Kansas Geological Survey

High Plains Aquifer Index Well Program: 2023 Annual Report

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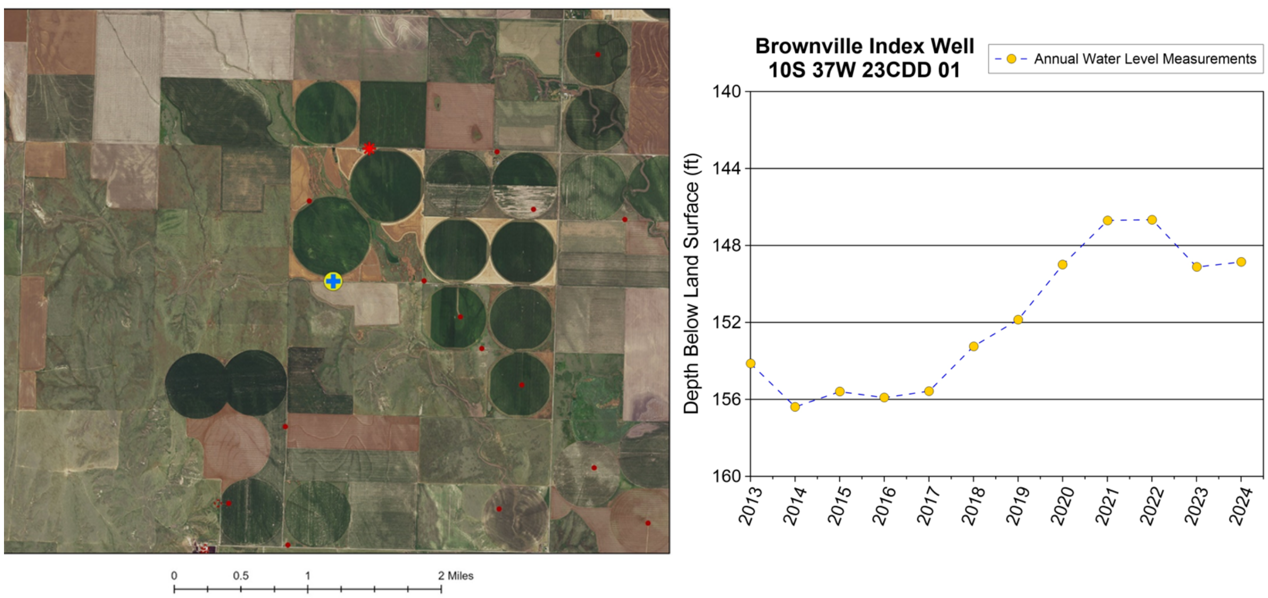

Brownville Index Well – Aerial View and Annual Measurement Hydrograph

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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 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 November of 2023 with the addition of an existing well in GMD5 and in late spring of 2024 with the addition of an existing well in GMD4. The network now consists of 31 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 2024. 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 (Q_{stable}) 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 descriptions in this report, these findings are discussed in previous program reports, KGS publications (Whittemore, Butler, and Wilson, 2023; 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, Bohling et al., 2023; Whittemore, Butler, Bohling et al., 2023).

The focus of activities for the remainder of 2024 and the first half of 2025 will be on the continuation of monitoring at all program wells; continued analysis of hydrographs from all wells; the drilling and installation of equipment for real-time monitoring of one well in Cheyenne County in GMD4 and one well in eastern 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, Bohling et al., 2023; Butler and Johnson, 2024). 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).

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 also has 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 sixteen 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 (Q_{stable}) 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 the second half of 2023 and the first half of 2024 by the addition of an existing well in GMD5 (St. John index well) and an existing well in GMD4 (Brownville index well). 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 here.

This report provides a concise description of conditions as of late spring 2024. 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.

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 (Belpre index well). 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 index well). In mid-May 2021, telemetry equipment was added to the westernmost monitoring well in the SD-6 LEMA (Steiger index 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 (Baalman, Beckman, and Moss index wells) 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 index 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 (Sherman County index well). 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 (Kearny-Finney 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 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 (Larned 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.

In the fall of 2023, we converted an existing monitoring well in Stafford County to an index well (St. John index well). An integrated pressure transducer-datalogger unit and telemetry equipment were placed in the well on November 9, 2023. In late spring of 2024, we converted an existing well in far southeastern Sherman County to an index well (Brownville index well). An integrated pressure transducer-datalogger unit and telemetry equipment were placed in the well on June 25, 2024. 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 31 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.

Percent Change in Aquifer Thickness, Predevelopment to Average 2022-2024, Kansas High Plains Aquifer

