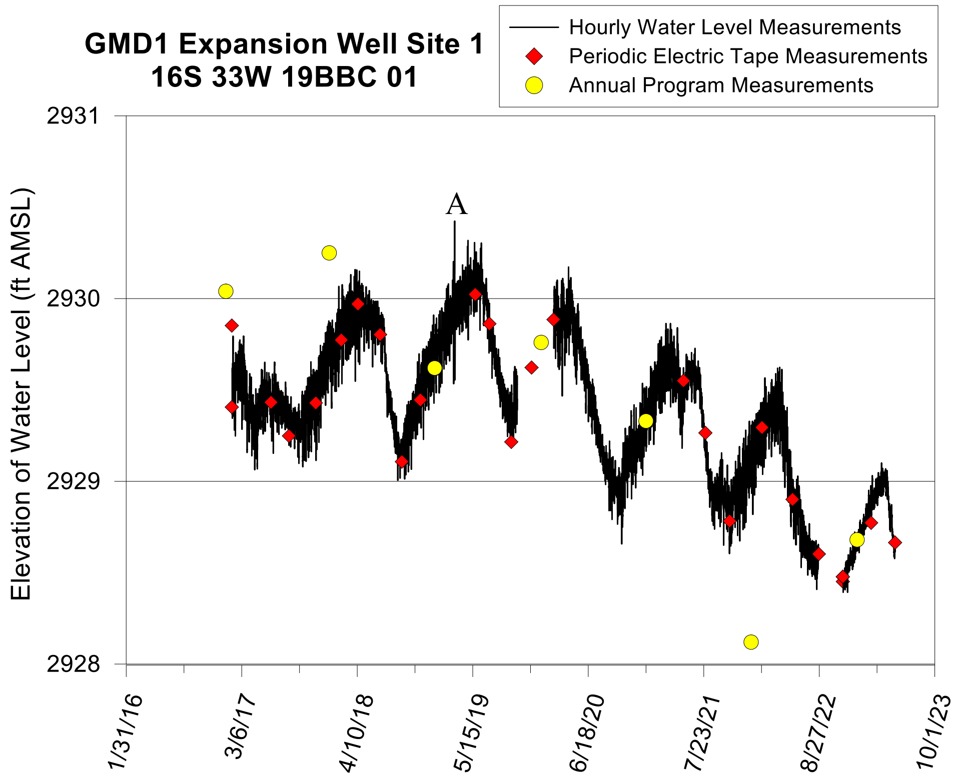


Figure 43—GMD1 Expansion Site 1 well hydrograph—total data run to 5/16/23. A water-level elevation of 2,930 ft corresponds to a depth to water of 168 ft below lsf. Bottom of well is 193.2 ft below lsf (elevation of 2,904.8 ft). A defined in text.

Major Points

- Moderate amplitude fluctuations superimposed on the water levels, which are particularly prominent during the recovery period, are an indication of unconfined conditions.
- The effect of individual wells cutting on and off is difficult to discern.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The battery of the transducer-datalogger unit died on 10/16/19 and was replaced on 2/18/20. The sensor failed on 8/23/22 and was replaced on 11/16/22.
- The water level in this well has fallen 7.9 ft since January 1998 (0.3 ft/yr) and 3.1 ft since 2013 (0.3 ft/yr).
- Minimum water level at the time of the 5/16/23 download was the lowest during the monitoring period.
- The water-level spike on March 13, 2019, (A) was produced by a bomb cyclone (Butler, Knobbe et al., 2021).
- Transducer readings are in good agreement with electric-tape measurements after commencement of monitoring; 2018 and 2022 annual program measurements appear to be in error.

3.6.1.3 Expansion Site 2 – Wichita County

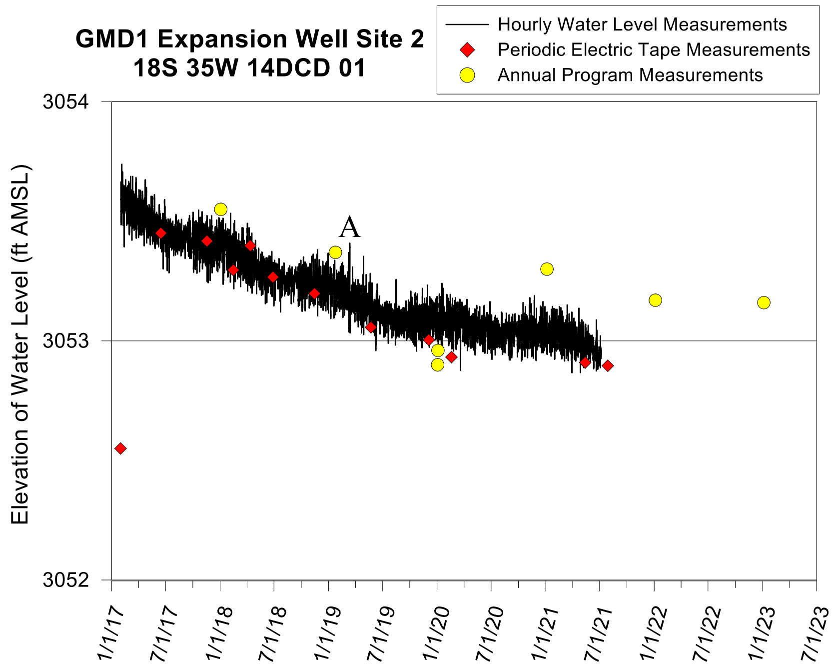


Figure 44—GMD1 Expansion Site 2 well hydrograph—total data run to 1/5/23. A water-level elevation of 3,053 ft corresponds to a depth to water of 118 ft below lsf. Bottom of well is 130.9 ft below lsf (elevation of 3,040.1 ft). First electric-tape measurement may be a transcription error. A defined in text.

Major Points

- Relatively small amplitude fluctuations superimposed on the water levels are an indication of a shallow unconfined aquifer; the seasonal variations in the amplitude are produced by seasonal changes in the range over which barometric pressure can vary with a smaller range during the summer (Butler, Knobbe et al., 2021).
- It is difficult to discern pumping and recovery seasons; cannot discern effect of individual wells cutting on and off. There is very little pumping within a 2-mi radius of the well.
- The water-level spike on March 13, 2019, (A) was produced by a bomb cyclone (Butler, Knobbe et al., 2021).
- The water level in this well dropped 29.7 ft between December 1958 and January 1982 but has only declined about 3.8 ft since January 1982. Water levels declined 1.5 ft between January 2014 and January 2022.
- Transducer readings are generally in reasonable agreement with manual measurements except for the first electric-tape measurement and the recent annual program measurements. Except for the annual measurements, the most recent manual measurements are near the lower boundary of the water-level band (likely a sensor calibration issue).
- The transducer failed on 7/6/21. This well is now only measured as part of the annual measurement program.

3.6.1.4 Expansion Site 3 – Wallace County

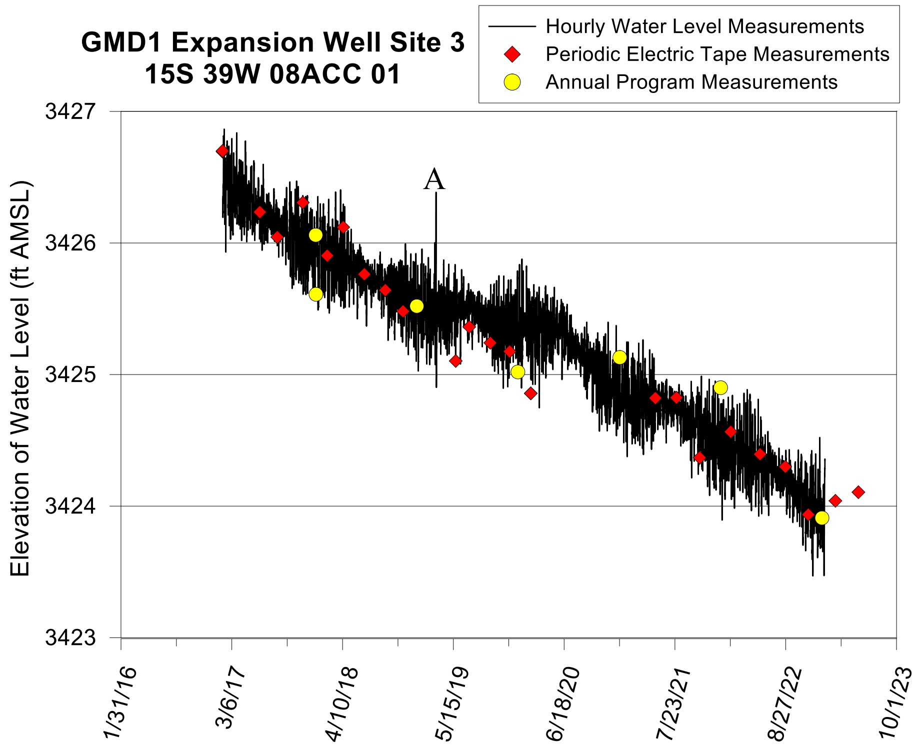


Figure 45—GMD1 Expansion Site 3 well hydrograph—total data run to 5/16/23. A water-level elevation of 3,426 ft corresponds to a depth to water of 197 ft below lsf. Bottom of well is 219.9 ft below lsf (elevation of 3,403.1 ft). A defined in text.

Major Points

- Relatively large amplitude fluctuations superimposed on the water levels are an indication of an unconfined aquifer; the seasonal variations in the amplitude are produced by seasonal changes in the range over which barometric pressure can vary with a smaller range during the summer (Butler, Knobbe et al., 2021).
- It is difficult to discern pumping and recovery seasons; cannot discern the effect of individual wells cutting on and off.
- The water level has declined 79.1 ft since 1964 (1.3 ft/yr) and 7.4 ft since 2013 (0.7 ft/yr). Decline rate diminished in 2019 as a result of a lower level of pumping due to wet conditions. The decline rate increased in 2020 as a result of more pumping due to much drier conditions.
- The water-level spike on March 13, 2019, (A) was produced by a bomb cyclone (Butler, Knobbe et al., 2021).
- Transducer readings are generally in good agreement with manual measurements.
- There appears to be little justification for continuous monitoring at this well, so the sensor was removed from the well after the battery died on 1/15/23. The well is now measured quarterly.

3.6.1.5 Expansion Site 4 – Greeley County

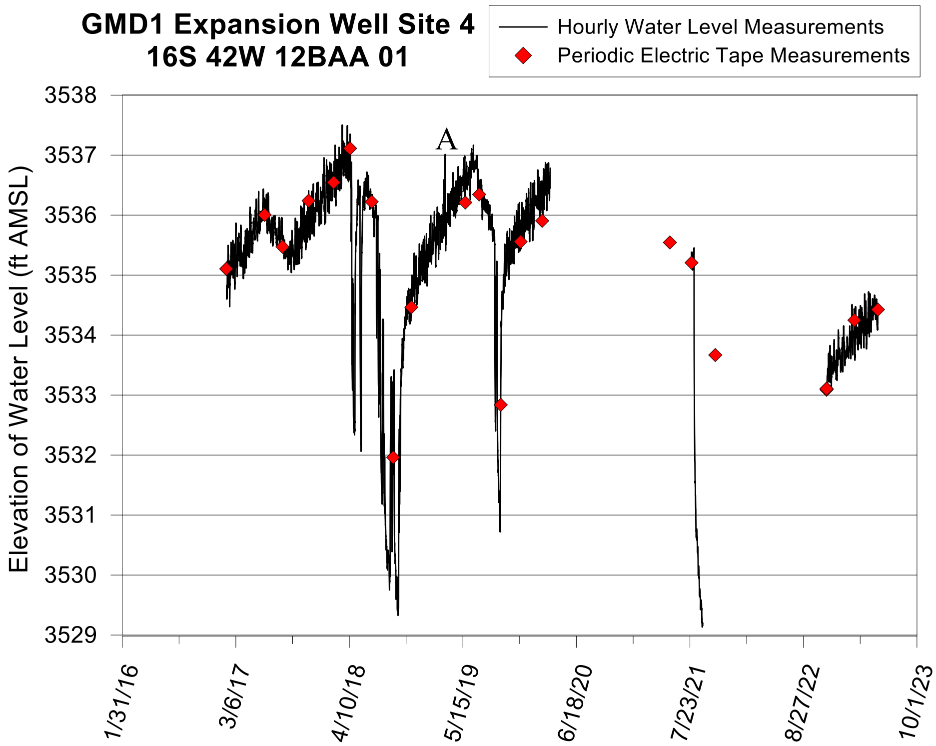


Figure 46—GMD1 Expansion Site 4 well hydrograph—total data run to 5/16/23, hourly measurements to 3/17/20, from 7/28/21 to 9/5/21, and from 11/16/22 on. A water-level elevation of 3,537 ft corresponds to a depth to water of 236 ft below lsf. Bottom of well is 264.5 ft below lsf (elevation of 3,508.5 ft). A defined in text.

Major Points

- Hydrograph form and relatively large amplitude fluctuations superimposed on the water levels are an indication of an unconfined aquifer.
- Little nearby pumping occurred in the 2017 irrigation season but much more from 2018 onward. The effect of one or more nearby individual wells cutting on and off is clearly seen in the 2018 and 2019 irrigation seasons.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels do not stabilize).
- The water-level spike on March 13, 2019, (A) was produced by a bomb cyclone (Butler, Knobbe et al., 2021).
- The transducer failed on March 17, 2020, most likely as a result of a water leak. The pandemic limited travel, so the failure was not recognized until May 13, 2021; the sensor was removed from the well and was replaced on July 28, 2021. That sensor then failed on September 9, 2021. A new more robust sensor was placed in the well on 11/16/22.
- Sensor readings are in reasonable agreement with manual measurements.

3.6.1.6 Expansion Site 5 – Scott County

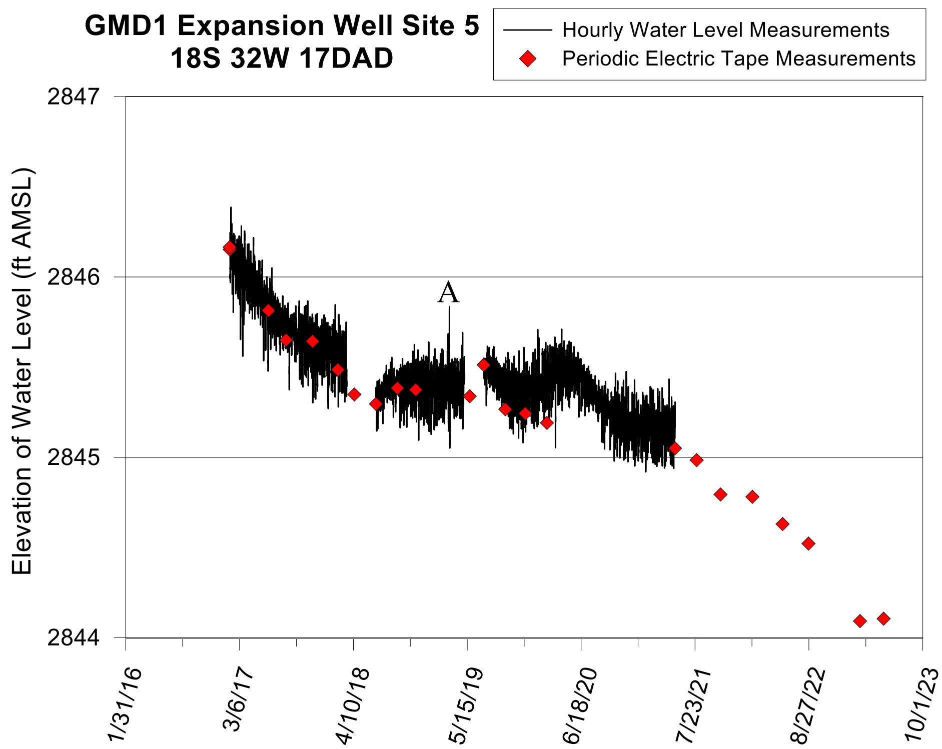


Figure 47—GMD1 Expansion Site 5 well hydrograph—total data run to 5/16/23. A water-level elevation of 2,845 ft corresponds to a depth to water of 131 ft below lsf. Elevation of well bottom is not known. A defined in text.

Major Points

- Moderate amplitude fluctuations superimposed on the water levels are an indication of an unconfined aquifer; the seasonal variations in the amplitude are produced by seasonal changes in the range over which barometric pressure can vary with a smaller range during the summer (Butler, Knobbe et al., 2021).
- It is difficult to discern the effect of individual wells cutting on and off.
- The battery of the transducer-datalogger unit died on 3/17/18 and was restarted on 6/28/18. The unit stopped functioning again on 5/5/19 and was removed from the well on 5/23/19. It was cleaned, evaluated in the lab, and reinstalled on 7/11/19.
- The water level at a nearby annual well (T. 18 S., R. 32 W., 17ABA 02) has fallen 6.8 ft since 2013 (0.7 ft/yr) and 35.4 ft since 1981 (0.8 ft/yr).
- The water-level spike on March 13, 2019, (A) was produced by a bomb cyclone (Butler, Knobbe et al., 2021).
- Transducer readings were generally in good agreement with manual measurements.
- There appears to be little justification for continuous monitoring at this well, so the sensor was removed from the well on May 13, 2021, and the well is now measured quarterly.

3.6.1.7 Expansion Site 6 – Wichita County

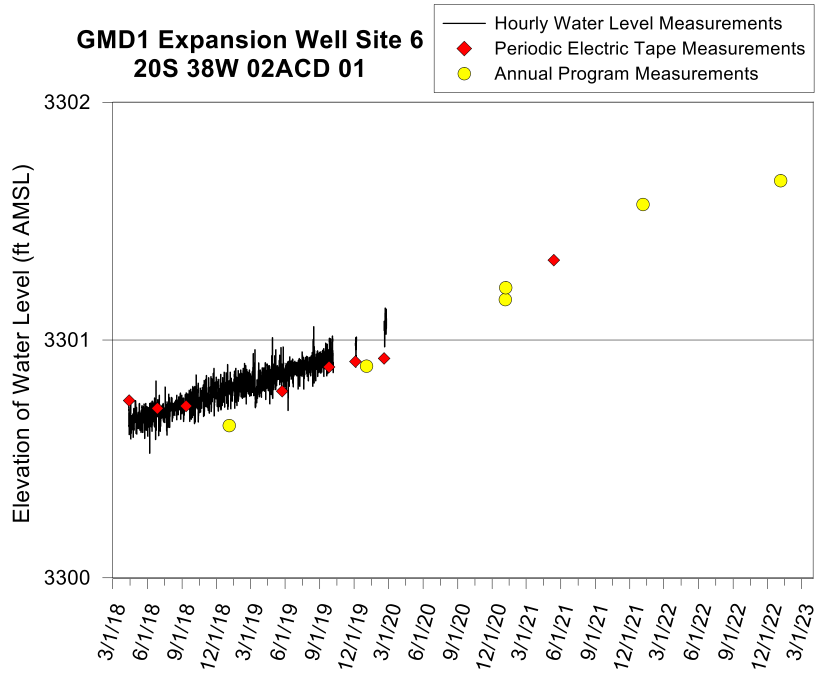


Figure 48—GMD1 Expansion Site 6 well hydrograph—total data run to 1/5/23; continuous hourly measurements ended on 10/6/19. A water-level elevation of 3,301 ft corresponds to a depth to water of 104 ft below lsf. Elevation of well bottom is not known. Bottom of aquifer is at an elevation of 3,221 ft (184 ft below lsf).

Major Points

- Small amplitude fluctuations superimposed on the water levels are an indication of a relatively shallow unconfined aquifer overlain by a vadose zone with high air permeability.
- It is difficult to discern the effect of any nearby or regional pumping.
- The battery of the transducer-datalogger unit died on 10/6/19 and was replaced on 12/4/19. The battery then died again on 12/7/19 and was replaced on 2/18/20. The battery then died again on 2/24/20. The pandemic limited travel, so this last failure was not recognized until May 13, 2021. There appears to be little justification for continuous monitoring at this well, so the sensor was removed from the well and the well is now measured annually.
- The water level has been slowly rising over the monitoring period in comparison with the slowly declining water level during 2005 to 2016 measured at a former annual measurement well about 0.25 mi distant (that well was plugged in 2016). We are exploring mechanisms that could produce this slow rise in water levels.
- No reported 2022 water use in 1 mi radius centered on well; smallest 2022 water use for 5 mi radius of any index or expansion well.