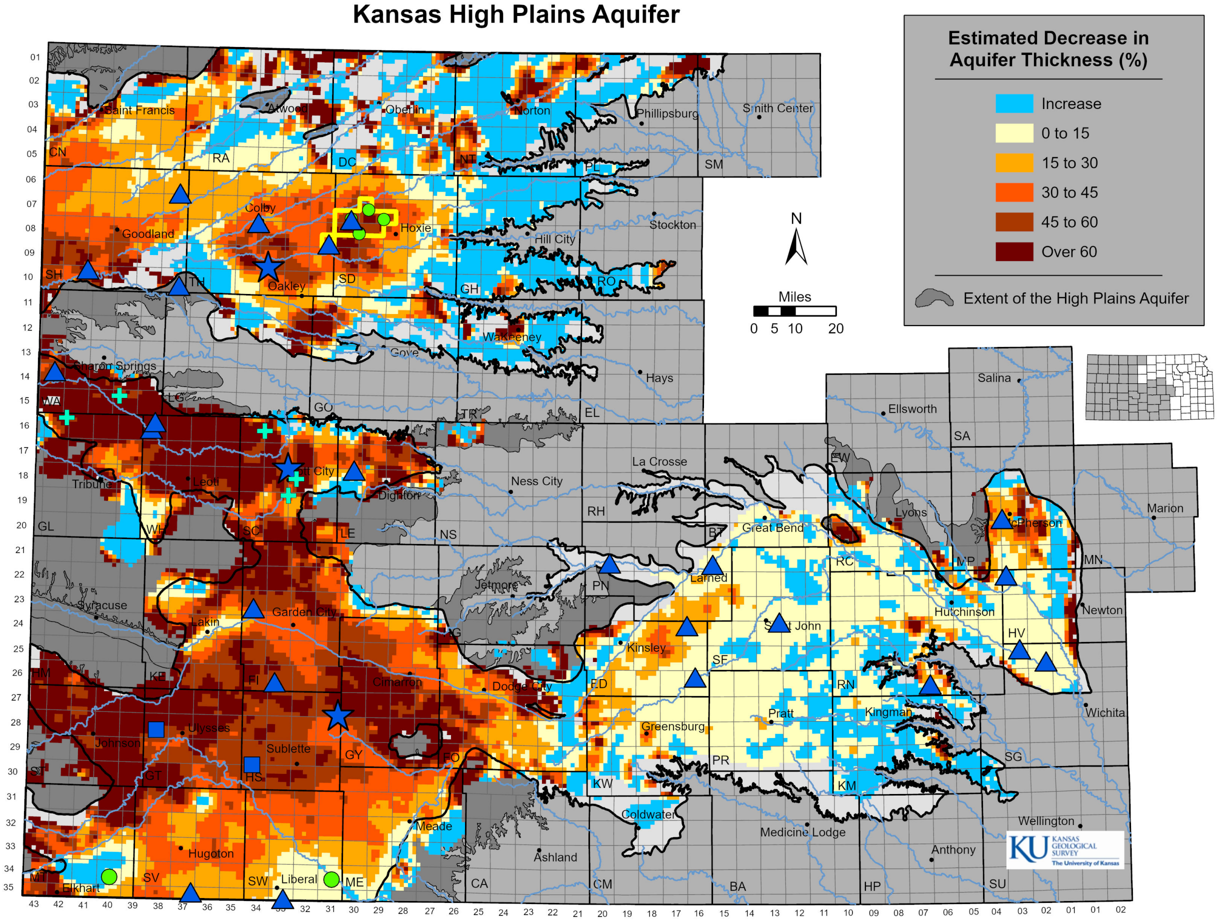

Figure 1—The Kansas portion of the High Plains aquifer, with aquifer and county boundaries shown. Each colored pixel represents one section (1 mi^2), coded for the degree of groundwater depletion from the beginning of large-scale development to the average of conditions in 2022–2024. The blue stars indicate 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 five 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 37 index wells and additional GMD1 expansion wells currently in operation. The duration of monitoring ranges from about 17 years of hourly measurements at the three original index wells to less than one month at the most recently added well. 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 fall of 2023 and late spring of 2024, 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.

Site	2024 WL elev. (ft)[a]	2024 Saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2023 Water Use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Lane	2,768.3	34.3	118	105–115	424	1,042	3,040[b]
Scott	2,823.9	79.7	223	215–225	713	2,295[c]	11,197[d]
Wallace	3,542.3	108.3	394	375–385	680[e]	4,316[e]	12,164[f]
Wichita	3,287.3	29.3	190	175–185	178	1,532	5,866[g]
Wichita 2	3,276.7	38.7	221	189–226	717	2,406	5,603[g]

[a] 2024 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html). Wichita 2 is not part of the annual measurement program; 2024 water-level measurement estimated from sensor data on 01/5/2024 from 0800 to 1700.
[b] Includes 44 ac-ft of municipal water and 2 ac-ft of non-irrigation stock water.
[c] Includes 20 ac-ft of non-irrigation stock water.
[d] Includes 3 ac-ft of industrial water, 942 ac-ft of municipal water, and 408 ac-ft of non-irrigation stock water.
[e] Includes 44 ac-ft of municipal water.
[f] Includes 44 ac-ft of municipal water and 7 ac-ft of non-irrigation stock water.
[g] Includes 51 ac-ft of non-irrigation stock water.

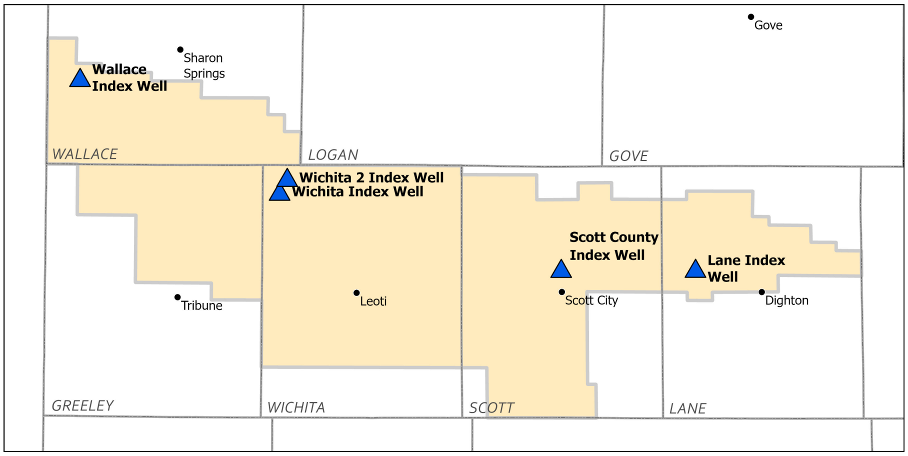

Figure 2—Map of index wells in GMD1; data from these wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

3.1.1 Lane County Index Well

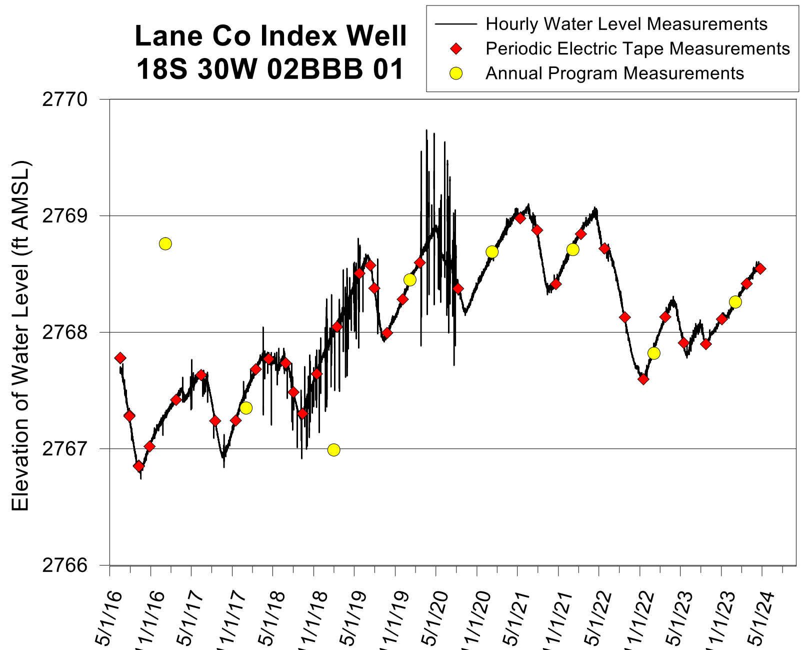

Figure 3—Lane County index well hydrograph—total data run to 4/23/24. A water-level elevation of 2,767 ft corresponds to a depth to water of 85 ft below land surface (lsf). The top of the screen is 105 ft below lsf (elevation of 2,747 ft), and the bottom of the aquifer is 118 ft below lsf (elevation 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 in-field calibration approach described in Butler, Knobbe et al. (2021) has been applied to the transducer data to correct the drift noted in previous annual reports.

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 2023 irrigation season ended on 8/25/23, the earliest ending of the irrigation season since the start of monitoring at the Lane County well (the next earliest was 9/4/2018).
- 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

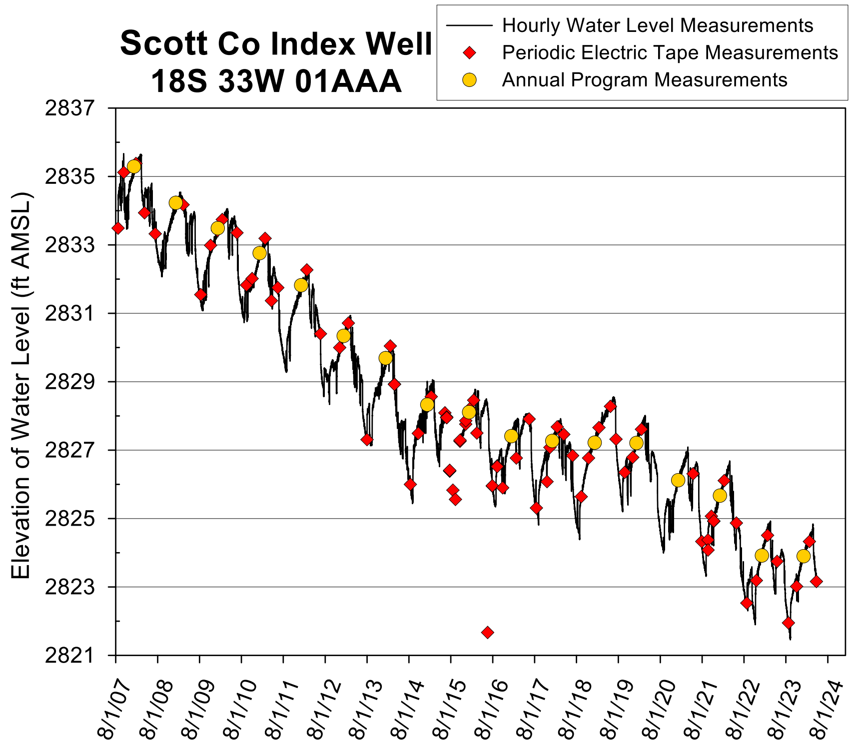

Figure 4—Scott County index well hydrograph—total data run to 4/23/24. A water-level elevation of 2,823 ft corresponds to a depth to water of 144.2 ft below lsf. The top of the screen is 215 ft below lsf (elevation of 2,752.2 ft), and the bottom of the aquifer is 223 ft below lsf (elevation of 2,744.2 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). The in-field calibration approach described in Butler, Knobbe et al. (2021) has been applied to the transducer data to correct for sensor drift.

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 2023 was the lowest of the monitoring period and 0.4 ft below that for 2022.
- Transducer readings are in good agreement with manual measurements after in-field calibration except for one electric-tape measurement that appears to be a transcription error.