3.6.2 Thomas County Expansion Wells

As the index well program continues to expand, we must periodically examine the value of continuing to monitor expansion wells. In late 2017, we decided that the information gained from the expansion wells in the vicinity of the Thomas County index well was insufficient to justify continued monitoring. We therefore ceased monitoring at wells TH7, TH9, TH10, and TH11. See Butler, Whittemore et al. (2017) and earlier reports for a discussion of the hydrographs from those wells.

3.6.3 Haskell County Expansion Wells

We examined the hydrographs from wells in the vicinity of the Haskell well in 2010 and 2017 (Buddemeier et al., 2010; Butler, Whittemore et al., 2017). In both analyses, we found hydrographs that indicated some wells are screened in isolated aquifer compartments. The relatively rapid recovery after the cessation of irrigation pumping, the lack of response to nearby pumping, and the step changes in water level across the pumping periods were determined to be diagnostic indicators of an aquifer unit that is surrounded by low permeability materials (Butler, Stotler et al., 2013). The major finding of the 2017 assessment of the Haskell County expansion wells was that the permeable interval at the bottom of the HPA in the vicinity of the Haskell index well does not appear to be continuous. This lack of continuity is likely partly responsible for the large drawdowns observed during the pumping season at the Haskell index well.

We will reassess the Haskell County expansion wells in a future report.

4 Relationships among Water-Level Changes, Water Use, and Climatic Conditions

4.1 Introduction

The measurement and interpretation of water-level changes at the index wells have provided an improved understanding of hydrologic responses at the local scale (section to township) in the HPA in western Kansas. In addition, the interpretation of water-level responses at these wells has helped to enhance the understanding of the relationships among water-level change, water use (groundwater pumping), and changes in climatic conditions at both local and GMD scales.

The main driver of water-level declines in the HPA is the amount of water pumped for irrigation. The major drivers for irrigation water use are the type of crop, the additional water needed for crop growth above that provided by precipitation, and the irrigated area. In addition to the amount, the timing of precipitation relative to crop stage is also important. If the number of irrigation wells, the average mix of crops, and the irrigated area remain relatively constant, and the aquifer transmissivity is not near the lower limit for an irrigation well, then the main factor controlling the annual pumping is meteorological conditions.

Since 1997, the number of water-right permitted wells (mainly irrigation wells) in the three western GMDs has remained nearly constant. The increase in the number of points of diversion (wells) from 1997 to 2022 ranged from less than a percent to several percent of the current total, depending on the county. For example, the number of active points of groundwater diversion authorized through appropriated and vested groundwater rights in Thomas, Scott, and Haskell counties in 2022 were 856, 898, and 1,074, respectively. The number of these added after 1997 were 35 (4.1% increase), 22 (2.4% increase), and 9 (0.8%) for these three counties, respectively. Thus, for the last 20+ years, the main driver for water-level changes in the HPA in western Kansas has been the amount of pumping from each well.

The main driver of water-level recovery after an irrigation pumping season is the net inflow (Butler et al., 2023). The components of net inflow are described in previous index well reports. The main drivers of variation in irrigation water use across the HPA have been the acreage of irrigated fields, crop type, climatic conditions, and the irrigation application rate. Of these, the climatic conditions have generally had the greatest influence over the last few decades because the irrigated acreage, crop type, and application rate have not changed substantially over most of the HPA in Kansas. The most significant exception is in the Sheridan-6 LEMA, where the crop type and application rate have been altered the last 10 years, relative to practices for similar climatic conditions before the establishment of the LEMA, to achieve true water savings. These changes are also now being implemented in other LEMAs in GMDs 1 and 4 as well as in Water Conservation Areas (WCAs) in these and other GMDs. Water savings have been apparent for the last several years in GMD1, especially in Wichita County.

The relationships among pumping, water-level changes, and meteorological conditions are explored further in the following sections. The index well program has been the primary driver for improving our understanding of these relationships, which has led to development of additional approaches for better assessing the properties and behavior of the HPA, especially in stressed areas. That understanding and those approaches are essential for providing a sound scientific foundation for management of the groundwater resources of the Kansas HPA. The relationship between pumping and precipitation is also explored in the recently published scientific journal article (Whittemore et al., 2023) that is provided as an appendix to this report.

4.2 Annual Winter Water-Level Measurements

Annual winter groundwater levels have been measured in a network of irrigation and other well types in the Kansas HPA for many decades. Before 1997, the USGS and DWR measured the water levels. Starting in January 1997, the KGS took over administrative responsibilities of the annual network with DWR continuing to provide its measurements. The KGS then developed standardized procedures, software, and equipment for measurement, acquisition, and transfer of the data to a relational database (WIZARD). The KGS and DWR now measure water levels in a network of about 1,400 wells (mainly irrigation wells) across the HPA. These measurements are typically made in late December and early January.

4.3 Radar Precipitation

Radar precipitation has been found to be a good indicator of the climatic conditions that drive pumping and thus water-level changes in the Kansas HPA (Whittemore, Butler, and Wilson, 2015; Whittemore, Butler, Wilson, and Woods, 2015; Whittemore et al., 2023). The Advanced Hydrologic Prediction Service of the National Weather Service (NWS) provides spatial images and data coverages of radar precipitation for the United States (available at http://water.weather.gov/precip/). The radar precipitation data are adjusted using data from a network of precipitation gages. A brief description of the observation methods that apply to the general Kansas region from the "About NWS Precip Analysis" tab on the above web page was included in a previous project report (Butler, Whittemore et al., 2015). Coverages for radar precipitation are available from the NWS website beginning in 2005.

We now use radar precipitation as the primary metric for characterizing climatic conditions in the Kansas HPA. Figure 49 shows an image of the percent of normal annual precipitation during 2022 from the NWS website. The data have a spatial resolution of approximately 4x4 km; the pixel size as measured from the data for western Kansas is 2.57 mi north-south and 2.58 mi west-east.

The annual precipitation in 2022 was substantially below average (between 50% and 75% of normal) over most of the High Plains aquifer area in Kansas. Although parts of western GMDs 4 and 1 and eastern GMD2 received between 75% and 90% of normal precipitation, portions of GMD3 and eastern GMD1 had only between 25% and 50% of normal. The map reveals that substantial spatial variation in precipitation existed within the GMDs; the precipitation ranged from near normal (plus or minus 10% of normal) to less than 50% of normal.

The mean spatial radar precipitation for March–October, which covers the extended irrigation season, ranged widely during 2005–2022 (fig. 50). The 2022 precipitation was much below the average for the period for all of the GMDs.

The nine-month Standardized Precipitation Index (SPI) for October covers the extended irrigation season and was found to correlate well with water-level change and water use for the GMDs (Whittemore, Butler, and Wilson, 2016). The 2022 values of this SPI for Kansas climatic divisions 1, 4, 7, and 8, in which are located GMDs 4, 1, 3, and 2 and 5, respectively, are -1.90, -2.15, -1.89, and -1.30, respectively, in comparison to -0.40, 0.35, 0.11, and -0.01 for 2021. An SPI value of zero plus or minus

1 represents average conditions whereas values above 1 or below -1 indicate wet or dry conditions, respectively. Therefore, the 2022 climate for the irrigation season was very dry in GMD4 (second driest season since 1956), GMD1 (driest season since 1956), and GMD3 (second driest season since 1956), and dry in GMDs 2 and 5 (the third driest season since 1956). In all five GMDs, the 2022 climate for the irrigation season was much drier compared to 2021.

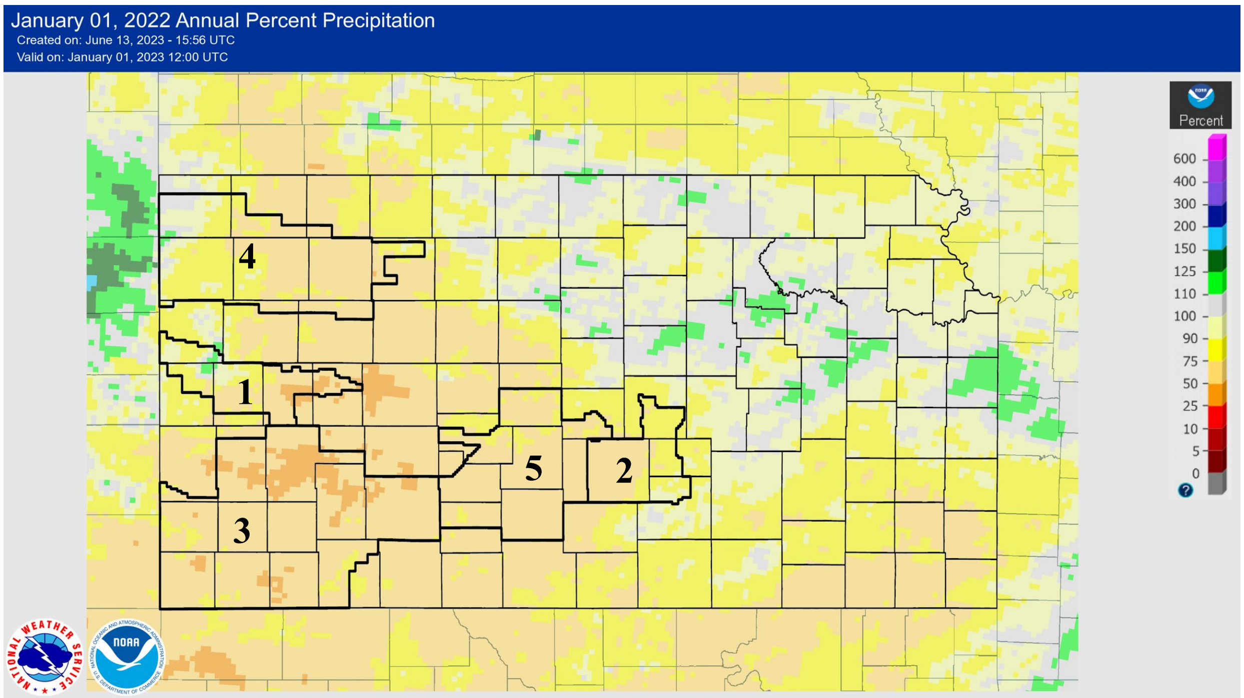


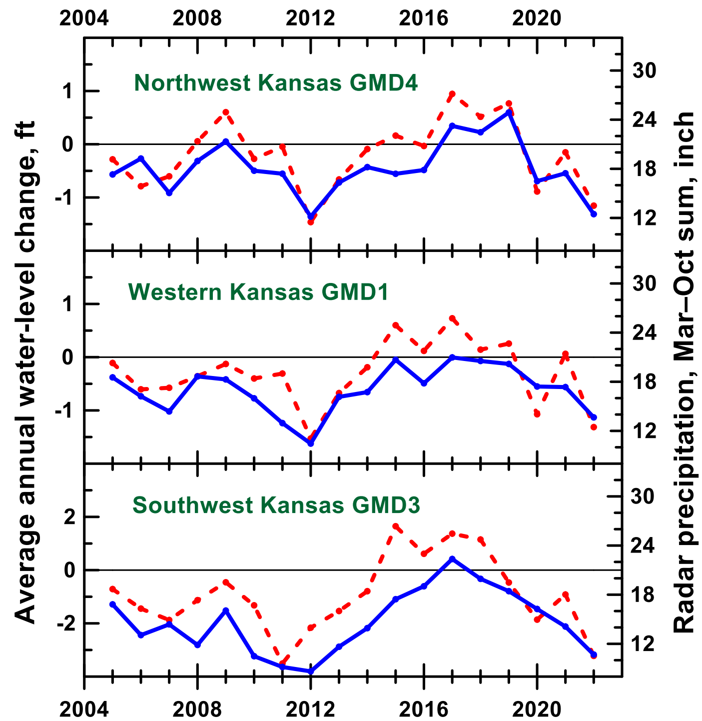
Figure 49—Percent of normal radar precipitation for Kansas in 2022. County lines are displayed, and the GMD numbers and boundaries are bolded.

4.4 Water-Level Change in the Groundwater Management Districts

Figure 50 displays the mean annual year-to-year changes in winter water levels during 2005–2022 for all five GMDs; these values are based on every well available for measurement each year (total can vary from year to year) from 2005 to 2023. The changes have been relatively modest in northwestern and west-central Kansas; the annual water-level changes in GMDs 1 and 4 have fluctuated between +0.6 and -1.6 ft. The annual changes in GMD3 during this period were substantially greater (between +0.4 and -3.8 ft), but the largest annual changes were in GMD5 (between +3.0 and -2.7 ft) and GMD2 (between +2.8 and -3.2 ft). Some similarity is evident in the patterns of the water-level changes for the three western GMDs (4, 1, and 3).

The mean annual water-level changes in the five GMDs generally mimic the variations in radar precipitation (March–October sum), which are also displayed on fig. 50. The annual water-level changes in 2022 were moderately large in GMDs 1 and 4 (-1.1 to -1.3 ft), considerably greater in GMDs 2 and 5 (-2.3 to -2.4 ft), and substantially greater in GMD3 (-3.2 ft). In all cases, the declines were considerably larger than in 2021, consistent with the drought conditions experienced across the Kansas HPA in 2022.

a)



b)

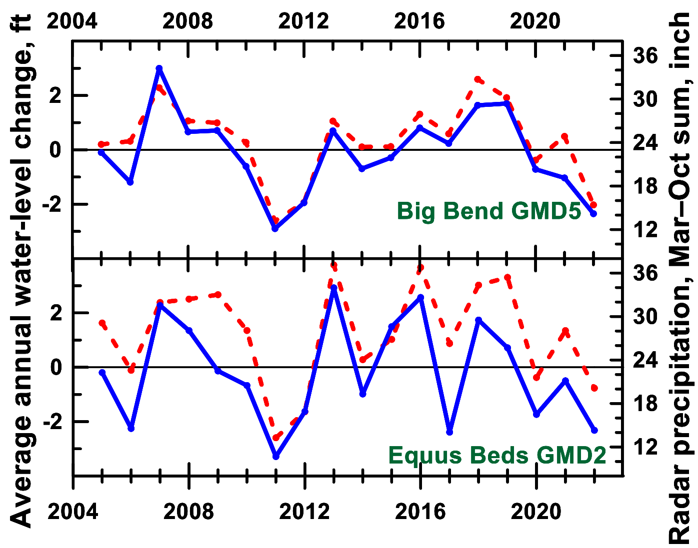


Figure 50—Mean annual water-level change (blue line) and radar precipitation (red dashed line, sum of March–October precipitation) during 2005–2022 for (a) GMDs 4, 1, and 3 and (b) GMDs 2 and 5. The water-level change for a particular year is the water-level difference between the following year and that year. The horizontal black lines represent zero water-level change. The ranges in the y-axes for water-level change in (a) the upper two plots are half those of the other plots. The ranges in the y-axes for radar precipitation are four inches larger for (b) the lower two plots.

4.4.1 Water-Level Change in the Thomas, Scott, and Haskell Index Wells

Winter water levels have been measured in the original three index wells since January 2008. Figure 51 shows the annual water-level changes for both the tape and transducer values for January 2008–2023 (transducer values are for the same time as the annual tape measurements) along with the mean water-level changes for the GMDs based on the maximum number of wells measured each year (same as values in fig. 50). The annual changes in the Scott index well have been within a relatively narrow range (between -0.05 and -1.75 ft for tape measurements, a total absolute range of 1.70 ft), whereas the changes have been appreciably larger at the Thomas index well (between +2.3 and -2.5 ft for tape measurements; a total absolute range of 4.8 ft), and much greater at the Haskell index well (between +4.0 and -10.4 ft for tape measurements; a total absolute range of 14.4 ft).

The range in the annual water-level changes for the Scott index well is somewhat larger than that for the mean annual water-level change for GMD1 during 2008–2022. In contrast, the ranges in the annual water-level changes for the Thomas and Haskell index wells are substantially greater than the mean water-level changes for GMDs 4 and 3, respectively. Except for the 2015, 2016, 2018, and 2019 change in the Thomas well and the 2016 and 2021 change in the Scott well, the directions of change in the annual water-level changes for the Thomas and Scott index wells are relatively similar to those for the mean annual changes for the GMDs. This indicates that these two wells are usually representative of the patterns in regional water-level variations in the GMDs in which they are located. The main discrepancy in the Thomas well change is for 2018, when a hail storm damaged crops in the vicinity of the well, resulting in cessation of irrigation during the growing season and, thus, greater recovery of water levels than usually expected. If this year is removed from the plot, the changes from 2017 to 2019 for the Thomas well and GMD4 are relatively similar.

Although the changes in water levels in the Haskell index well (the transducer values) showed a decline from 2009 to 2011 followed by a rise from 2011 to 2013 that is similar to the more muted changes for GMD3, the pattern in the variations in the index well water-level changes from 2013 to 2016 was often substantially different from that for the same period for GMD3. This difference is mainly related to late fall pumping (late November to mid-December 2014) in the confined aquifer and variations in pumping related to the court-ordered shutdown of nearby irrigation wells (see section 3.3.2.). From 2017 to 2020, water-level declines generally lessened in the Haskell well in comparison to a small increase in declines for GMD3, but that pattern abruptly changed in 2021 with the large relative decline in the Haskell well.

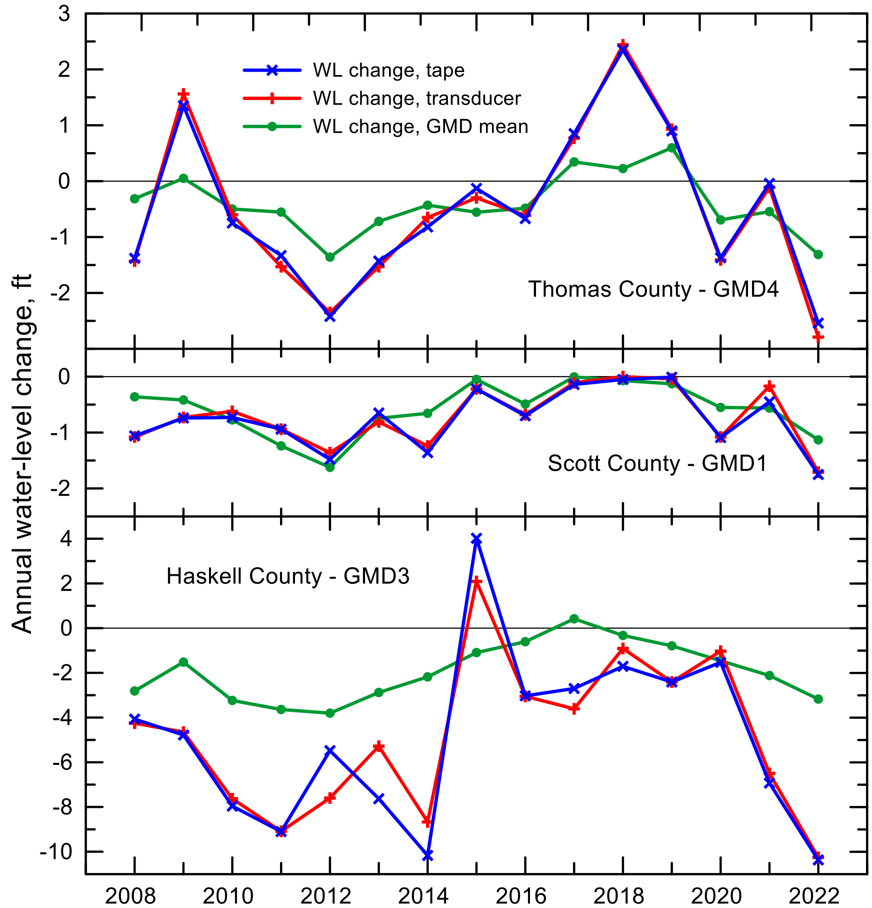


Figure 51—Annual winter (January) water-level changes in the original three index wells and the mean annual changes in the three GMDs in western Kansas in which they are located. Note the different y-axis range for Haskell County versus that for Thomas and Scott counties. Suspect 2013 tape measurement at the Haskell index well causes the 2012 and 2013 tape water-level change values to be markedly different from those based on the transducer measurements.

4.5 Correlation of Annual Water Use with Annual Water-Level Change

One of the major accomplishments of the index well program has been the discovery of the strong linear relationship between annual water use and annual water-level change in the Kansas HPA and the development of the theoretical support for that relationship. As shown in previous project reports and peer-reviewed publications (e.g., Butler, Whittemore et al., 2015; Butler, Whittemore, Wilson et al., 2016, 2018; Butler et al., 2023), this relationship can be used to assess the aquifer response to pumping reductions over a wide range of spatial scales. For example, the pumping reduction that would achieve stable water levels (i.e., a water-level change of zero) for the near future (commonly referred to as Q_{stable}) can be estimated from the relationship.

We have previously examined the correlations between annual water use and annual water-level change for the three original index wells and three additional wells in GMDs 4 (Colby), 1 (SC-8), and 5 (Belpre). In the 2016 report (Butler, Whittemore et al., 2017), we presented the results of a comprehensive examination of the correlations in which we varied the distance over which the water use was summed and used both manual- and transducer-measured water-level change data (see tables 38–39 of Butler, Whittemore et al. [2017] and associated discussion). In this section, we update those correlations with the radius of water use that produced the highest correlation for a particular well, but only for either the 1- or 2-mile radius of water use around a well. Although we found that the correlations were sometimes greater for larger areas around the index wells, the area around which water-level changes are significantly affected by pumping during one year is not expected to exceed 2 miles in a largely unconfined aquifer such as the HPA.

4.5.1 Water Use versus Water-Level Change at the Thomas Index Well

Figure 52 displays the correlation between annual water-level change and annual water use in the vicinity of the Thomas index well for 2008–2022. As indicated earlier, the substantial water-level rise and small water use for 2018 resulted from the cessation of irrigation near the well due to a hail storm. The drought of 2022 produced the second greatest water use and largest water-level decline since monitoring began. The apparent pumping reduction for stable water levels is 10.8%, which is lower than the 14.4% for 2008–2017 that omits the hail year of 2018 and following years and considerably smaller than the 16.9% for all of GMD4 for 2008–2022. The average annual water use during 2008–2022 was 3.8 in/yr for the 2 mi radius area centered on the well, which is substantially greater than the 1.5 in/yr for the entire GMD4 area. The water use for stable water levels (net inflow) was 3.4 in/yr for the 2 mi radius area, which again is substantially greater than the 1.2 in/yr for GMD4. The greater density of water use may have produced a locally depressed water table that induces more lateral groundwater inflow, including, potentially, focused recharge along ephemeral stream valleys 1–2 mi to the north and south of the Thomas well. In addition, the greater water-use density would be expected to result in more irrigation return flow and more drainage from the newly formed unsaturated zone.

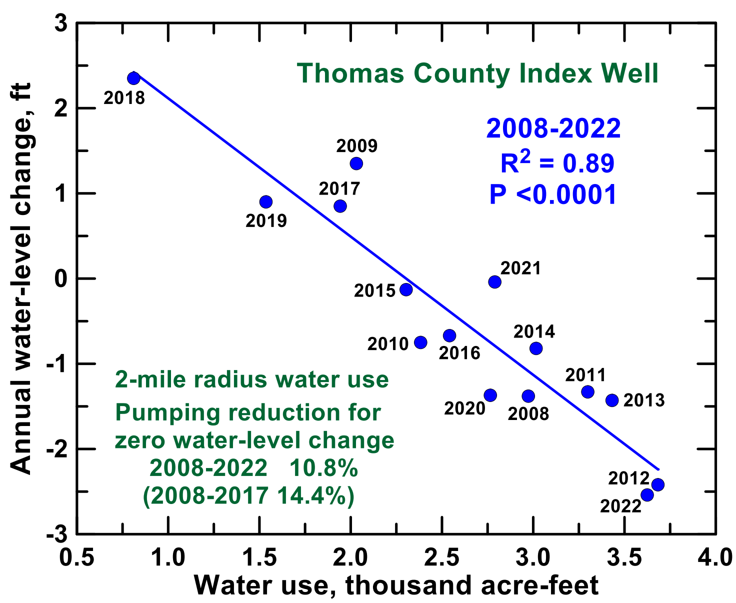


Figure 52—Correlation of annual water-level change based on manual measurements in the Thomas County index well with annual water use within a 2 mi radius centered on the well during 2008–2022.

4.5.2 Water Use versus Water-Level Change at the Scott Index Well

Figure 53 displays the correlation between annual water-level change and annual water use in the vicinity of the Scott index well for 2008–2022. The pumping reduction for stable water levels is 35%, which is slightly below the 37% for all of GMD1 for 2008–2022. The average annual water use was 4.5 in/yr for the 2 mi radius area centered on the well, which is substantially greater than the 1.7 in/yr for all of GMD1. The water use for stable water levels (net inflow) was 2.9 in/yr for the 2 mi radius area, which again is substantially greater than the 1.1 in/yr for the entire GMD1 area. As with the Thomas index well, the greater density of water use may have produced a locally depressed water table that induces more lateral groundwater inflow, as well as resulting in more irrigation return flow and more drainage from the newly formed unsaturated zone.

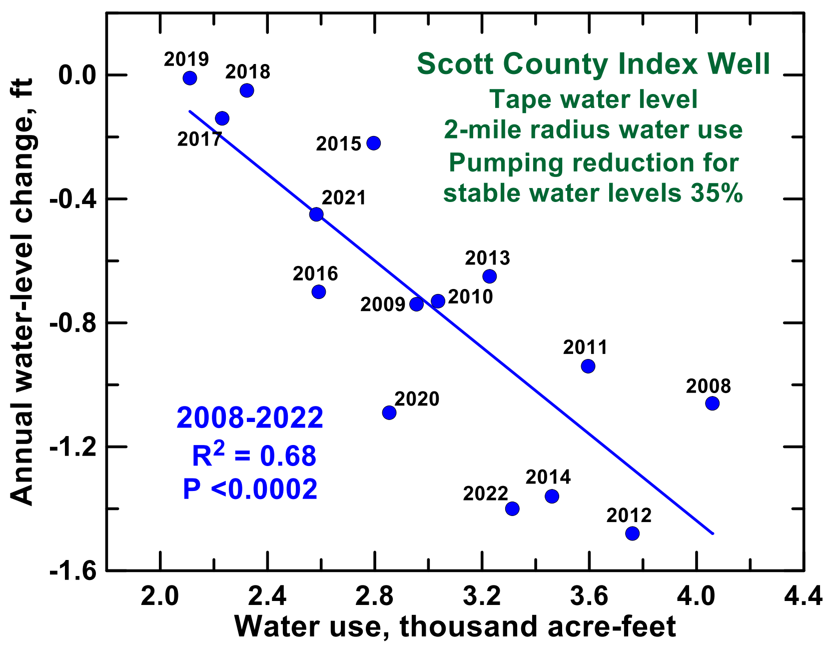


Figure 53—Correlation of annual water-level change based on manual measurements in the Scott County index well with annual water use within a 2 mi radius centered on the well during 2008–2022.

4.5.3 Water Use versus Water-Level Change at the Haskell Index Well

Figure 54 displays the correlation between the annual change in the water level at maximum recovery in February and annual water use in the vicinity of the Haskell index well for 2008–2022. We found that we could not get a good correlation with the annual January water-level change, likely because of the effect of late fall pumping, but we could get a good correlation with the maximum recovered water level. The correlation was better for the maximum recovery in February than for the final maximum recovery level because the time of the maximum recovery can vary from year to year. The water-level recovery continues at this index well through the winter and into the spring until pumping starts for the season; the selection of February for the maximum value provided better consistency in the data.

The water use around the Haskell County index well for 2013–2022 (especially during 2015–2020) was substantially lower than for 2008–2012. The lower use is related to both the court-ordered shutdown of nearby pumping wells described in section 3.3.2 and to the greater-than-average precipitation in

2013–2020 (especially during 2015–2019) in comparison to that during 2008–2012 in GMD3 (see fig. 50). The pumping reduction for stable water levels for the average annual water use before the court-ordered pumping shutdowns (2008–2012) is 68% (using the linear regression for 2008–2022 and the average annual water use for 2008–2012), which is much larger than the 25% for all of GMD3 for 2008–2022. The pumping reduction for stable water levels for the average annual water use after the shutdowns (2013–2022) is 50% (again using the linear regression for 2008–2022), which, although much greater than the reduction for all of GMD3, is appreciably less than for the period before the shutdowns. The average annual water-use rates were 14.3 in/yr and 9.1 in/yr for the 2 mi radius area centered on the well during 2008–2012 and 2013–2022, respectively, which are considerably greater than the 3.9 in/yr for the entire GMD3 area. The water use for stable water levels (net inflow) was 4.6 in/yr for the 2 mi radius area based on the 2008–2022 data, which again is substantially greater than the 2.9 in/yr for all of GMD3. As with the Thomas and Scott index wells, these values indicate that the area of the Haskell well is more heavily pumped than average for GMD3, thereby resulting in a greater net inflow. In this case, the greater density of water use may have induced upward vertical flow from the underlying Dakota aquifer as well as leakage from the thick clay interval overlying the sand unit at the bottom of the HPA in the vicinity of the Haskell well.

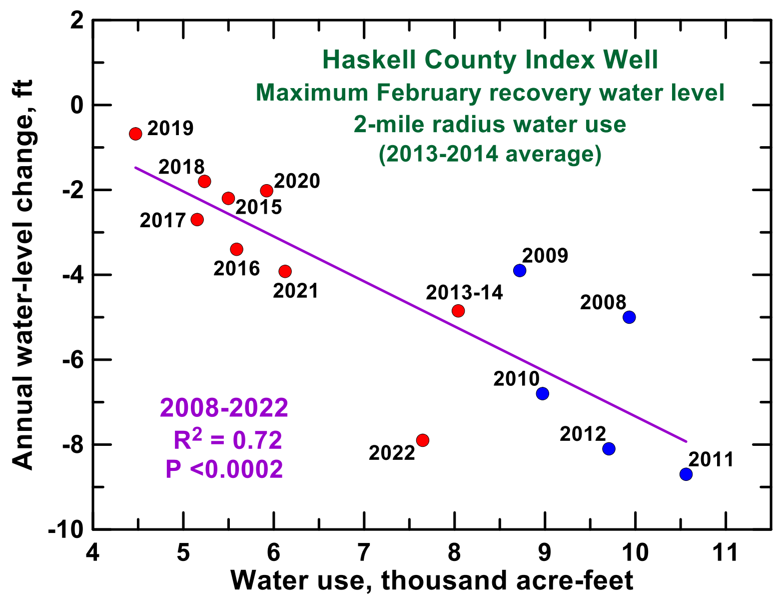


Figure 54—Correlation of change in maximum recovery water level during February based on transducer measurements in the Haskell County index well with annual water use within a 2 mi radius centered on the well during 2008–2022. Red points designate values after the court-ordered shutdowns (see section 3.3.2); 2013 and 2014 values are averaged because of equipment failure at the time of the 2013 maximum recovery, and 2022 value appears to have been affected by late-season pumping.

4.5.4 Water Use versus Water-Level Change at the Colby, SC-8, and Belpre Wells

The water-level change versus water use relationship is only statistically significant for the 1 mi radius of water use around the Colby index well (fig. 55). In contrast to conditions in the vicinity of most of the index wells, substantial water is pumped for municipal use in the vicinity of the Colby well (51% for 2022 for the 1 mi radius area centered on the well). The percent pumping reduction required to attain stable water levels (55%) is the largest of any of the index wells for which relationships have been developed in the GMD4 and GMD1 areas. The average annual water use was 3.2 in/yr for the 1 mi radius area, which is less than that in the vicinity of the Thomas index well (3.7 in/yr for 2 mi radius) but substantially greater than the 1.5 in/yr for all of GMD4. The water use for stable water levels (net inflow) was 1.4 in/yr for the 1 mi radius area, which is somewhat greater than the 1.2 in/yr for all of GMD4 but substantially below that in the vicinity of the Thomas index well (3.4 in/yr for a 2 mi radius).

The correlation for the water-level change versus water use relationship at the SC-8 well is higher for the 1 mi than the 2 mi radius area centered on the well (fig. 55). The percent pumping reduction required to attain stable water levels (26%) is considerably less than that required in the vicinity of the Scott County index well (35% for 2 mi radius) and for all of GMD1 (37%). The average annual water use was 4.0 in/yr for the 1 mi radius area, which is somewhat less than that in the vicinity of the Scott index well (4.5 in/yr for 2 mi radius) but substantially greater than the 1.7 in/yr for all of GMD1. The water use for stable water levels (net inflow), however, was 2.9 in/yr for the 1 mi radius area, which is similar to that in the vicinity of the Scott index well (2.9 in/yr for 2 mi radius) but much greater than the 1.1 in/yr for all of GMD1. Note that the January 2022 annual measurement appears to have been affected by late season pumping, as the water-level decline is greater than would have been expected for that volume of pumping.

The correlation for the water-level change versus water use relationship at the Belpre well is higher for the 2 mi than the 1 mi radius area centered on the well (fig. 55). The percent pumping reduction to attain stable water levels was essentially zero, meaning that net inflow was approximately equal to annual pumping for the generally wet period of 2005–2022, and is close to the 1.7% for all of GMD5 for the same period. The much smaller pumping reduction for stable water levels than for the Ogallala region are mainly related to the greater precipitation recharge. The average annual water use was 3.5 in/yr for the 2 mi radius area, which is greater than the 2.3 in/yr for the entire GMD5 area. The water use for stable water levels (net inflow) was 3.5 in/yr for the 2 mi radius area, which again is larger than the 2.3 in/yr for all of GMD5.

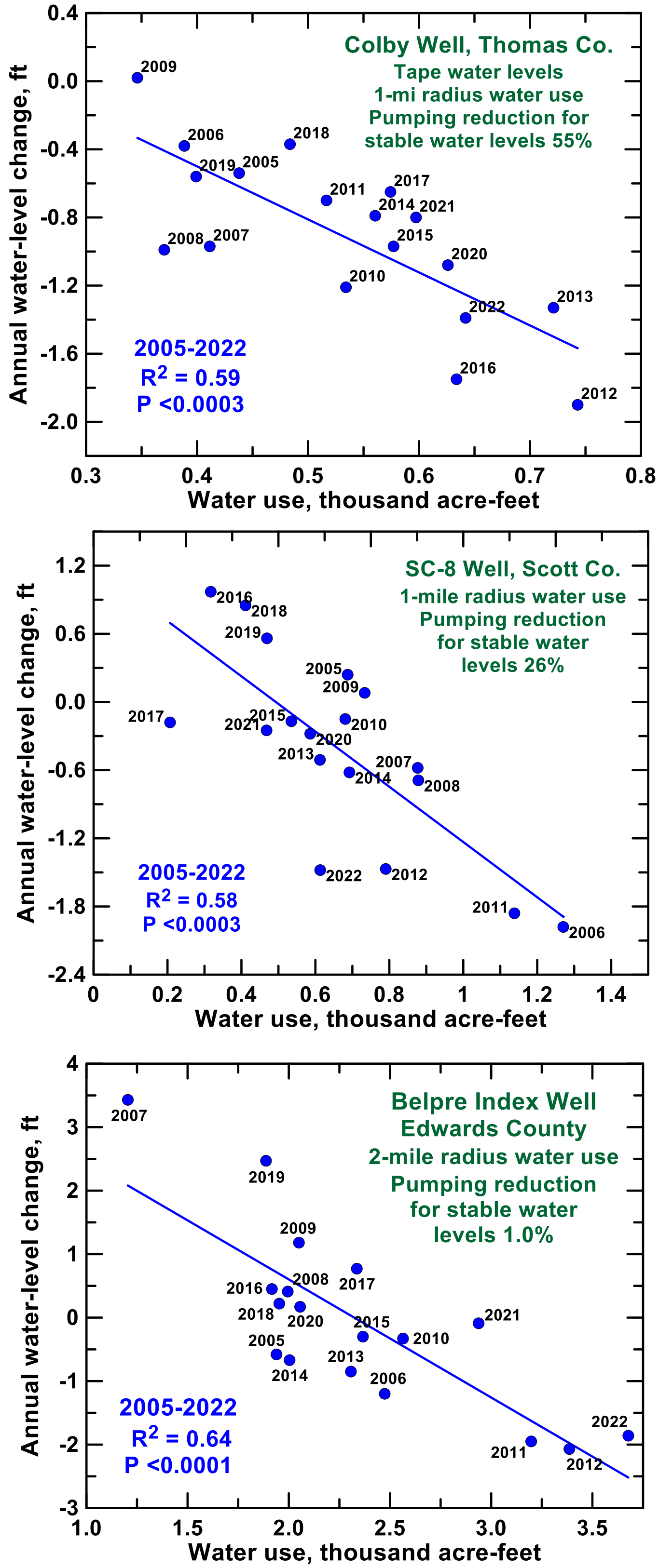


Figure 55—Correlation of annual water-level change in the Colby, SC-8, and Belpre wells with annual water use within a 1 or 2 mi radius centered on the wells during 2005–2022.

4.6 Relationship of Water Use and Climatic Conditions

As indicated earlier, climatic conditions have generally had the greatest influence on water-use variations over the last few decades because the irrigated acreage, crop type, and application rate have not changed substantially over the HPA in Kansas. We have found that the sum of the radar precipitation for March to October generally captures the precipitation that drives pumping in support of irrigated agriculture in the Kansas HPA, although other monthly ranges give optimum correlations with water use for particular index wells. Figure 50 includes the variation in radar precipitation versus time since 2005 for all five GMDs. This plot shows that 2017 was the wettest year experienced in GMDs 1 and 4 since 2005 and the second wettest year in GMD3 based on March–October precipitation. The wettest year for this monthly range since 2005 in GMD5 was 2018, which even exceeded the wet year of 2007, and 2013 in GMD2. The driest years were during the drought of 2011–2012; the lowest precipitation in GMDs 2, 3, and 5 occurred during 2011 and the lowest in GMDs 1 and 4 during 2012.

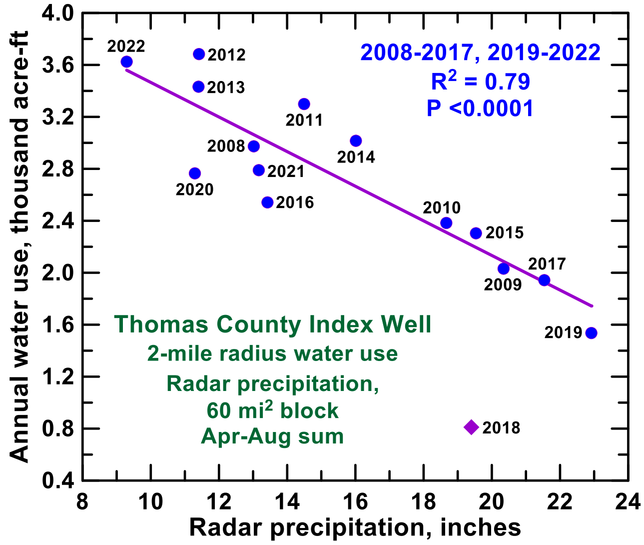
4.6.1 Correlation of Annual Water Use with Radar Precipitation

In previous years' index well reports, we have examined the correlations between annual groundwater use and radar precipitation (within selected areas around the wells) for the three original index wells and three additional wells in GMDs 4 (Colby), 1 (SC-8), and 5 (Belpre). In the 2016 report (Butler, Whittemore et al., 2017), we presented the results of a comprehensive examination of the correlations in which we varied the area in which the water use was summed and the range and number of months for which the radar was summed; results were presented for both the nearest point or pixel of radar data (representing a 6.6 mi^2 area) and the spatial mean of the nine-point (pixel) block (representing a 60 mi^2 area) of radar precipitation values centered on the well (see table 40 of Butler, Whittemore et al. [2017] and associated discussion). In this section, we update the correlations using the 2 mi radius of water use (based on the explanation in section 4.5 above) and the 60 mi^2 area for radar precipitation for the three original index wells and the three additional wells except for a plot for the Haskell well, for which both the 1 mi and 2 mi radii for water use are used.