3.1.3 Wallace County Index Well

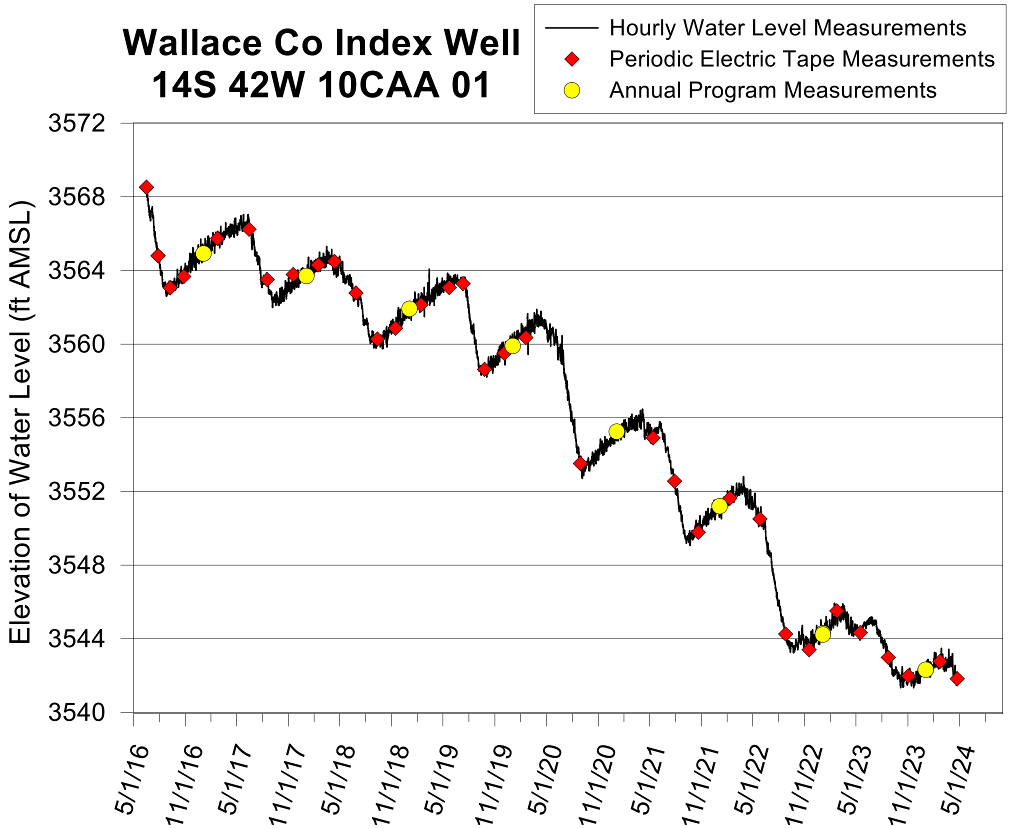

Figure 5—Wallace County index well hydrograph—total data run to 4/23/24. A water-level elevation of 3,544 ft corresponds to a depth to water of 284 ft below lsf. The top of the screen is 375 ft below lsf (elevation of 3,453 ft), and the bottom of the aquifer is 394 ft below lsf (elevation of 3,434 ft). The screen terminates 9 ft above the bottom of the aquifer. The in-field calibration approach described in Butler, Knobbe et al. (2021) has been applied to the transducer data to correct for sensor drift.

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 2023 maximum water level was 21.0 ft below that of 2017 for an average decline rate of 3.5 ft/yr.
- 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

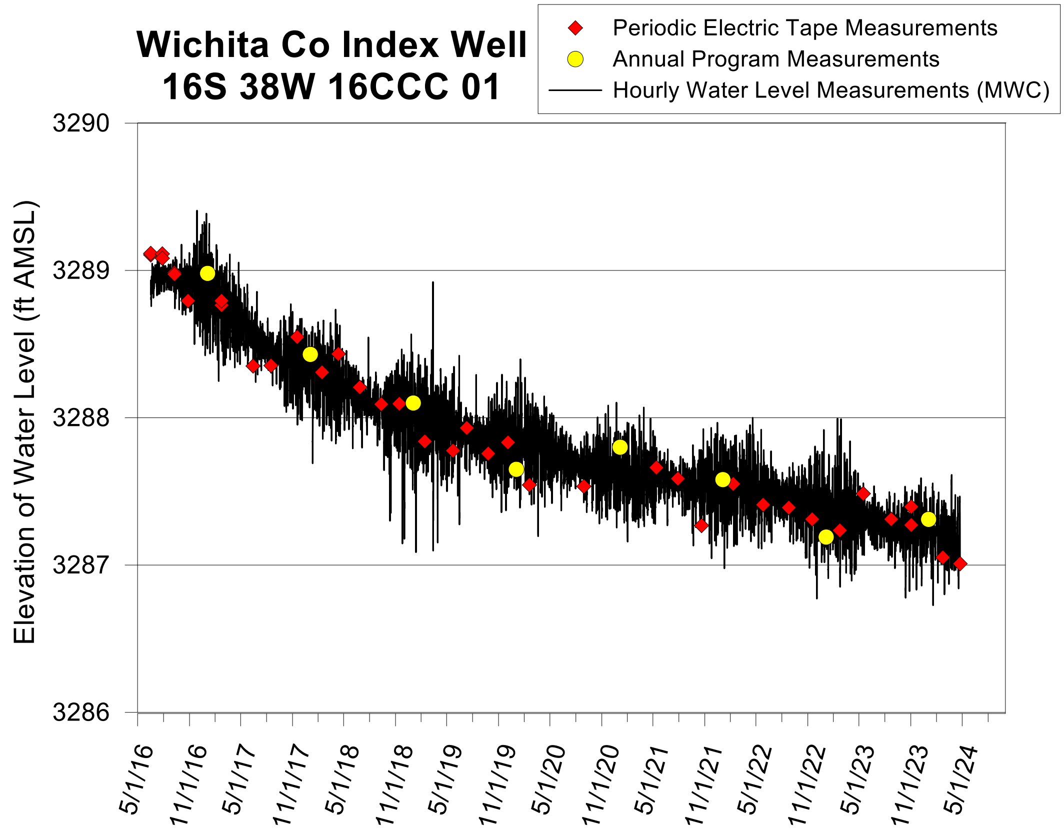

Figure 6—Wichita County index well hydrograph—total data run to 4/23/24. A water-level elevation of 3,288 ft corresponds to a depth to water of 160 ft below lsf. The top of the screen is 175 ft below lsf (elevation of 3,273 ft), and the bottom of the aquifer is 190 ft below lsf (elevation of 3,258 ft). The screen terminates 5 ft above the bottom of the aquifer. The in-field calibration approach described in Butler, Knobbe et al. (2021) has been applied to the transducer data to correct for sensor drift.

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 good agreement with manual measurements after in-field calibration. 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