The monthly precipitation sums that give optimum correlations for the Thomas County and Scott County index wells are April–August and February–September, respectively (fig. 56), which essentially span the main part of the irrigation season. The 2019 and 2017 precipitation were the greatest during 2008–2022 for the Thomas and Scott wells, respectively. However, the water use surrounding the Thomas County well in 2018 was substantially lower than the water use for any other year, which was caused by the shutdown of irrigation wells in the vicinity due to destruction of crops by a hail storm. Thus, 2018 is plotted as a separate, anomalous point, and data for 2008–2017 and 2019–2022 are used for the regression line in fig. 56. The hail storm occurred in mid-May 2018 and the precipitation for that month within the 60 mi^2 area surrounding the Thomas County well was anomalously high (7.48 in).

The linear regression for 2018–2022 for the Scott County well is significantly offset to lower water use than for the regression for 2008–2017, indicating less water use for the same climatic conditions. Similar offsets in the water use and precipitation relationship are observed for the Sheridan-6 LEMA, Wichita County, and GMD1 (Whittemore et al., 2023). Possible explanations for the lower water use include more efficient irrigation, decreased irrigated area, and increased difficulty in pumping due to the declining aquifer thickness in the area of the Scott index well. A plot of irrigation water use per irrigated area versus radar precipitation (fig. 57), which should show a significant difference in regression lines for 2008–2017 and 2018–2022 if irrigation efficiency were the main explanation, indicates that the 2018–2022 regression line does not appear to have been significantly different from that of 2008–2017. Instead, a decrease in irrigated area during 2008–2022 (fig. 58) is a more probable explanation for the decreased water use during 2018–2022 compared to 2008–2017 than improved irrigation efficiency. The general decrease in irrigated area occurred during 2008–2017; the irrigated area has not changed substantially since 2017.

Two plots are shown for the water use and radar precipitation relationship for the Haskell index well (fig. 59). The first plot (a) for a 1 mi radius of water use gives the best correlation for the data before the court-ordered shutdown of nearby irrigation wells (see section 3.3.2.); the second plot (b) for a 2 mi radius gives a slightly better correlation for post-shutdown data. The plots show the lower water use for a given precipitation value after compared to before the well shutdowns. A similar break in the relationship is seen for the correlation between annual water use and radar precipitation in the Sheridan-6 LEMA (Butler, Whittemore, Wilson et al., 2018; Whittemore, Butler, and Wilson, 2018; Whittemore et al., 2023), although the two regression lines are closer to being parallel for the LEMA than for the Haskell County index well. The 2013–2014 period was for a limited shutdown and thus may not be appropriate for plotting with the data after the complete shutdown.



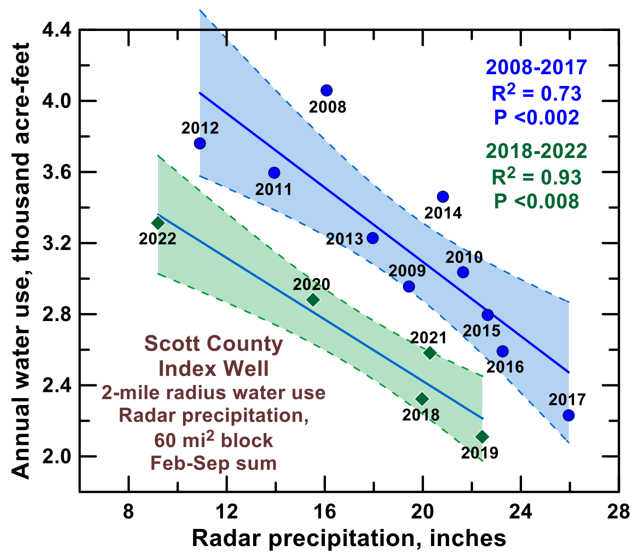


Figure 56—Correlation of annual total groundwater use with radar precipitation at the Thomas and Scott index wells for 2008–2017 and 2019–2022 (Thomas) and 2008–2022 (Scott). The shaded intervals for the Scott well represent 95% confidence intervals for the two linear regressions.

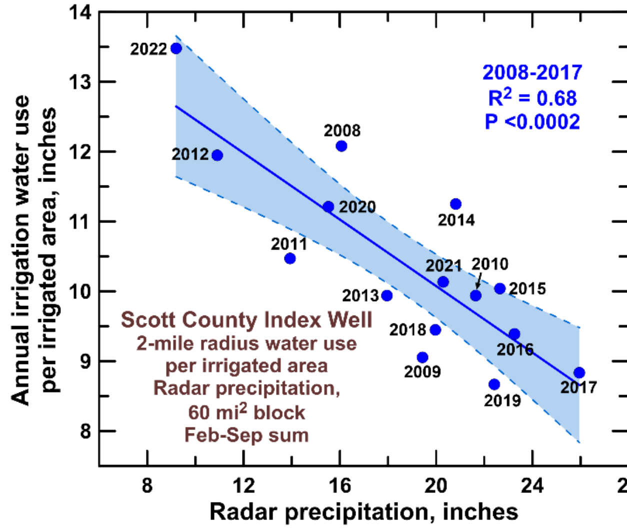


Figure 57—Correlation of annual irrigation groundwater use per irrigated area with radar precipitation at the Scott index well for 2008–2022. The shaded interval represents the 95% confidence interval for the linear regression.

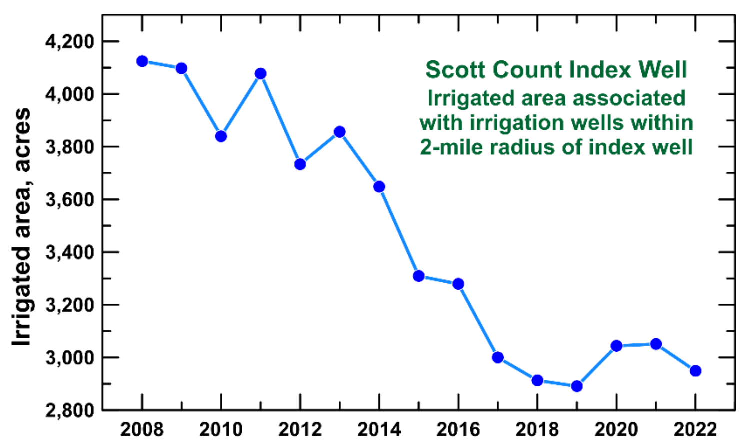


Figure 58—Change in irrigated area associated with the irrigation wells within the 2 mi radius of the Scott index well for 2008–2022.

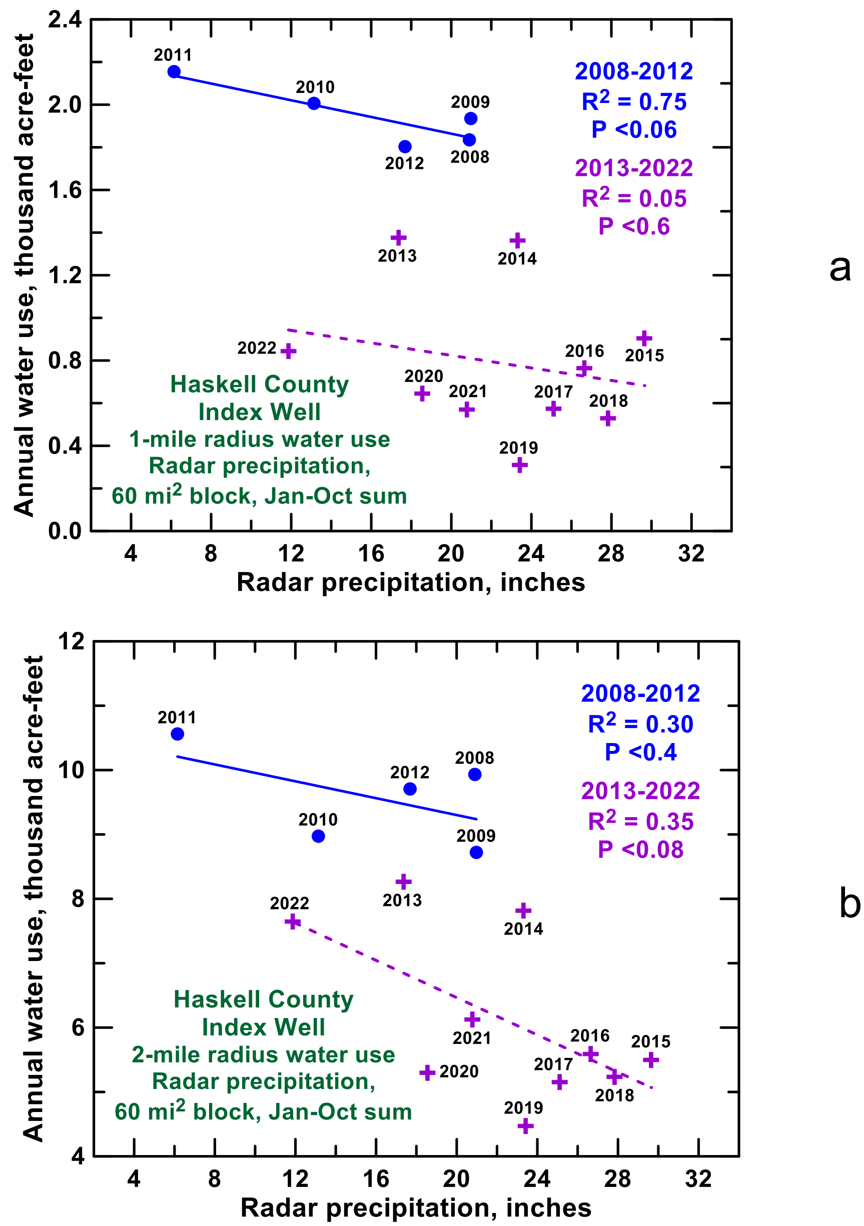


Figure 59—Correlation of annual total groundwater use with radar precipitation at the Haskell index well for 2008–2022 for (a) a 1 mi radius and (b) a 2 mi radius of water use. The 2008–2012 and 2013–2022 periods represent years before and after the onset of a court-ordered shutdown of nearby irrigation well pumping; the 2013–2014 period was for a limited shutdown (see section 3.3.2).

Figure 60 shows the correlations between water use and radar precipitation for the three additional wells (Colby, SC-8, and Belpre). The water-use values for 2005–2007 appear to be high for the Colby well (possibly as a result of conversion of rate meters to total flow meters); the correlation is better if only the data for 2008–2022 are used. The month range for the precipitation summation that gives the optimum correlation (March–October) is longer than that for the Thomas County well (April–August). The water use for 2018–2021 surrounding the Colby well is anomalously low in comparison with other years given the precipitation. However, the point for 2022 is close to the regression line for all of the data. Thus, the recent and earlier periods were not plotted as separate regressions as was done for the

Scott index well. Additional years of data will allow better assessment of whether the lower use during 2018–2021 indicates that conservation measures have been implemented since the establishment of the district-wide LEMA in GMD4 in April 2018 or if there has been a change in irrigated area.

The water-use data for 2005–2007 for the SC-8 well also appear to be high; as for the Colby well, a higher correlation is obtained using the 2008–2022 data (fig. 60). The monthly precipitation range for the SC-8 well optimum correlation is the same as for the Scott County index well. Just as for the Colby well, the water use during 2018–2021 was below the regression line and the point for 2022 is near the regression line. Given that the SC-8 and Scott County index wells are relatively near one another, a decrease in aquifer thickness is likely responsible for the lower 2018–2021 water use at the SC-8 well. The higher water use in 2022 for both the Colby and SC-8 wells than would be predicted for a regression line through the 2018–2021 data might indicate that irrigators had to pump more than consistent with the 2018–2021 water use and precipitation relationship due to the especially dry conditions; the 2022 precipitation was the lowest at the SC-8 well and next to the lowest at the Colby well for 2008–2022.

The water-use data for the Belpre well during 2005–2007 falls within the band of variation of the 2008–2022 data; thus, the longer time span of 2005–2022 was used in the plot for this well in fig. 60. Just as for the SC-8 well, the optimum monthly range for precipitation for the Belpre well started in February. This early monthly start may indicate that pre-irrigation, which is typically done in an effort to enhance soil moisture, is important enough to affect the correlation. In contrast to the Scott, Colby, and SC-8 wells, the points for 2018, 2019, 2021, and 2022 plot above (higher water use) the regression line; the point for 2020 is below but relatively near the line. No evidence of conservation measures or an effect of aquifer thickness is evident for this well.

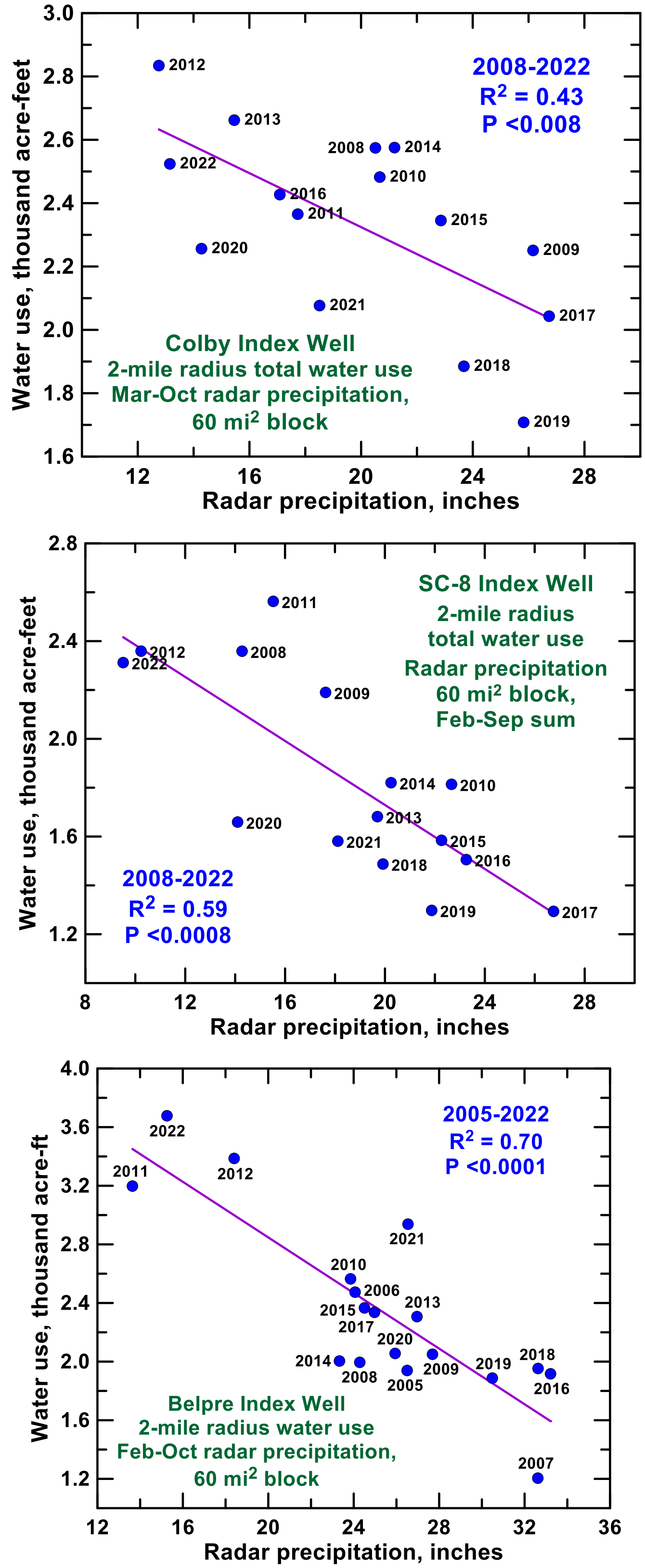


Figure 60—Correlation of annual total groundwater use with radar precipitation at the Colby, SC-8, and Belpre wells for 2008–2022 (Colby and SC-8) and 2005–2022 (Belpre).

5 Summary of 2022–2023 Accomplishments and Plans for 2023–2024

5.1 Accomplishments, 9/2022–6/2023

- Collected and processed data from all wells currently involved in the index well program. Telemetered data from 29 wells are served on the web in real time. Each well was visited approximately quarterly and downloads from all wells have been used for analysis and presentations.
- Drilled and equipped two well nests in GMD3; each nest has one well in the HPA and one well in the underlying Dakota aquifer.
- Continued analysis of hydrographs from all wells.
- Continued comparison of transducer data with the results of the annual water-level network.
- Continued an analysis of the utility of climatic indices and radar precipitation data for use in relationships with annual water-level change and water use in the vicinity of the index wells.
- Continued assessment of relationships among precipitation, annual water-level change, and annual water use at the index wells and the GMDs.
- Continued integration of program data into the digital Kansas High Plains Aquifer Atlas (Fross et al., 2012).
- Gave presentations about the index well program to KWO, DWR, and GMD personnel, among others.
- Wrote a paper on a simple approach for assessing the effectiveness of groundwater conservation measures that was developed through the index well program; the paper will be published in the journal Agricultural Water Management in the second half of 2023 and is included as an appendix to this report.

5.2 Planned Activities, 7/2023–6/2024

- Continue monitoring and processing water-level data from all wells currently involved in the index program. Visit each well quarterly to take manual measurements of water levels and download data from sensors.
- Continue analysis of hydrographs from all wells involved in the program.
- Drill and equip one well in Cheyenne County in GMD4 and one well near the Gray-Ford county line in GMD3.
- Water sampling at as many index wells as possible
- Install sensor and telemetry equipment and initiate monitoring in an existing well in GMD5.
- Continue assessment of the information that can be acquired from hydrograph inspection.
- Continue assessment of the relationships among climatic indices, radar precipitation data, annual water-level change, and annual water use for all five GMDs.

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7 Appendix

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

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Manuscript accepted for publication on June 7, 2023.

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.

Key words: water conservation−radar precipitation−irrigation−High Plains aquifer

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 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 (figure 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 (figure 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 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 figure 1. Figure 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 (figure 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.

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 (figure 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 figure 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.

3. 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 ~4x4 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 during 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.

4. 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 (figure 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% (figure 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 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 figure 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 (figure 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% (figure 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 (figure 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. Despite that, there is a separation between the 2005–2017 and 2018–2020 regression lines for GMD1 (figure 8). This separation is mainly produced by the Wichita County WCAs (figure 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 figure 8. The water use reduction based on a correlation of irrigation water use versus January–September precipitation is 24.1% (figure 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 yields p value 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 (figure 10); the plots for GMDs 2 and 5 are similar (figures 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 2019–2021 for GMD3 plot below the regression line in figure 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 (figure 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 figure 14. GMD3 has had the largest application rate (figure 10) and GMD1 the smallest (figure 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 figure 1, especially in Wichita County, including a decrease of over 20% from 2005 to 2021 (figure 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 (figure 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.

5. 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), the Kansas Water Office (KWO), and the United States Department of Agriculture (USDA) and the United States National Science Foundation (NSF) 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 that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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.

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Figure captions

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.

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.

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.

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 $W/A = -0.5063 \times P + 55.27$. See Fig. 3 for explanation of solid lines, shaded intervals, and regression equation terms.

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 $W/A = -0.3877 \times P + 45.55$ for 2005–2017 and $W/A = -0.3545 \times P + 41.24$ for 2018–2021. 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.

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.

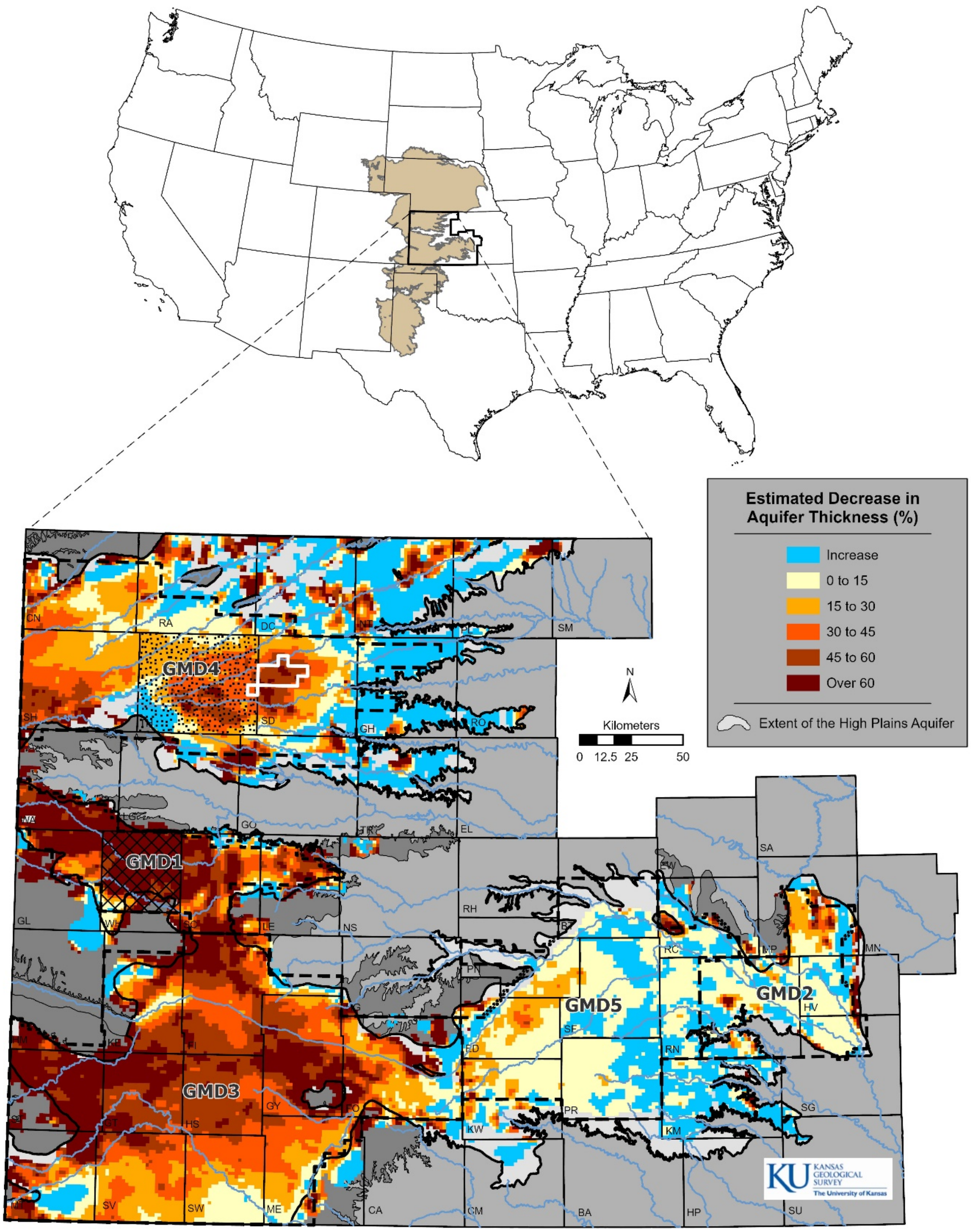
Fig. 11. Annual irrigation groundwater use per irrigated area versus January–September radar precipitation for GMD2 during 2005–2021. The regression equation is W/A = -0.3344 x P + 48.94. See Fig. 3 for explanation of solid lines, shaded intervals, and regression equation terms.

Fig. 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. 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.

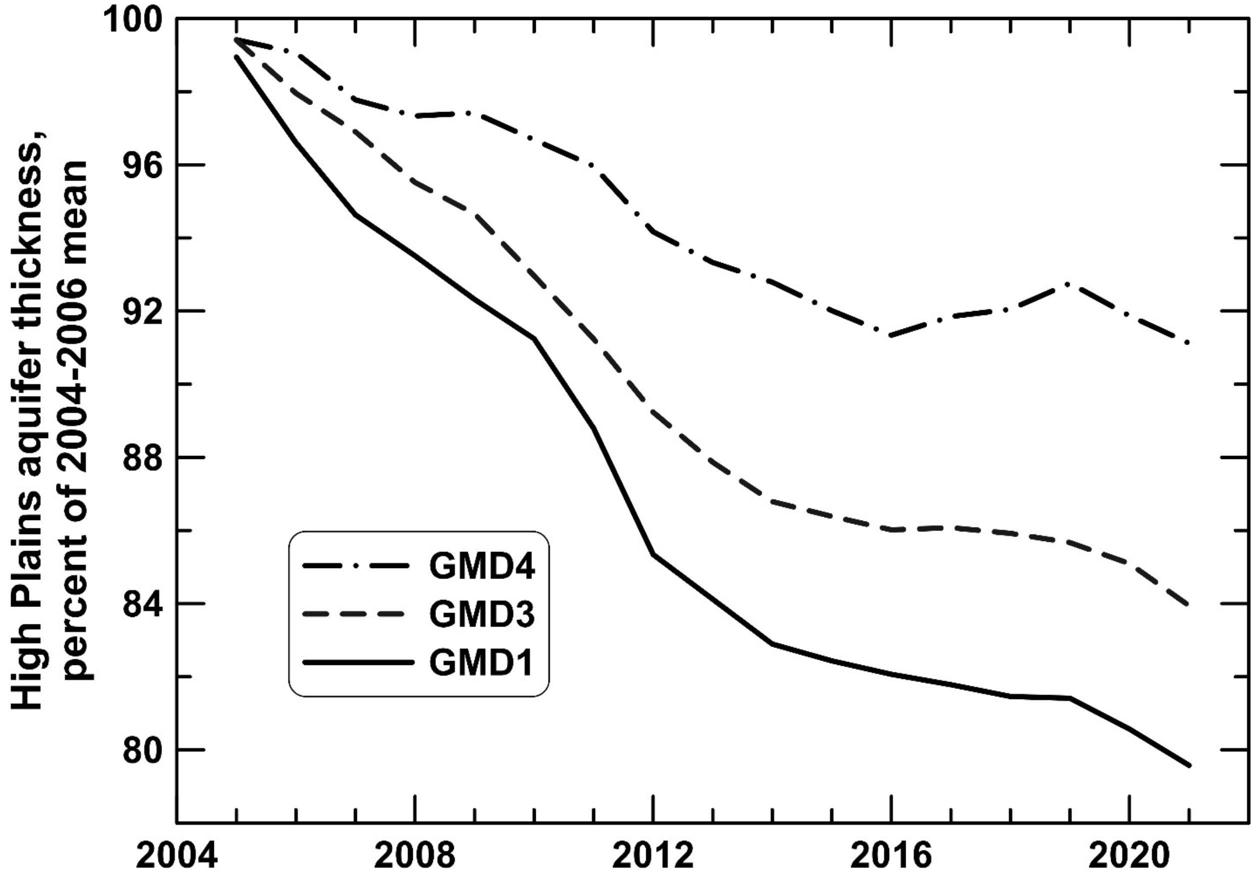
Fig. 14. Regression lines for irrigation water use per area versus January–September radar precipitation for the three GMDs in the Ogallala region of the HPA, the SD-6 LEMA in GMD4, and Wichita County in GMD1. The regression lines are the same as those in Fig. 2–6.

Figure 1



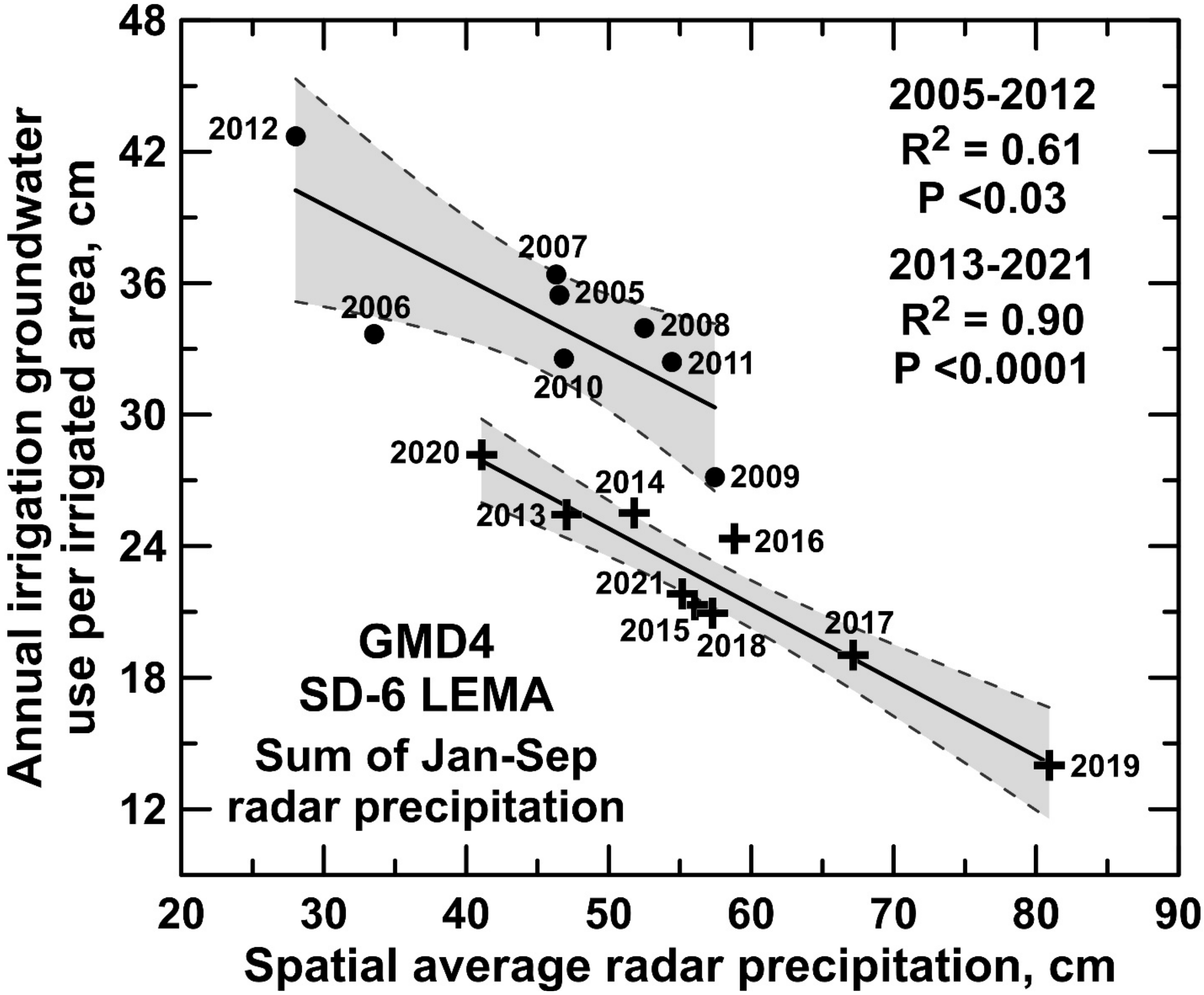
Estimated Decrease in Aquifer Thickness (%)
Increase
0 to 15
15 to 30
30 to 45
45 to 60
Over 60
Extent of the High Plains Aquifer
Kilometers
0 12.5 25 50
N
GMD4
GMD1
GMD3
GMD5
GMD2

Figure 2



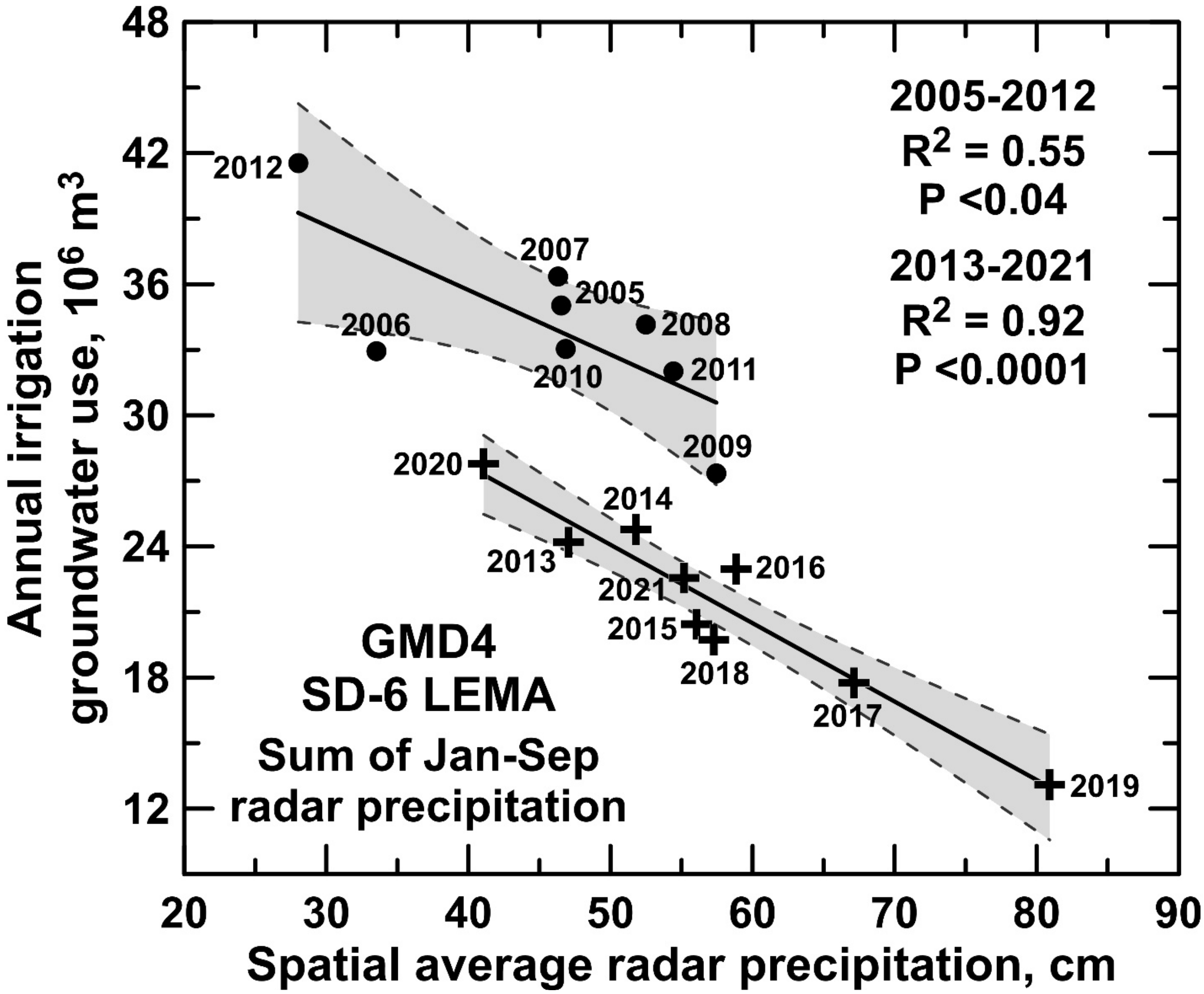
High Plains aquifer thickness, percent of 2004-2006 mean
100
96
92
88
84
80
2004
2008
2012
2016
2020
GMD4
GMD3
GMD1

Figure 3



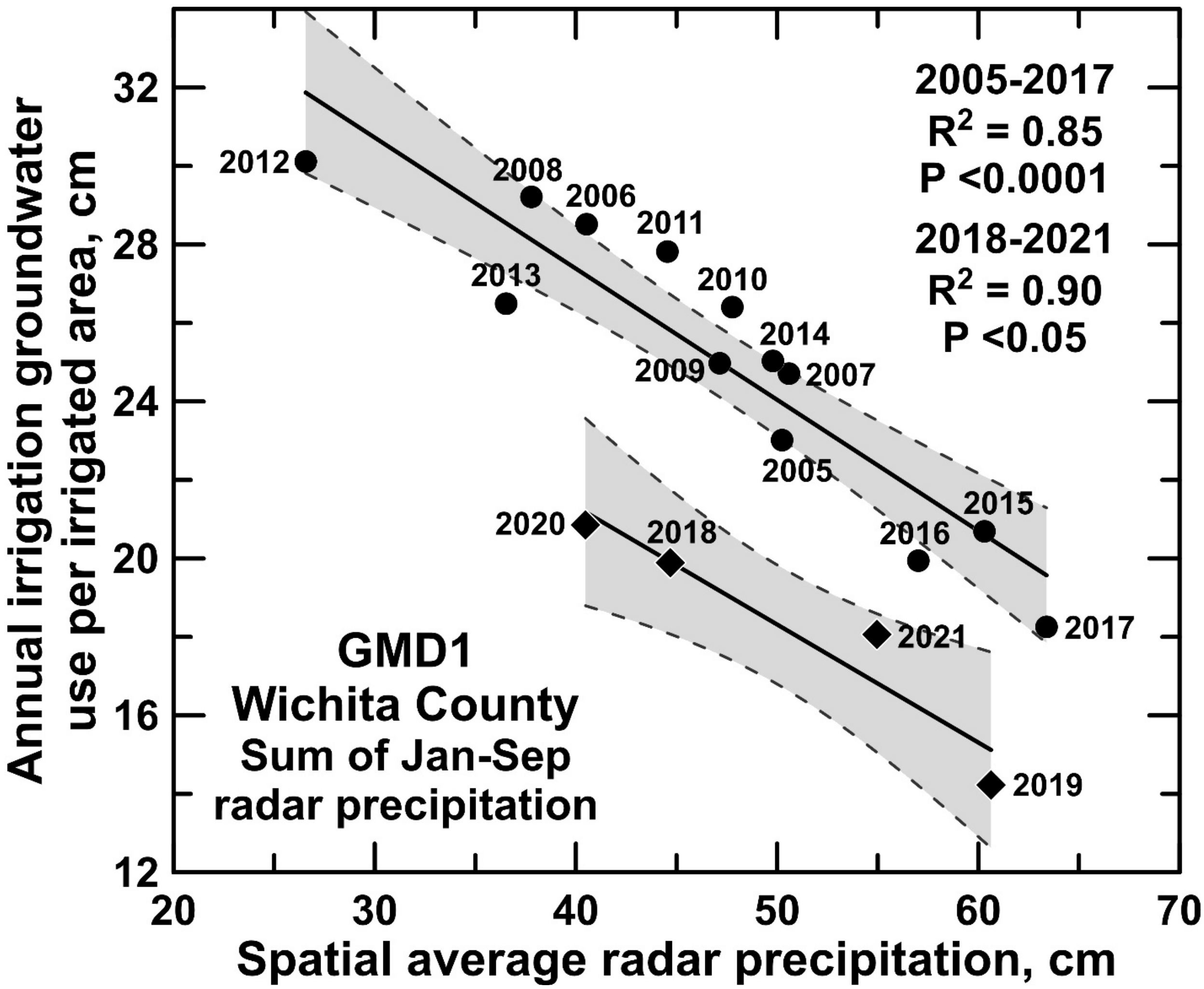
2005-2012
R2 = 0.61
P <0.03
2013-2021
R2 = 0.90
P <0.0001
GMD4
SD-6 LEMA
Sum of Jan-Sep
radar precipitation
2012
2007
2005
2006
2008
2011
2010
2009
2020
2014
2013
2016
2021
2015
2018
2017
2019
48
42
36
30
24
18
12
20
30
40
50
60
70
80
90
Annual irrigation groundwater use per irrigated area, cm
Spatial average radar precipitation, cm