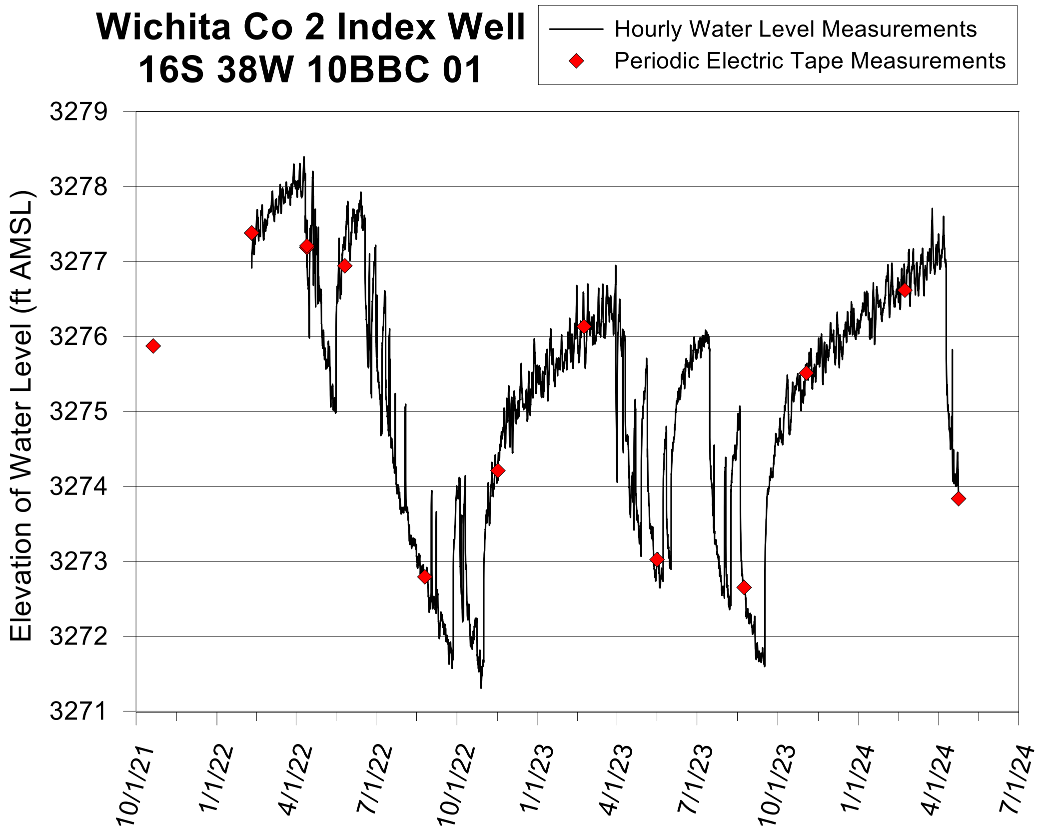

Figure 7—Wichita County 2 index well hydrograph—total data run to 4/23/24. A water-level elevation of 3,277 ft corresponds to a depth to water of 182 ft below lsf. The top of the screen is 189 ft below lsf (elevation of 3,270 ft), and the screen extends to the bottom of the well. The aquifer bottom is estimated to be 221 ft below lsf (elevation of 3,238 ft); the well bottom is 226.2 ft below lsf. The in-field calibration approach described in Butler, Knobbe et al. (2021) has been applied to the transducer data to correct for sensor drift.

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 after in-field calibration.

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	2024 WL elev. (ft)[a]	2024 Saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2023 Water Use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Harvey	1,406.1	157.1	206	198–208	873	4,450[b]	15,210[c]
McPherson	1,398.7	88.7	184	139–183	1,704[d]	6,525[e]	14,165[f]
Mount Hope	1,406.2	158.0	173	166–176	1,079	3,286[g]	23,515[h]
Pretty Prairie	1,543.4	45.4	71	61–71	755[i]	2,782[j]	9,062[j]
Bentley	1,370.2	205.2	216	23–33	1,249	3,793[k]	25,932[l]

[a] 2024 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html); Bentley is not part of the annual measurement program; 2024 water-level measurement estimated from sensor data on 1/9/24 from 0800 to 1700.

[b] Includes 238 ac-ft of municipal water.

[c] Includes 238 ac-ft of municipal water and 213 ac-ft of non-irrigation recreation water.

[d] Includes 1,447 ac-ft of municipal water.

[e] Includes 2,739 ac-ft of municipal water, 2,532 ac-ft of industrial water, and 2 ac-ft of non-irrigation stock water.

[f] Includes 3,205 ac-ft of municipal water, 2,801 ac-ft of industrial water, 2 ac-ft of non-irrigation stock water, 174 ac-ft of non-irrigation recreation water, and 1,166 ac-ft of other water.

[g] Includes 10 ac-ft of non-irrigation recreation water.

[h] Includes 3,896 ac-ft of municipal water, 9 ac-ft of domestic water, 8 ac-ft of industrial water, 153 ac-ft of other water, and 500 ac-ft of non-irrigation recreation water.

[i] Includes 4 ac-ft of municipal water.

[j] Includes 80 ac-ft of municipal water.

[k] Includes 66 ac-ft of municipal water.

[l] Includes 9,146 ac-ft of municipal water, and 255 ac-ft of industrial water.

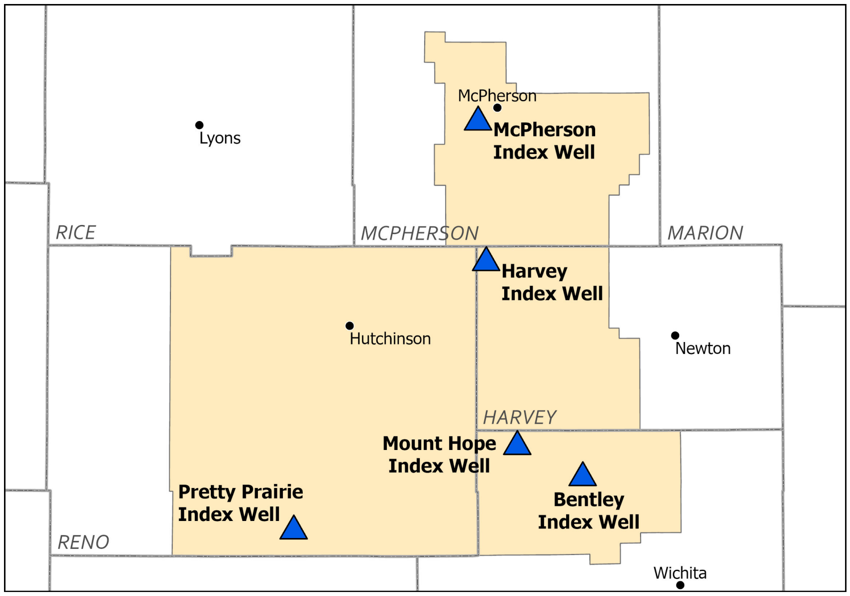

Figure 8—Map of index wells in GMD2; data from these wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_ program/index.shtml).