Figure 4



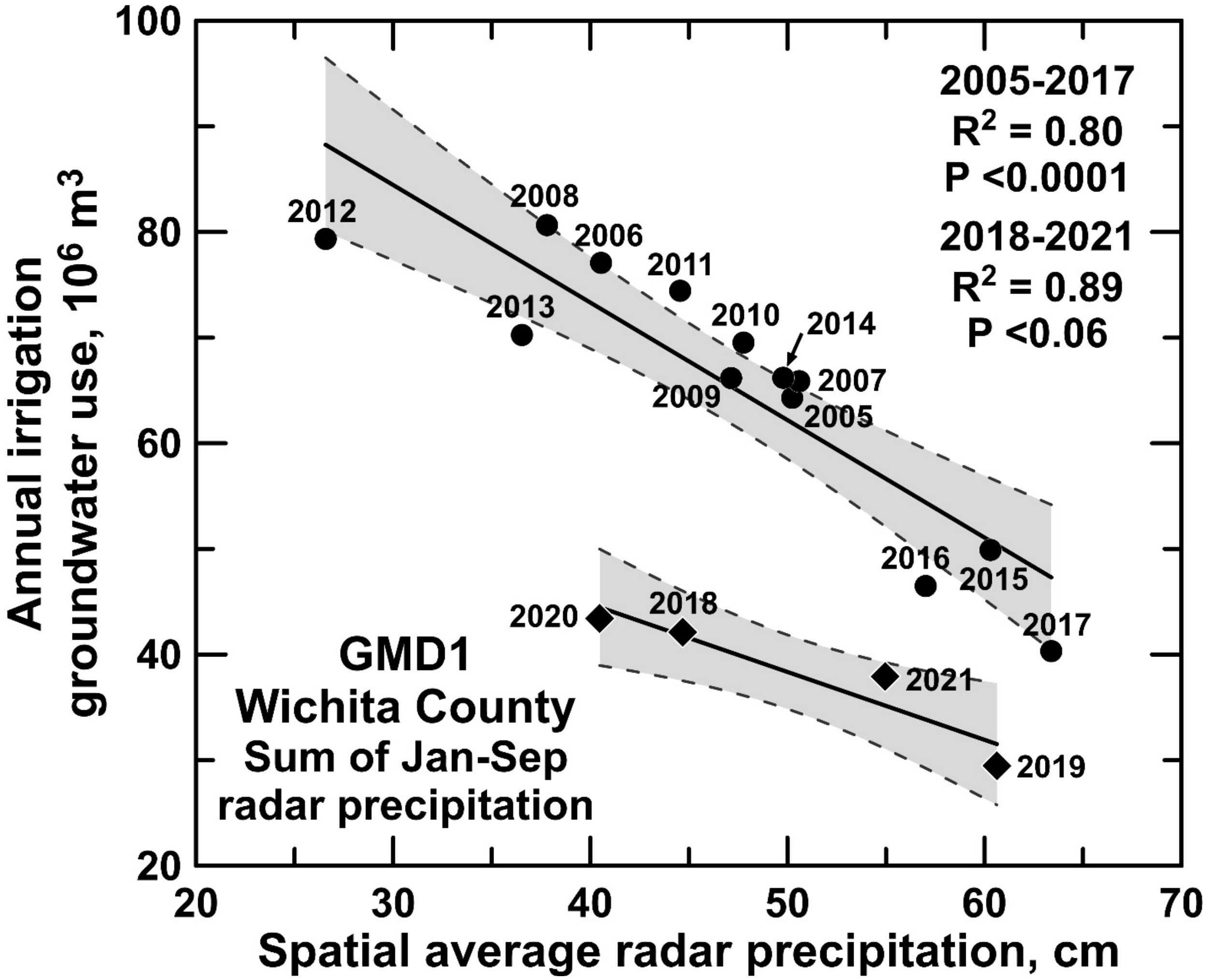
48
42
36
30
24
18
12
20
30
40
50
60
70
80
90
Annual irrigation groundwater use, 10^6 m^3
Spatial average radar precipitation, cm
2005-2012
R2 = 0.55
P <0.04
2013-2021
R2 = 0.92
P <0.0001
GMD4
SD-6 LEMA
Sum of Jan-Sep
radar precipitation
2012
2007
2005
2006
2008
2010
2011
2009
2020
2014
2013
2016
2021
2015
2018
2017
2019

Figure 5



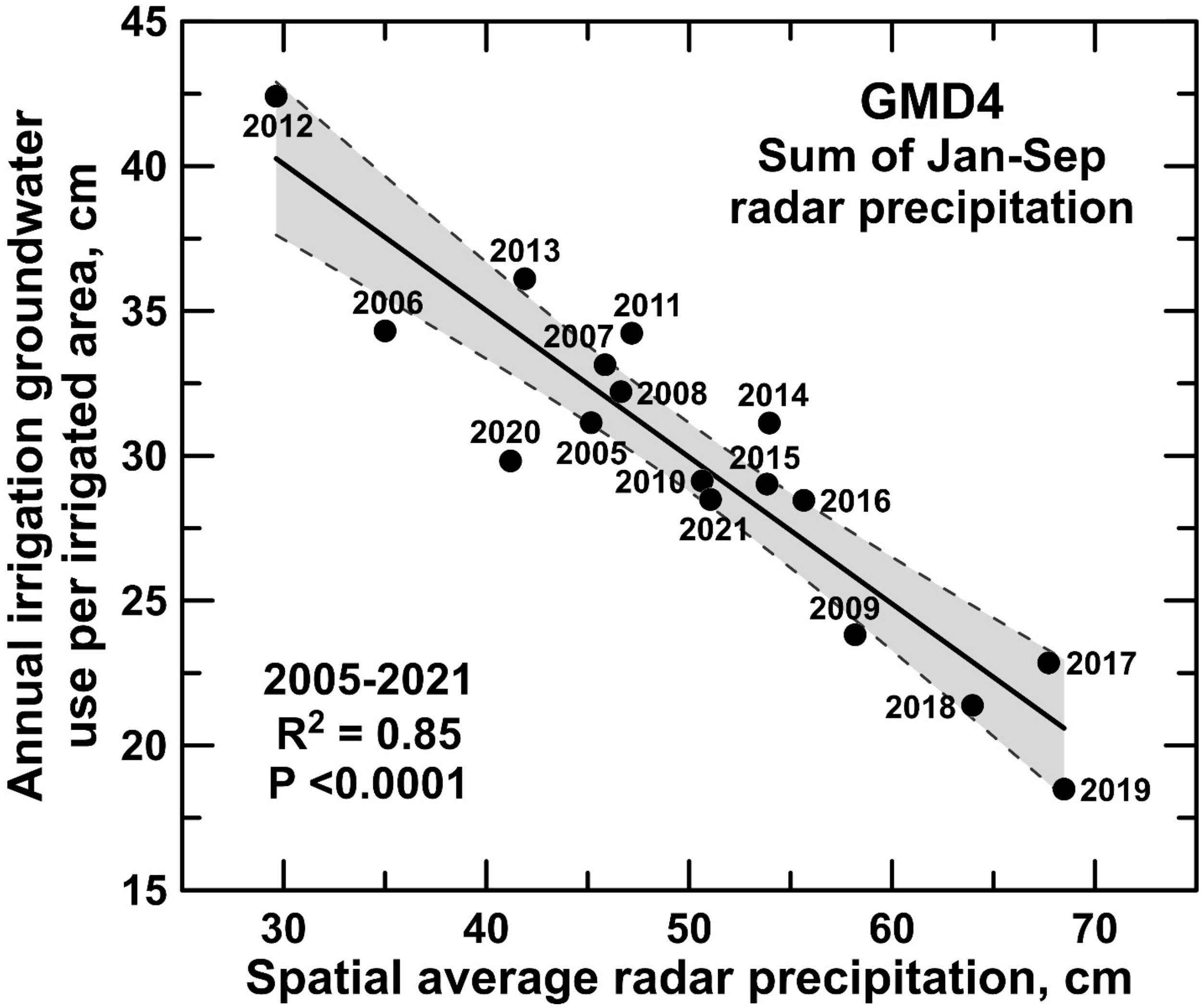
2005-2017
R^2 = 0.85
P <0.0001
2018-2021
R^2 = 0.90
P <0.05
2012
2008
2006
2011
2013
2010
2014
2009
2007
2005
2015
2016
2017
2020
2018
2021
2019
GMD1
Wichita County
Sum of Jan-Sep
radar precipitation
Annual irrigation groundwater use per irrigated area, cm
Spatial average radar precipitation, cm
32
28
24
20
16
12
20
30
40
50
60
70

Figure 6



2005-2017
R2 = 0.80
P <0.0001
2018-2021
R2 = 0.89
P <0.06
GMD1
Wichita County
Sum of Jan-Sep
radar precipitation
2012
2008
2006
2011
2013
2010
2014
2009
2007
2005
2016
2015
2017
2020
2018
2021
2019
Annual irrigation groundwater use, 106 m3
Spatial average radar precipitation, cm
100
80
60
40
20
20
30
40
50
60
70

Figure 7



GMD4
Sum of Jan-Sep
radar precipitation
2005-2021
R^2 = 0.85
P <0.0001
Annual irrigation groundwater use per irrigated area, cm
Spatial average radar precipitation, cm
45
40
35
30
25
20
15
30
40
50
60
70
2012
2013
2006
2011
2007
2008
2014
2020
2005
2015
2010
2021
2016
2009
2017
2018
2019

Figure 8

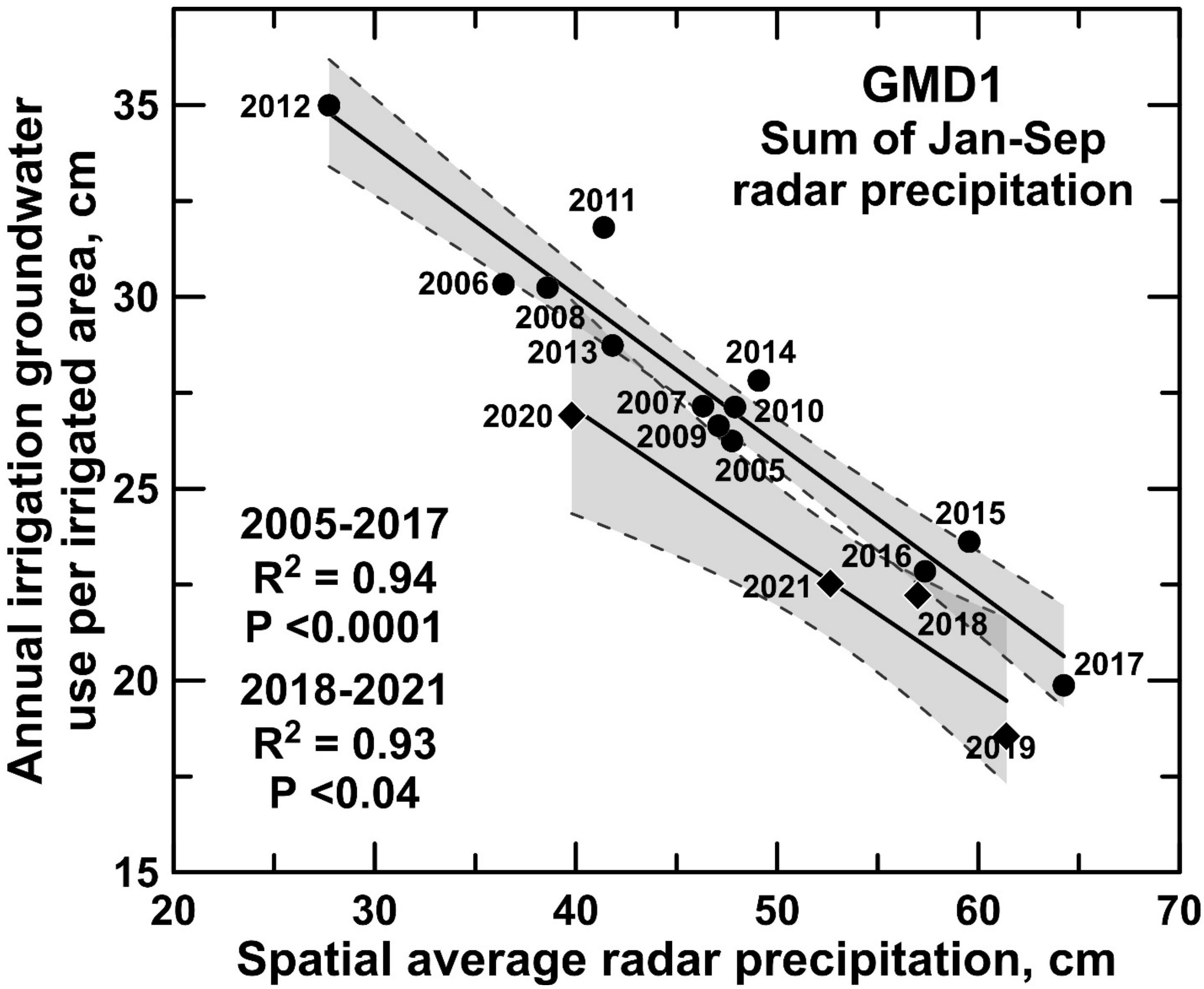
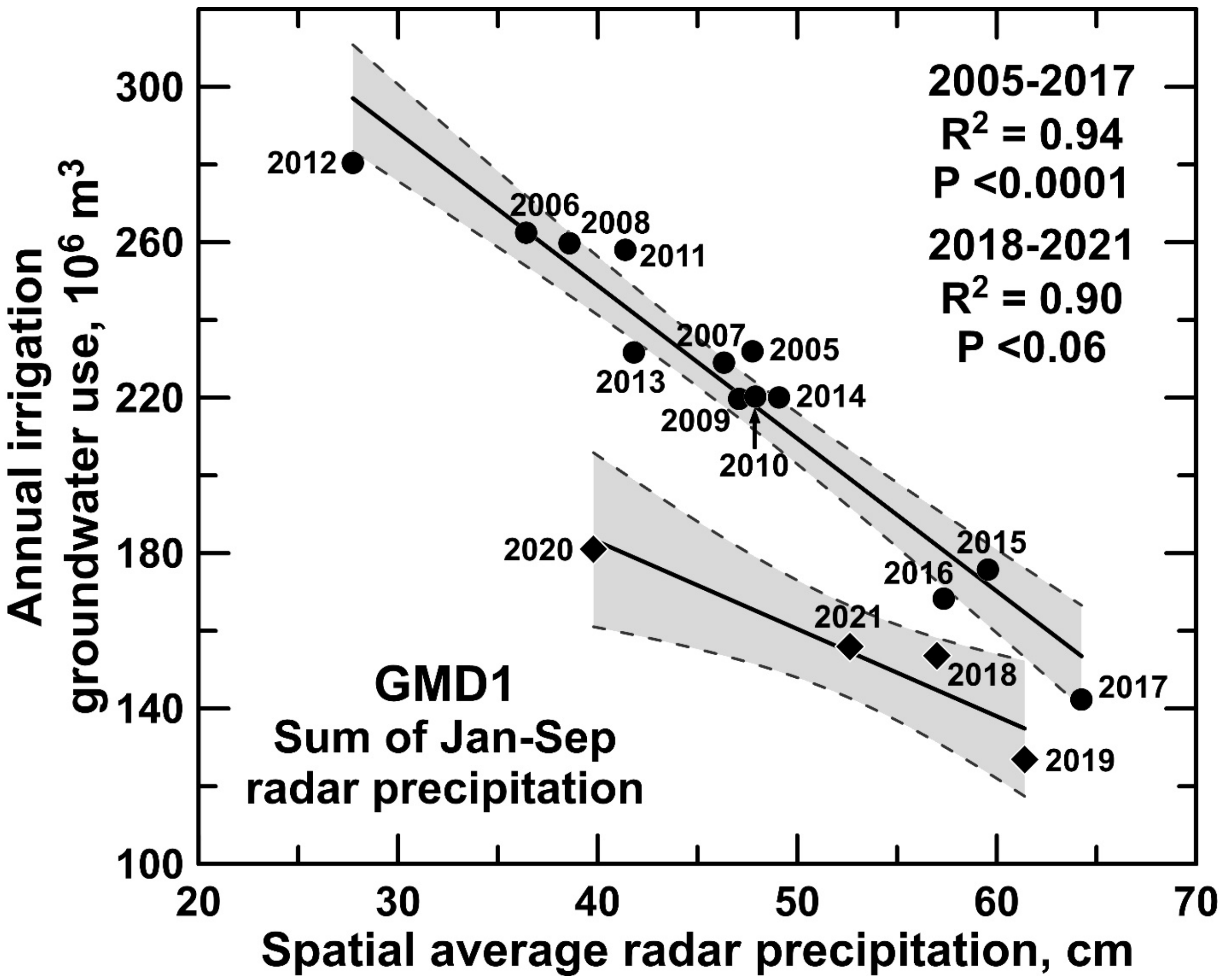

GMD1
Sum of Jan-Sep
radar precipitation
2005-2017
R2 = 0.94
P <0.0001
2018-2021
R2 = 0.93
P <0.04
2012
2011
2006
2008
2013
2014
2020
2007
2010
2009
2005
2015
2016
2021
2018
2017
2019
Annual irrigation groundwater use per irrigated area, cm
Spatial average radar precipitation, cm
15
20
25
30
35
20
30
40
50
60
70

Figure 9



2005-2017
R² = 0.94
P <0.0001
2018-2021
R² = 0.90
P <0.06
2012
2006
2008
2011
2007
2005
2013
2014
2009
2010
2015
2016
2020
2021
2018
2017
2019
GMD1
Sum of Jan-Sep
radar precipitation
Annual irrigation groundwater use, 10⁶ m³
Spatial average radar precipitation, cm
300
260
220
180
140
100
20
30
40
50
60
70

Figure 10

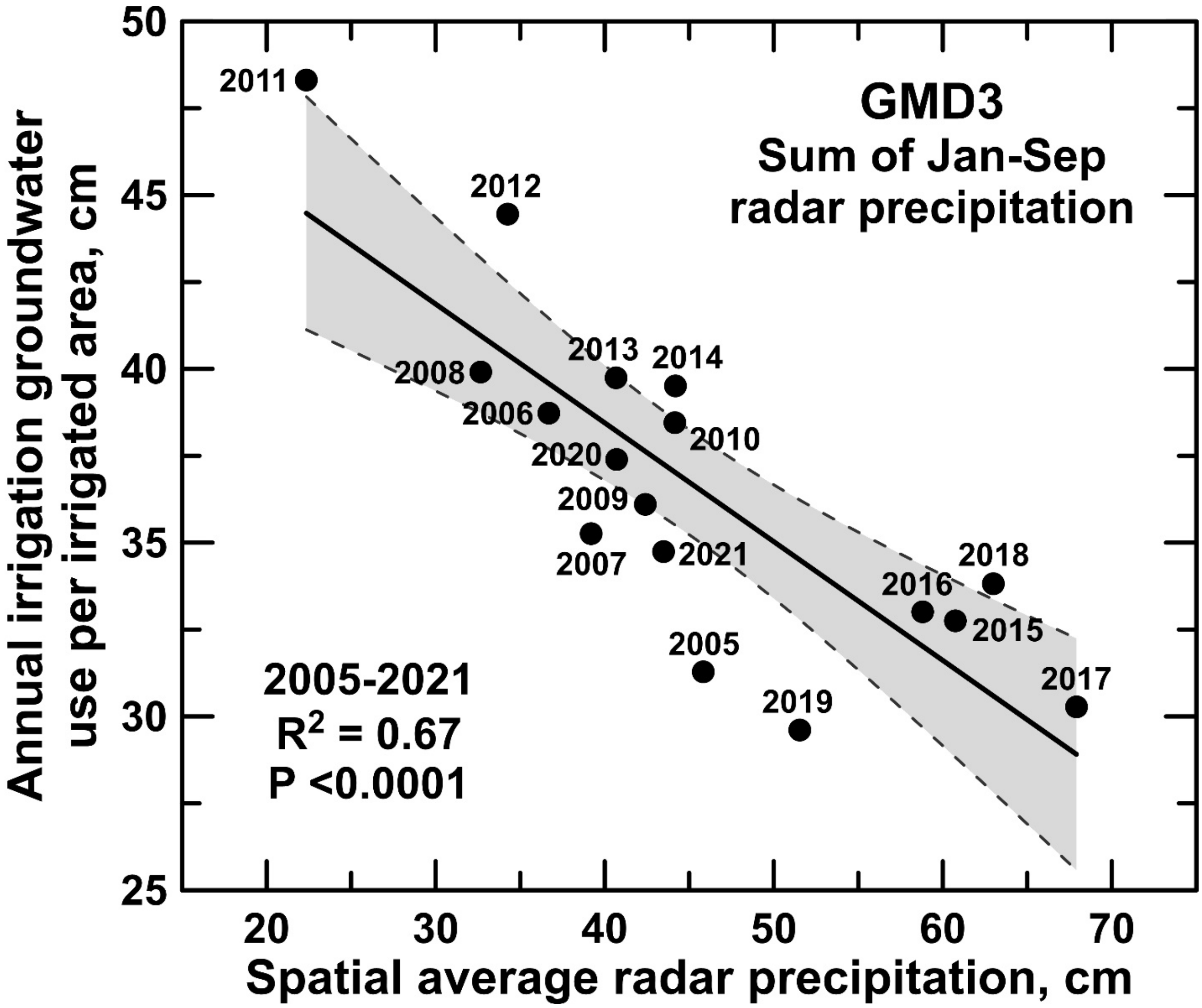

GMD3
Sum of Jan-Sep
radar precipitation
2005-2021
R2 = 0.67
P <0.0001
2011
2012
2013
2014
2008
2006
2010
2020
2009
2007
2021
2018
2016
2015
2005
2019
2017
Annual irrigation groundwater
use per irrigated area, cm
Spatial average radar precipitation, cm
25
30
35
40
45
50
20
30
40
50
60
70