3.2.1 Bentley Index Well

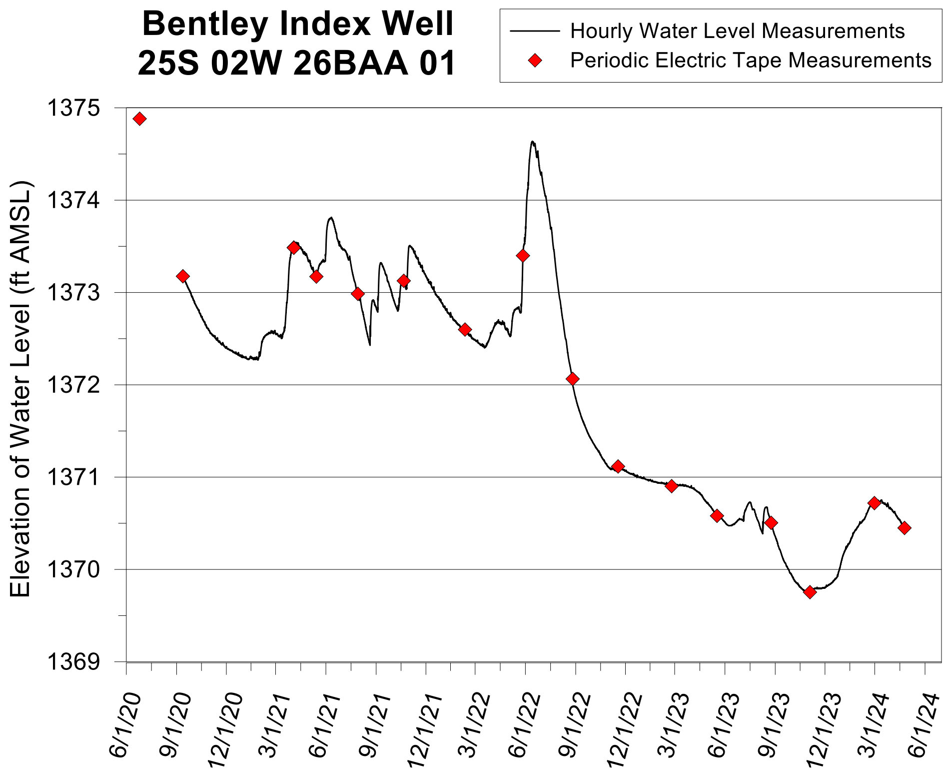

Figure 9—Bentley index well hydrograph—total data run to 4/24/24. A water-level elevation of 1,373 ft corresponds to a depth to water of 8 ft below lsf. The top of the 10 ft screen is 23 ft below lsf (elevation of 1,358 ft). The bottom of the aquifer is approximately 216 ft below lsf (elevation of 1,165 ft), and the bottom of the well is 33 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

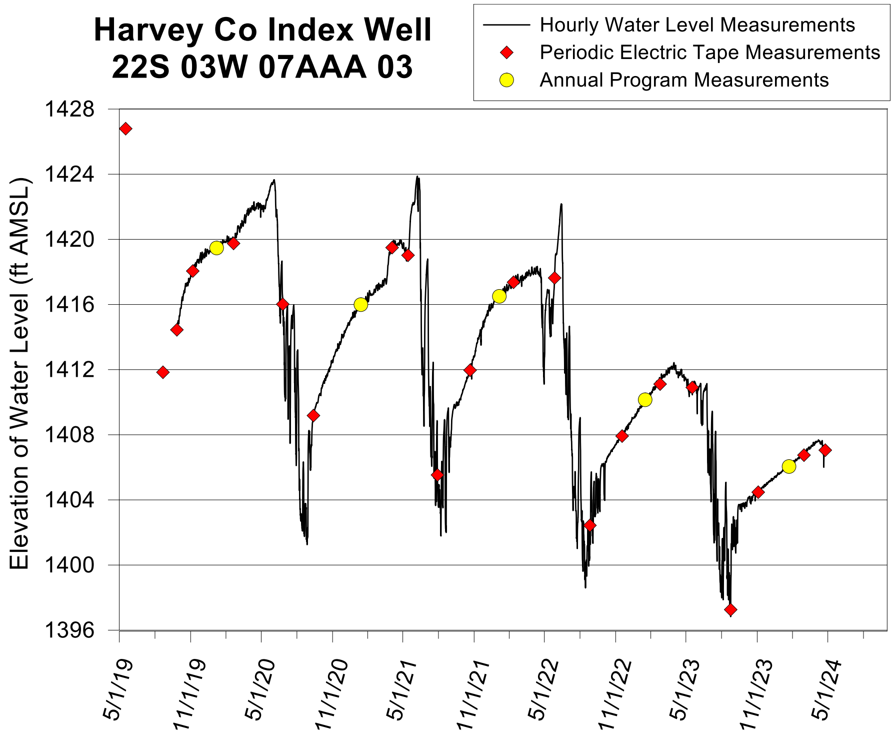

Figure 10—Harvey County index well hydrograph—total data run to 4/24/24. A water-level elevation of 1,408 ft corresponds to a depth to water of 47 ft below lsf. The top of the 10 ft screen is 198 ft below lsf (elevation of 1,257 ft), and the bottom of the aquifer is 206 ft below lsf (elevation of 1,249 ft). The in-field calibration approach described in Butler, Knobbe et al. (2021) has been applied to the transducer data to correct for sensor drift.

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 (water levels never stabilize).
- Abrupt rises in water level during the recovery period are likely produced by precipitation.
- The linear responses during the 2022-2023 and 2023-2024 recovery periods indicate little precipitation and a steady rate of recharge during those periods. The difference in slopes of the linear responses indicate that the rate of recharge differs between the two recovery periods.
- The agreement between manual measurements and the transducer is good after in-field calibration.