Figure 11

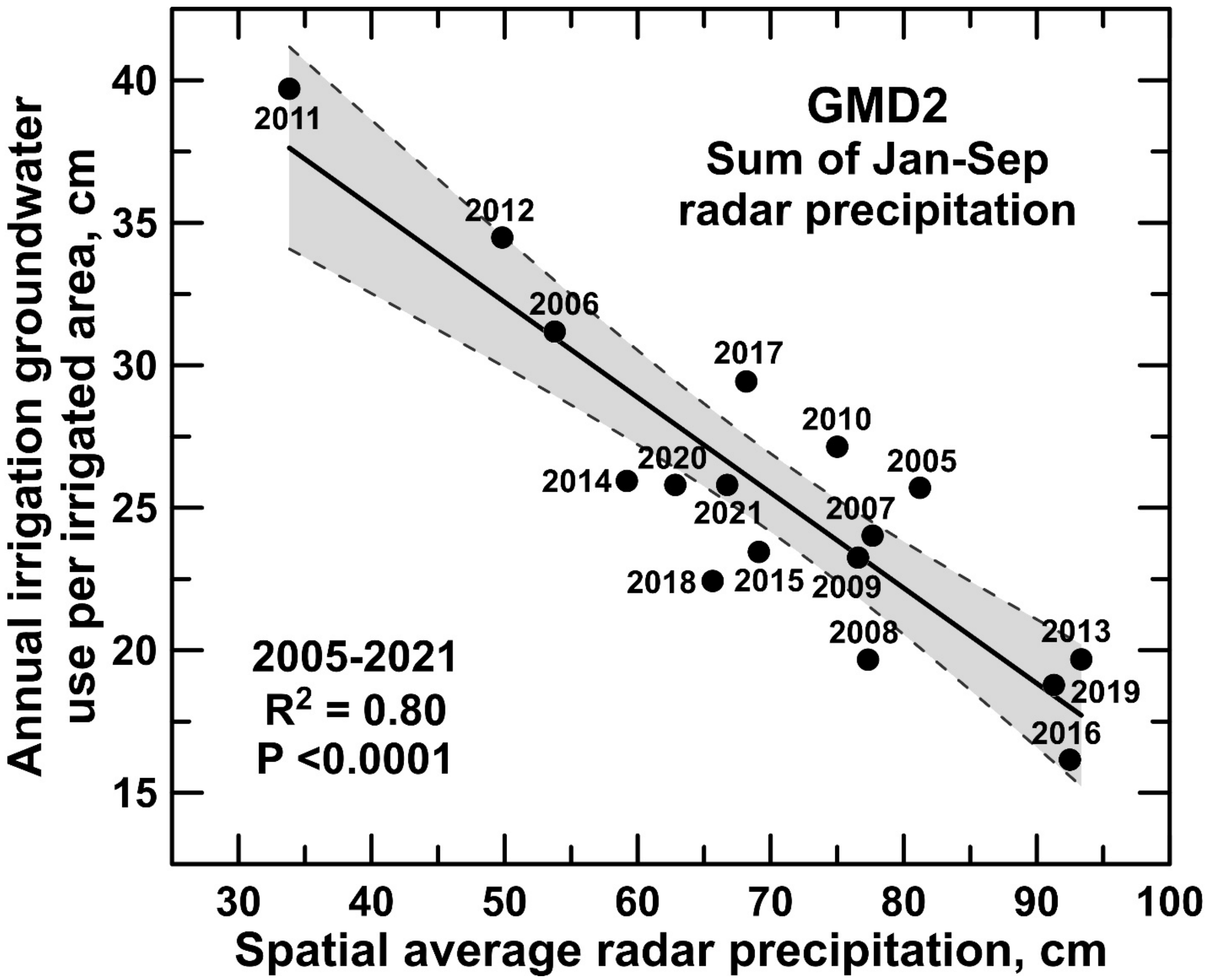

GMD2
Sum of Jan-Sep
radar precipitation
2005-2021
R^2 = 0.80
P <0.0001
2011
2012
2006
2017
2010
2005
2020
2014
2021
2007
2018
2015
2009
2008
2013
2019
2016
40
35
30
25
20
15
30
40
50
60
70
80
90
100
Annual irrigation groundwater use per irrigated area, cm
Spatial average radar precipitation, cm

Figure 12

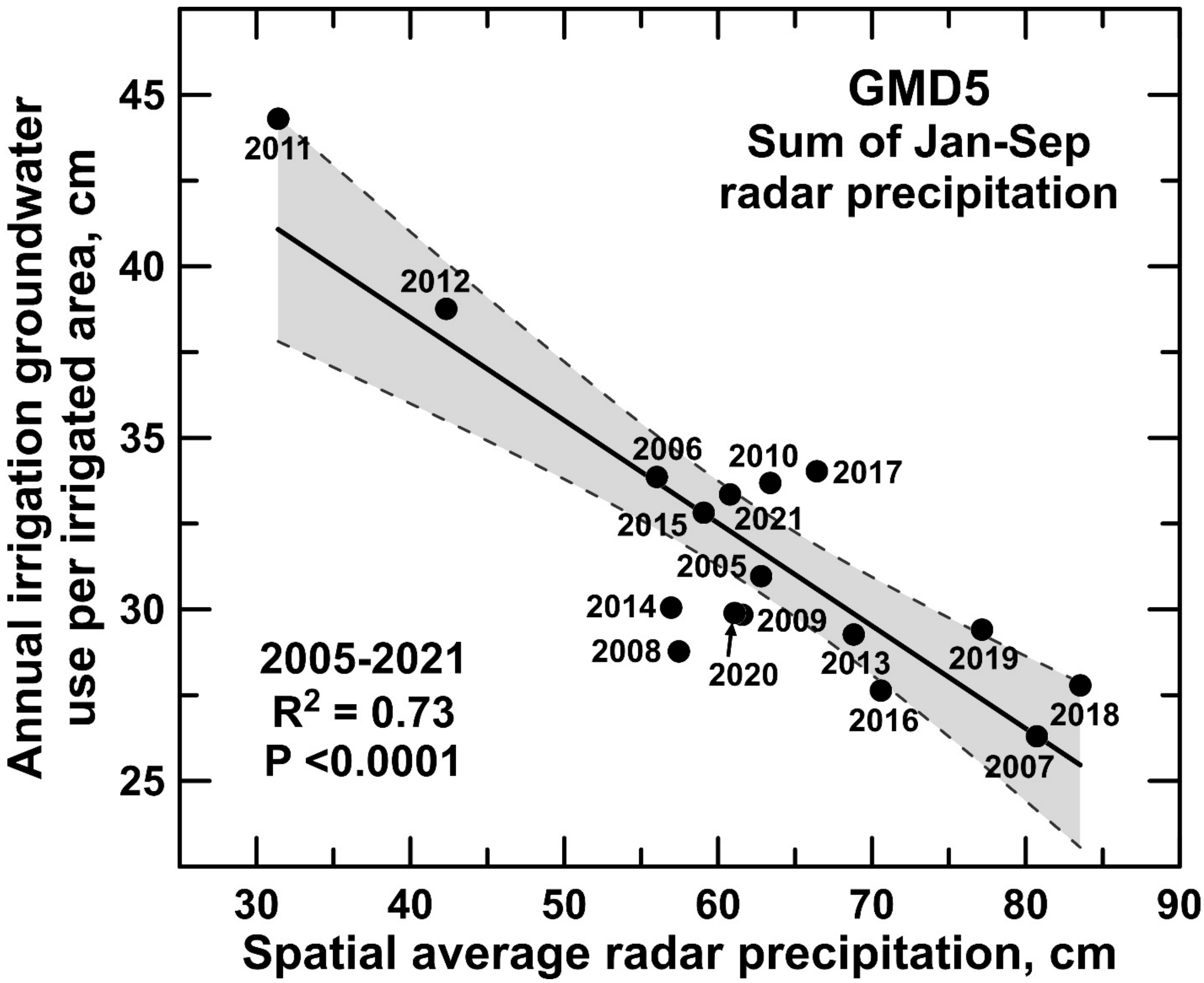

GMD5
Sum of Jan-Sep
radar precipitation
2005-2021
R^2 = 0.73
P <0.0001
2011
2012
2006
2010
2017
2015
2021
2005
2014
2009
2008
2020
2013
2019
2016
2018
2007
45
40
35
30
25
30
40
50
60
70
80
90
Annual irrigation groundwater use per irrigated area, cm
Spatial average radar precipitation, cm

Figure 13

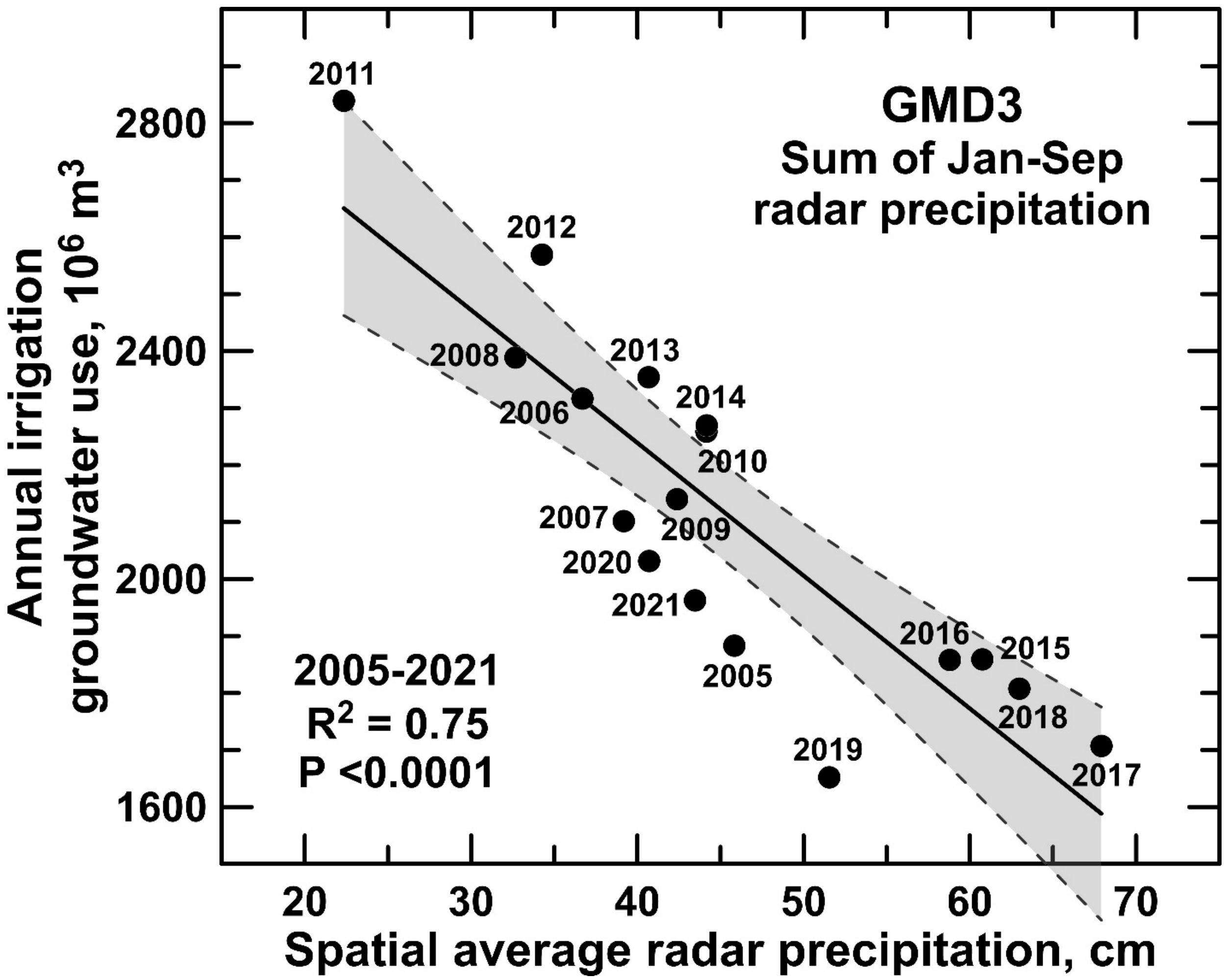
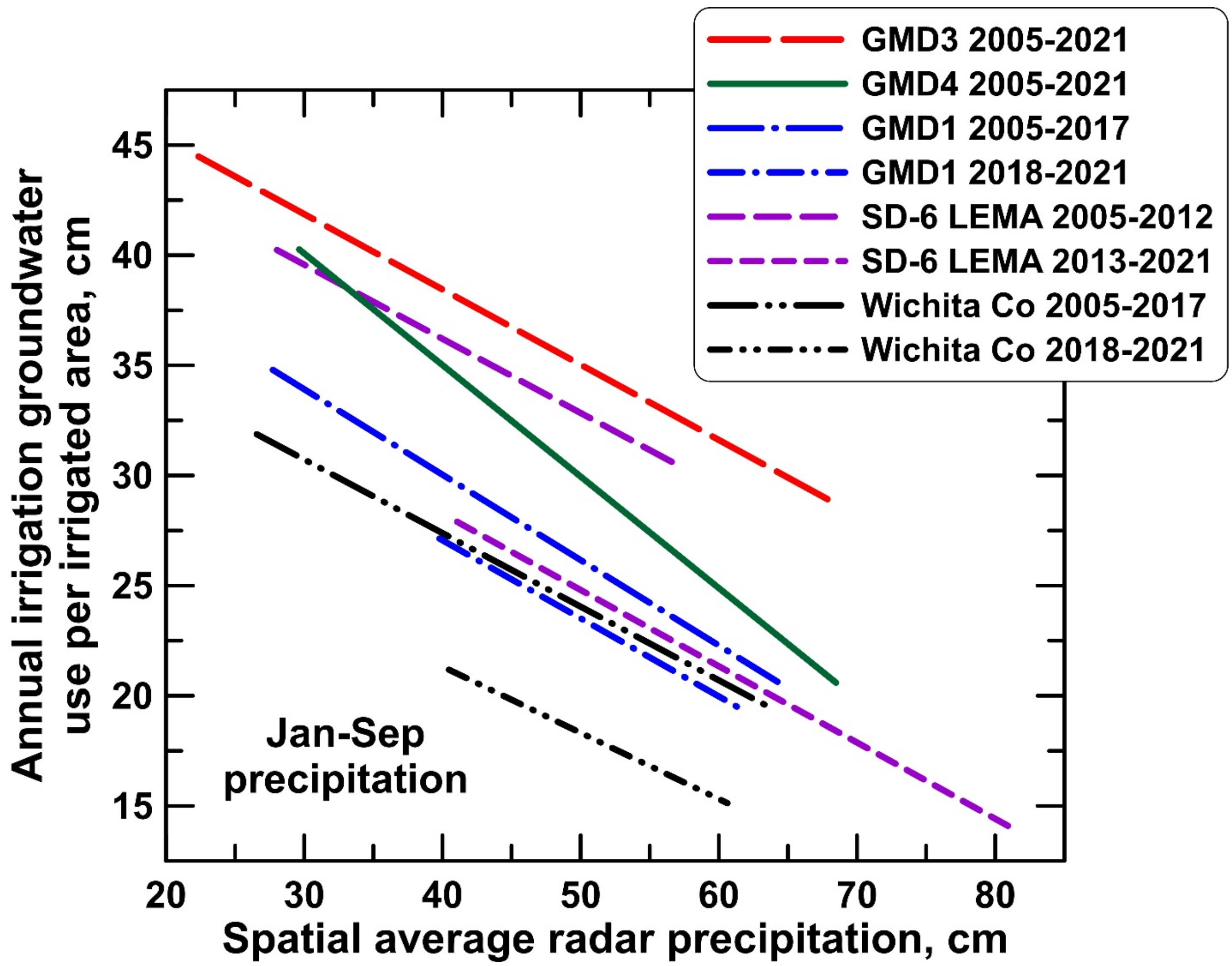

GMD3
Sum of Jan-Sep
radar precipitation
2005-2021
R2 = 0.75
P <0.0001
2011
2012
2008
2013
2006
2014
2010
2007
2009
2020
2021
2016
2015
2005
2018
2019
2017
2800
2400
2000
1600
20
30
40
50
60
70
Annual irrigation groundwater use, 10^6 m^3
Spatial average radar precipitation, cm

Figure 14 (Color should be used for this figure.)



Supplementary Material

Comparison of radar and PRISM precipitation

A commonly used dataset for precipitation is that produced by the PRISM Climate Group (http://www.prism.oregonstate.edu/). In this work, we compared the radar data with the M3 data from the AN81m PRISM dataset covering the conterminous U.S. In the central and eastern U.S., data from January 2002 to present are based on climatologically-aided interpolation (CAI) processing of station data combined with interpolation of radar data from the AHPS (http://www.prism.oregonstate.edu/documents/PRISM_datasets.pdf). Thus, both the radar and PRISM precipitation datasets for the central and eastern U.S. are hybrid in nature; the differences are the starting data and the processing methods.

The distribution of Kansas precipitation stations used in PRISM is uneven. Although some counties in the Kansas HPA have up to several stations, others have only one or two and one county has none. In comparison, the spatial coverage of the radar precipitation data represents a distribution of about 87–164 points for counties within the Kansas HPA. However, as indicated above, PRISM precipitation data for the central and eastern U.S. include radar data in a combined interpolation process.

Although radar and PRISM precipitation are well correlated and both utilize a combination of station and radar data, PRISM precipitation is typically less than that of radar precipitation for areas within the Kansas HPA, regardless of their size (figure S1). The reason may be that precipitation from short but intense spring through fall thunderstorms that are recorded by radar can have areas smaller than the distance between some of the PRISM precipitation stations. Thus, the emphasis on radar data for the radar precipitation dataset compared to station data for the PRISM dataset may allow the radar precipitation dataset to capture better the precipitation distribution between stations. For areas that may not include many or any ground stations (less than about 1,000 km^2) spatial PRISM means could be lower than for radar precipitation when intense, local rainstorms occur between PRISM ground stations, and higher than for radar precipitation when those storms extend over PRISM stations.

Water use versus precipitation correlations at the scale of individual GMDs

The correlations between annual and the January–September monthly sum of radar precipitation and annual water use per irrigated area for the five GMDs over the HPA were determined for 2005–2021. The correlations for January–September precipitation are greater than for annual precipitation for the three western Kansas (Ogallala region) GMDs (1, 3, and 4) and about the same for the two south-central (Quaternary region) GMDs (2 and 5), (table S1). Precipitation is substantially lower in western than south-central Kansas. Thus, anomalously high precipitation or snowfall during the fall in western Kansas can introduce significant variation into annual precipitation for some years that is not closely associated with irrigation. In addition, increases in soil moisture in south-central Kansas from winter precipitation could remain in soil longer than in western Kansas where lower humidity and wind can more quickly dry out soil. The periods of 2005–2017 and 2018–2021 are also included for GMD1 in table S1. Radar precipitation explains from 67% of the variation in applied water use per irrigated area for GMD3 and up to over 90% for GMD1 (table S1).