3.2.3 McPherson County Index Well

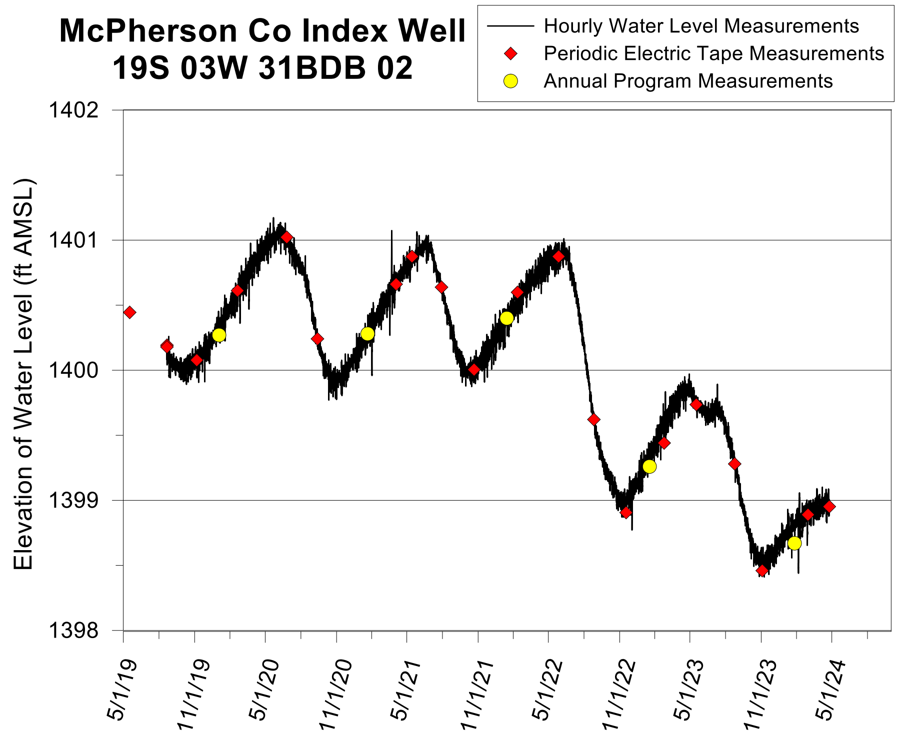

Figure 11—McPherson County index well hydrograph—total data run to 4/24/24. A water-level elevation of 1,400 ft corresponds to a depth to water of 94 ft below lsf. The top of the 44 ft screen is 139 ft below lsf (elevation of 1,355 ft), and the bottom of the screen is 183 ft below lsf (elevation of 1,311 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 (water levels never stabilize).
- 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.
- 2023 total water use (1 and 2 mi radii centered on well) was the highest of any of the index wells; unlike at most of the index wells, where irrigation use dominates, there is a significant amount of industrial and municipal use at the McPherson County index well.
- The 2023 minimum water level was the lowest observed during the monitoring period and 0.4 ft below the 2022 minimum.

3.2.4 Mount Hope Index Well

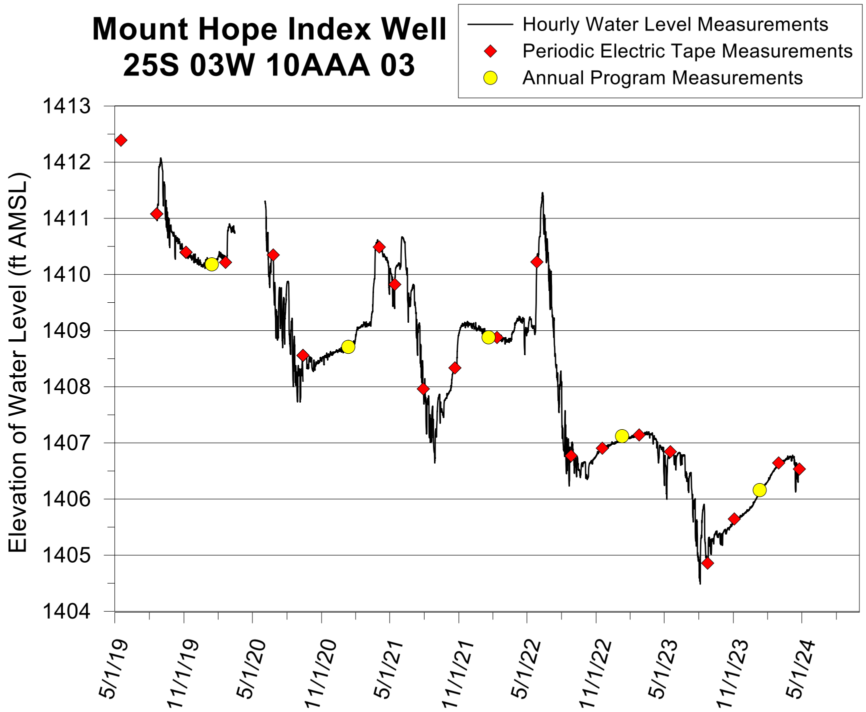

Figure 12—Mount Hope index well hydrograph—total data run to 4/24/24. A water-level elevation of 1,410 ft corresponds to a depth to water of 11.4 ft below lsf. The top of the 10 ft screen is 163 ft below lsf (elevation of 1,258.4 ft), and the bottom of the aquifer is 173 ft below lsf (elevation of 1,248.4 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 other years as a result of drought conditions.
- Transducer readings are in good agreement with manual measurements.