Uncertainty in water savings based on values for the main irrigation season

We evaluated water savings in this work using the January-September period as explained in the main text. The water savings estimates do depend on the analysis period. In this section, we assess the impact of that dependence.

Different sums of contiguous monthly precipitation within the main irrigation season of March–September were examined for comparing correlations (coefficient of determination [R^2]) of precipitation with water use per irrigated area and water use such that the start was either March or April and the end either August or September. Precipitation patterns and irrigation practices varied for different areas during the period used in this study (2005–2021), which resulted in differences substantial enough within the March–September irrigation season to produce optimum correlations for different monthly sums. In general, correlations for January–September and the main irrigation season were appreciably greater than for annual precipitation for GMDs in the Ogallala region of the HPA; correlations for annual, January–September, and main irrigation season precipitation were approximately equivalent for GMDs in the Quaternary region of the HPA as indicated in table S1.

The optimum correlation for irrigation water use per irrigated area versus precipitation for the SD-6 LEMA during the main irrigation season is for March–August; the R^2 values are 0.68 and 0.96 for 2005–2012 and 2013–2021, respectively; the reduction in the water use rate was 27.6% compared to 25.0% based on January–September precipitation. The R^2 values are 0.64 and 0.92 for March–August precipitation during 2005–2012 and 2013–2021, respectively, for the correlation of precipitation and water use; the reduction in water use was 29.9% compared to 27.4% for January–September precipitation. The reduction in water use minus the reduction in water use per area was 2.4% for both precipitation sums. The optimum correlation for irrigation water use per irrigated area versus precipitation for Wichita County during the main irrigation season is for March–September; 0.84 and 0.76 for 2005–2017 and 2018–2021, respectively; the reduction in the water use rate was 24.9% compared to 23.4% for January–September. The R^2 values are 0.81 and 0.73 for 2005–2017 and 2018–2021, respectively, for the correlation of precipitation and water use; the reduction in water use was 39.7% compared to 38.5% for January–September precipitation. The reduction in water use minus that in water use per area for Wichita County was 14.9% for March–September compared to 15.1% for January–September. The R^2 values for irrigation water use per irrigated area versus precipitation for March–September in GMD1 are 0.93 and 0.89 for 2005–2017 and 2018–2021, respectively; the reduction in the water use rate was 14.5% compared to 10.1% for January–September. The R^2 values are 0.95 and 0.86 for 2005–2017 and 2018–2021, respectively, for the correlation of precipitation and water use; the reduction in water use was 27.8% compared to 24.1% for January–September precipitation. The reduction in water use minus that in water use per area for GMD1 was 13.3% for March–September compared to 14.0% for January–September.

The results of this assessment provide insights into the uncertainty of the estimates for the January-September period.

Formal Tests of Significance of Conservation Measures

In regression modeling, categorical predictor variables are typically represented using indicator (or dummy) variables (Draper and Smith, 1981). Here, we will use a binary indicator variable, Z, to distinguish data from the pre-conservation ($Z = 0$) and conservation ($Z = 1$) periods and use that variable to formulate two alternative models, one with different intercepts but a common slope for the two periods (the parallel-slopes model) and one with separate intercepts and slopes (the full model). We will compare these models to one in which the data from both periods are fit with a single line (the reference model - embodying the hypothesis that conservation measures have no impact) and also to each other.

The reference model is given by

$$Y = a_0 + b_0X \tag{S1}$$

where the response variable, Y, represents either irrigation water use per irrigated area or total irrigation water use and the predictor variable, X, is spatially averaged radar precipitation.

The parallel-slopes model is given by

$$Y = a_0 + b_0X + a_1Z. \tag{S2}$$

For the pre-conservation period ($Z = 0$), this model reduces to

$$Y = a_0 + b_0X \tag{S3}$$

and for the conservation period ($Z = 1$) it reduces to

$$Y = (a_0 + a_1) + b_0X. \tag{S4}$$

Thus, a_1 represents the change in intercept between the two periods.

The full model is given by

$$Y = a_0 + b_0X + a_1Z + b_1ZX. \tag{S5}$$

For the pre-conservation period, this model again reduces to

$$Y = a_0 + b_0X \tag{S6}$$

and for the conservation period to

$$Y = (a_0 + a_1) + (b_0 + b_1)X. \tag{S7}$$

Thus, in addition to a change in intercept between the periods, this model also allows a change in slope, b_1.

Figure S2 compares the reference, parallel-slopes, and full models for the water use per area data from SD-6. Note that fitting the full model to the data from both periods yields exactly the same intercepts and slopes for the two periods as one obtains from two separately fit regression lines, so that, for example, the regression lines in figure S2C are the same as those in figure 3. The motivation for formulating the problem in the fashion presented here is to provide a framework for testing the significance of the impacts of conservation using a model comparison F test (Draper and Smith, 1981), which is designed for comparing alternative models fit to the same data set rather than models fit to different data sets.

Consider two regression models, the second (larger) one containing all the terms in the first (smaller) one plus q additional terms. The F statistic for assessing the improvement in fit of the second model over the first one is given by

$$F = \frac{(SSR_1 - SSR_2)/q}{SSR_2/df_2}. \quad \text{(S8)}$$

where SSR_1 and SSR_2 are the sums of squared residuals for the first and second models, respectively, df_2 is the residual degrees of freedom for the second model, and q is the difference in residual degrees of freedom between the two models. The residual degrees of freedom for each model is given by $df_i = n - p_i$, where n is the number of data and p_i is the number of model of parameters (terms), so $q\ = df_1 - df_2 = p_2 - p_1$. The denominator of equation S8 represents the mean squared residual of the second model and the numerator represents the contribution of the q additional terms in that model to the improvement in fit over the first model, expressed in a mean-squared fashion. The null hypothesis associated with this statistic is that the true values of the parameters associated with the q terms are all zero, meaning the additional terms contribute nothing to the fit. Under the null hypothesis, the F statistic follows an F distribution with q and df_2 degrees of freedom. If the observed F statistic is sufficiently large, we can confidently reject the null hypothesis and state that the additional parameters contribute a significant improvement in fit (or, more accurately, that at least one of them does). This significance is typically measured using the p value, which represents the probability in the F distribution to the right of the observed statistic; this is the probability of being wrong should we choose to reject the null hypothesis. Thus, a smaller p value represents a more significant improvement in fit.

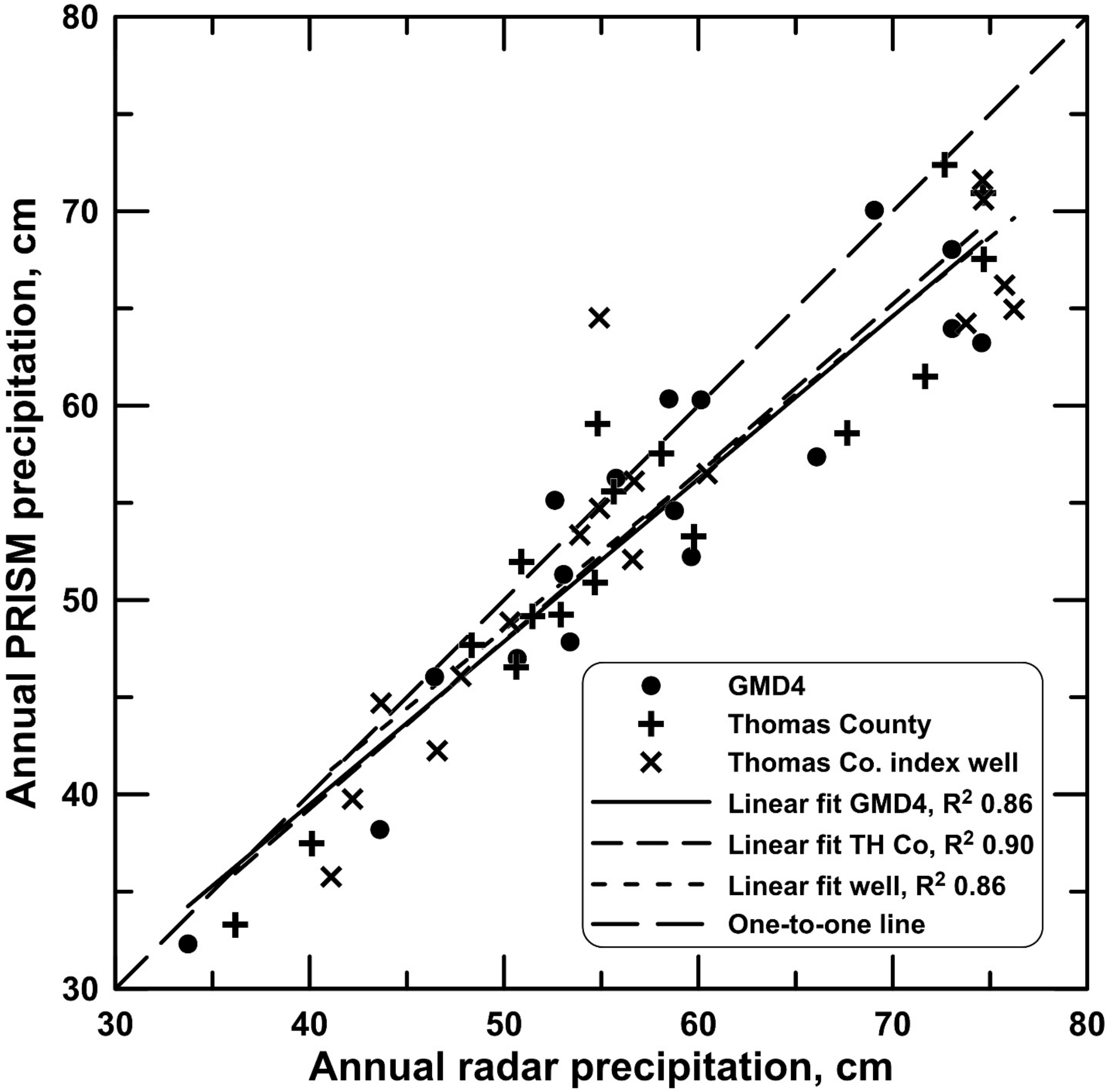
Table S2 presents the F test results for the water use per area regressions for SD-6, Wichita County, and GMD1 and Table S3 presents the same for the total water use regressions. In all cases, both the parallel-slopes and full models provide significant improvements in fit over the reference model, with p values ranging from 4.1×10^{-3} to 3.4×10^{-6}, indicating conservation measures have had a significant impact on total water use and use per area in all three areas. In five of the six cases, the full model fails to provide a significant improvement in fit over the parallel-slopes model; the exception is total water use in GMD1, where it yields a marginally significant improvement ($p = 0.03$, thus significant at the 5% level). That is, the impact of conservation measures so far can be generally characterized as a constant reduction in water use (per area or total) without a significant change in slope relative to the pre-conservation period. The a_1 estimates for the parallel-slopes models indicate water use per area reductions of 8.0, 5.7, and 2.6 cm and total water use reductions of 8.7×10^6, 24.0×10^6, and 46.3×10^6 m^3 for SD-6, Wichita County, and GMD1, respectively.

Figure captions

Fig. S1. Annual PRISM precipitation versus annual radar precipitation during 2005–2021 for GMD4, Thomas County (stippled area in Fig. 1), and an approximately 150 km^2 area around a Thomas County index well. The regression lines for GMD4 and the index well overlap one another.

Fig. S2. A) Reference, B) parallel-slopes, and C) full models fit to the annual irrigation water use per irrigated area versus spatially averaged radar precipitation data from SD-6. Circles represent the pre-LEMA period (2005–2012) and triangles represent the LEMA period (2013–2021). In B and C, the solid and dashed lines represent the fits to the pre-LEMA and LEMA period data, respectively. The shaded bands represent 95% confidence intervals on the regression lines.

Figure S1



Annual PRISM precipitation, cm
Annual radar precipitation, cm
30
40
50
60
70
80
30
40
50
60
70
80
GMD4
Thomas County
Thomas Co. index well
Linear fit GMD4, R^2 0.86
Linear fit TH Co, R^2 0.90
Linear fit well, R^2 0.86
One-to-one line

Figure S2

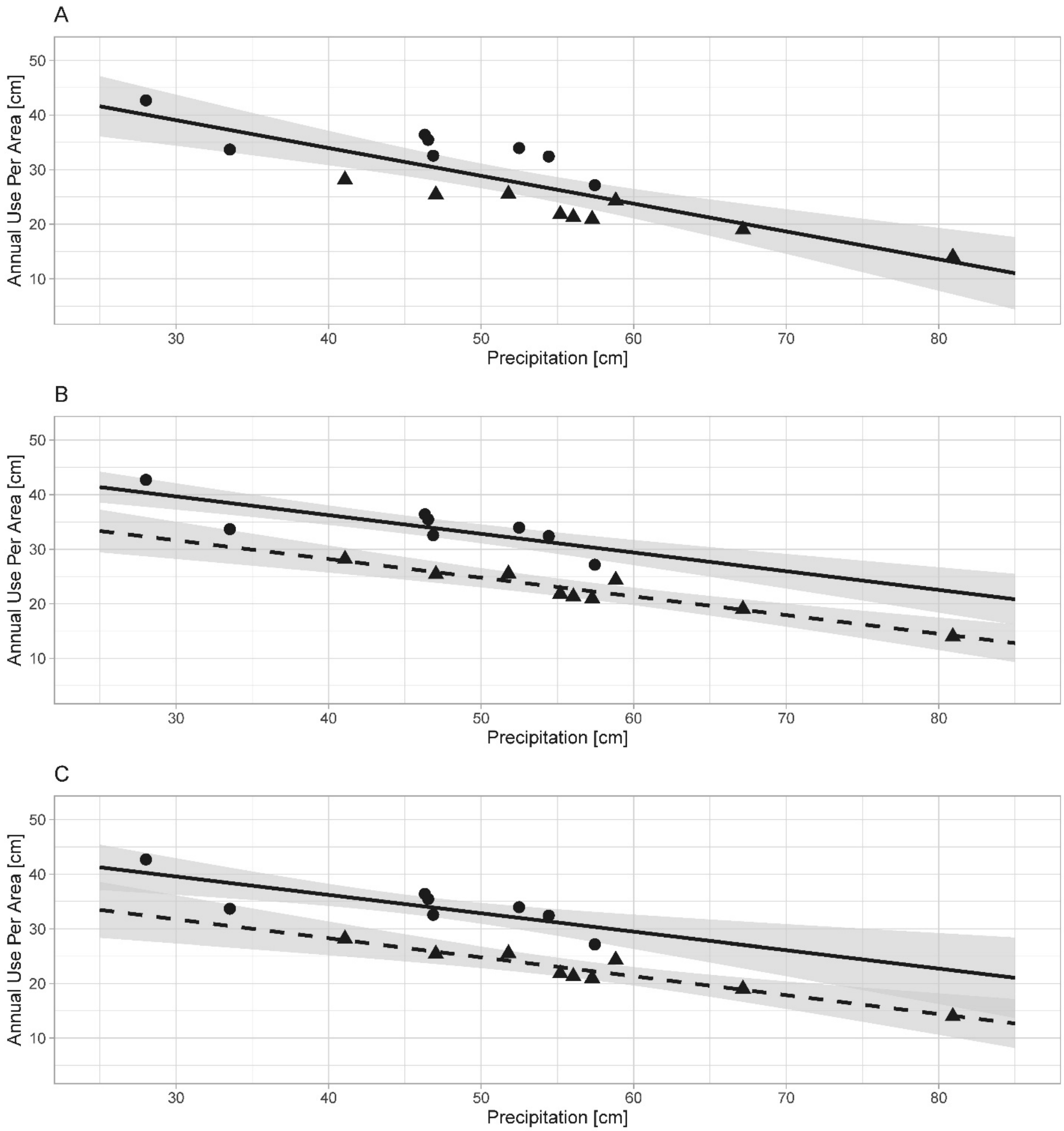

A
Annual Use Per Area [cm]
50
40
30
20
10
30
40
50
60
70
80
Precipitation [cm]
B
Annual Use Per Area [cm]
50
40
30
20
10
30
40
50
60
70
80
Precipitation [cm]
C
Annual Use Per Area [cm]
50
40
30
20
10
30
40
50
60
70
80
Precipitation [cm]

Table S1
Correlations between annual and monthly sums of radar precipitation for January–September and annual irrigation groundwater use per irrigated area for the five GMDs in the Kansas HPA during 2005–2021 and for GMD1 for 2005–2017 and 2018–2021. Differences between correlations for January–September and other monthly sums within the full irrigation season of March–September are generally a few to over ten percent of the R^2 values. Confidence intervals for R^2 values are for the 95% level and were determined using the R-square confidence interval calculator (https://www.danielsoper.com/statcalc/calculator.aspx?id=28).

GMD	Total GMD area, km^2	Period	R^2 annual precip.	P annual precip.	R^2 Jan–Sep precip. sum	P Jan–Sep precip. sum
1	4,786	2005–2021	0.55 ±0.28	<0.0007	0.88 ±0.09	<0.0001
1	4,786	2005–2017	0.61 ±0.27	<0.002	0.94 ±0.06	<0.0001
1	4,786	2018–2021	0.86 ±0.21	<0.07	0.93 ±0.11	<0.04
2	4,455	2005–2021	0.85 ±0.12	<0.0001	0.80 ±0.15	<0.0001
3	21,820	2005–2021	0.56 ±0.28	<0.0006	0.67 ±0.23	<0.0001
4	12,761	2005–2021	0.75 ±0.18	<0.0001	0.85 ±0.11	<0.0001
5	10,218	2005–2021	0.76 ±0.18	<0.0001	0.74 ±0.19	<0.0001

Table S2
Summary statistics and F tests comparing A) reference, B) parallel-slopes, and C) full regression models for irrigation water use per irrigated area in SD-6, Wichita County (W. Co), and GMD1. Columns are SSR: sum of squared residuals, df: residual degrees of freedom, RMSR: root-mean-squared residual ($= \sqrt{\mathrm{SSR}/\mathrm{df}}$), F_A: F statistic comparing model B or C to model A, p_A: p value corresponding to F_A, F_B: F statistic comparing model C to model B, p_B: p value corresponding to F_B.

Area	Model	SSR (cm^2)	df	RMSR (cm)	F_A	p_A	F_B	p_B
SD-6	A	274.3	15	4.28				
SD-6	B	66.4	14	2.18	43.8	1.2E-05		
SD-6	C	66.4	13	2.26	20.4	9.9E-05	0.01	0.93
W. Co	A	125.4	15	2.89				
W. Co	B	26.6	14	1.38	51.9	4.5E-06		
W. Co	C	26.4	13	1.43	24.4	4.0E-05	0.12	0.74
GMD1	A	33.7	15	1.50				
GMD1	B	14.7	14	1.02	18.1	8.0E-04		
GMD1	C	14.5	13	1.05	8.7	4.1E-03	0.21	0.65

Table S3
Summary statistics and F tests comparing A) reference, B) parallel-slopes, and C) full regression models for total irrigation water use in SD-6, Wichita County (W. Co), and GMD1. See Table S2 caption for explanation of columns.

Area	Model	SSR (10^{12} m^6)	df	RMSR (10^6 m^3)	F_A	p_A	F_B	p_B
SD-6	A	310.1	15	4.55				
SD-6	B	65.0	14	2.15	52.8	4.1E-06		
SD-6	C	63.2	13	2.21	25.4	3.3E-05	0.36	0.56
W. Co	A	2171.5	15	12.03				
W. Co	B	442.9	14	5.62	54.6	3.4E-06		
W. Co	C	396.1	13	5.52	29.1	1.6E-05	1.54	0.24
GMD1	A	8015.2	15	23.12				
GMD1	B	1935.9	14	11.76	44.0	1.1E-05		
GMD1	C	1330.3	13	10.12	32.7	8.5E-06	5.92	0.03