3.2.5 Pretty Prairie Index Well

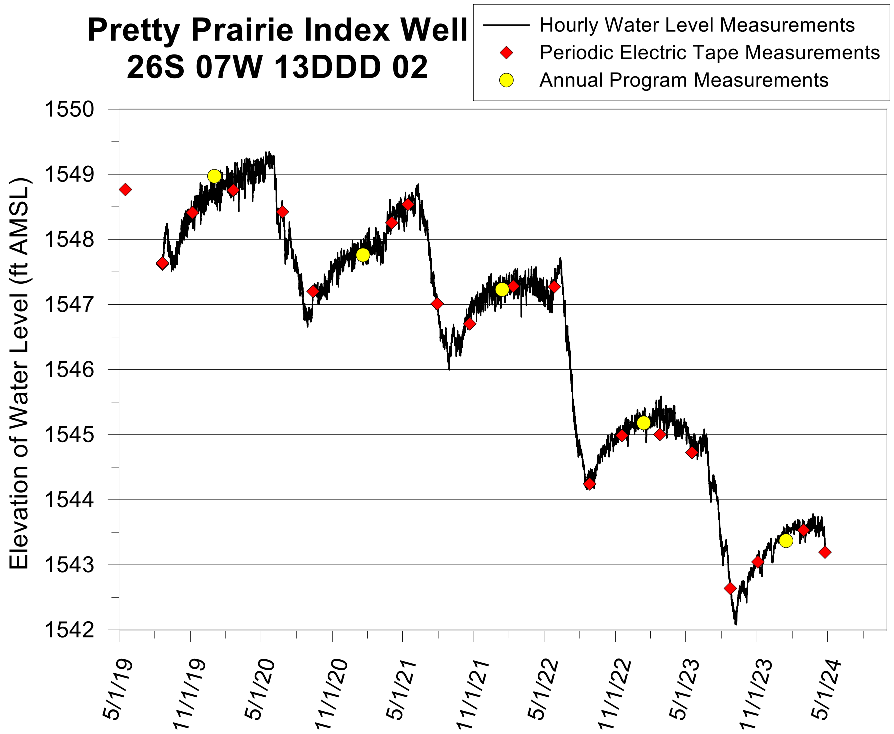

Figure 13—Pretty Prairie index well hydrograph—total data run to 4/24/24. A water-level elevation of 1,545 ft corresponds to a depth to water of 24 ft below lsf. The top of the 10 ft screen is 61 ft below lsf (elevation of 1,508 ft), and the bottom of the screen and aquifer is 71 ft below lsf (elevation 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 late 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 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), the 2022 annual report (Butler, Whittemore et al., 2023), 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	2024 WL elev. (ft)[a]	2024 Saturated thickness (ft)	Bedrock depth (ft below land surface)[b]	Screened interval (ft below land surface)[b]	2023 Water Use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Cimarron 210	2,474.18	290.21	345	200–210	23	23	8,395[c]
Haskell	2,514.85	109.98	433	420–430	428	4,898[d]	29,358[e]
Hugoton 495[f]	2,893.53	428.59	635	485–495	488	2,448	36,384[g]
Kearny-Finney	2,774.85	173.83[h]	360[h]	70–266[i]	1,590	4,813	30,324[j]
Liberal 436[f]	2,649.48	403.48	576	426–436	0.44[k]	1,048[l,m]	30,378[n,o]
Rolla 366	3,184.85	208.84	399	356–366	317[p]	1,1519[q]	8,925[r]
Satanta - HPA	2,600.73	150.73	525	515-525	114	3,200	22,437[s]
Satanta – Dakota	2,597.27	242.27	620	600-620			
Ulysses – HPA	2,960.51	225.51	445	425-445	1,339	3,314[t]	13,227[u]
Ulysses - Dakota	2,844.77	244.77	580	560-580			
Willis Tech Farm	2,619.60	181.61	502	262–482	514	4,237[v]	30,722[w]

[a] 2024 annual tape water-level measurements from WIZARD database.
[b] Measurements for the Cimarron, Hugoton, Liberal, and Rolla wells from table 2 in McMahon (2001).
[c] Includes 25 ac-ft of non-irrigation stock water.
[d] Includes 3 ac-ft of industrial water, and 8 ac-ft of municipal water.
[e] Includes 3 ac-ft of industrial water, and 8 ac-ft of municipal water, and 16 ac-ft non-irrigation of stock water.
[f] Wells originally on USGS telemetry systems; those systems were removed in 2017 because of a lack of funding.
[g] Includes estimates of water use in Oklahoma based on “permitted” quantities, 17,989 ac-ft.
[h] Based on logs of nearby wells to bedrock.
[I] Measurements estimated from borehole camera log.
[j] Includes 72 ac-ft of industrial water, 186 ac-ft of municipal water, and 443 ac-ft of non-irrigation stock water.
[k] Includes 0.44 ac-ft of industrial water.
[l] Includes estimates of water use in Oklahoma based on “permitted” quantities, 675 ac-ft.
[m] Includes 318 ac-ft of municipal water for the city of Liberal.
[n] Includes estimates of water use in Oklahoma based on “permitted” quantities, 20,909 ac-ft.
[o] Includes 2,819,009 ac-ft of industrial water, 2,503 ac-ft of municipal water, 44 ac-ft of recreational water, and 564 ac-ft of non-irrigation stock water.
[p] Includes 31 ac-ft of non-irrigation stock water.
[q] Includes 92 ac-ft of non-irrigation stock water.
[r] Includes 268 ac-ft of non-irrigation stock water, and 83 ac-ft of municipal water.
[s] Includes 262 ac-ft of municipal water and 343 ac-ft of non-irrigation stock water.

[t] Includes 3 ac-ft of industrial water.
[u] Includes 45 ac-ft of industrial water and 658 ac-ft of municipal water.
[v] Includes 7 ac-ft of non-irrigation stock water.
[w] Includes 676 ac-ft of industrial water and 7 ac-ft of non-irrigation stock water.

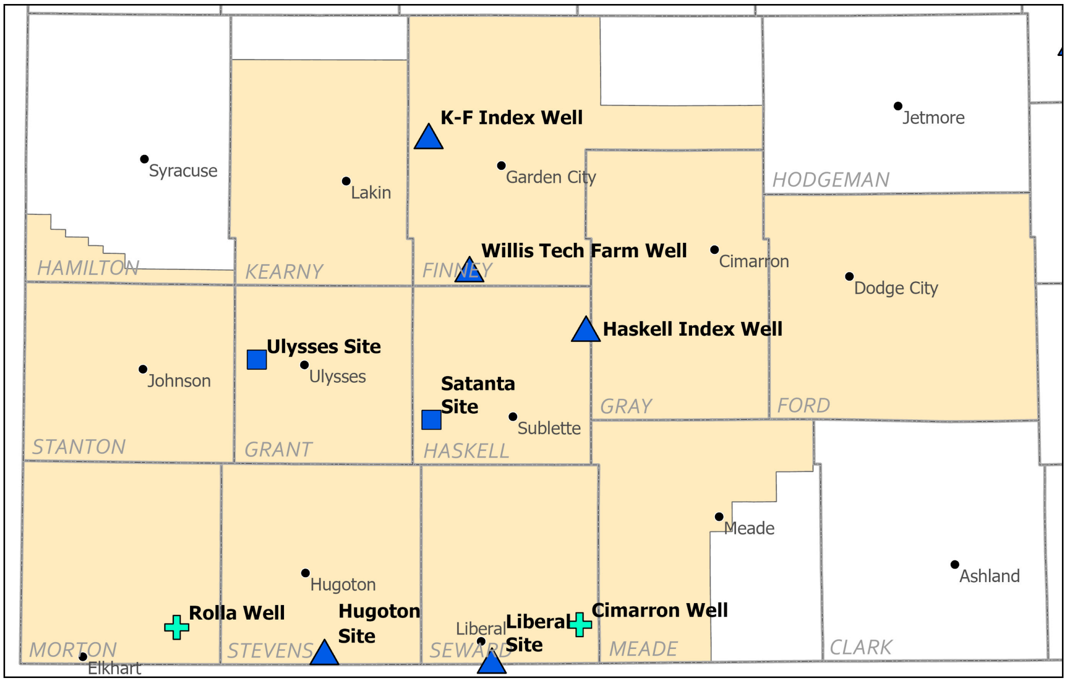

Figure 14—Map of index wells in GMD3. Triangles and squares designate wells with telemetry equipment, whereas plus signs designate wells without telemetry equipment. Data from wells with telemetry equipment can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml); 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

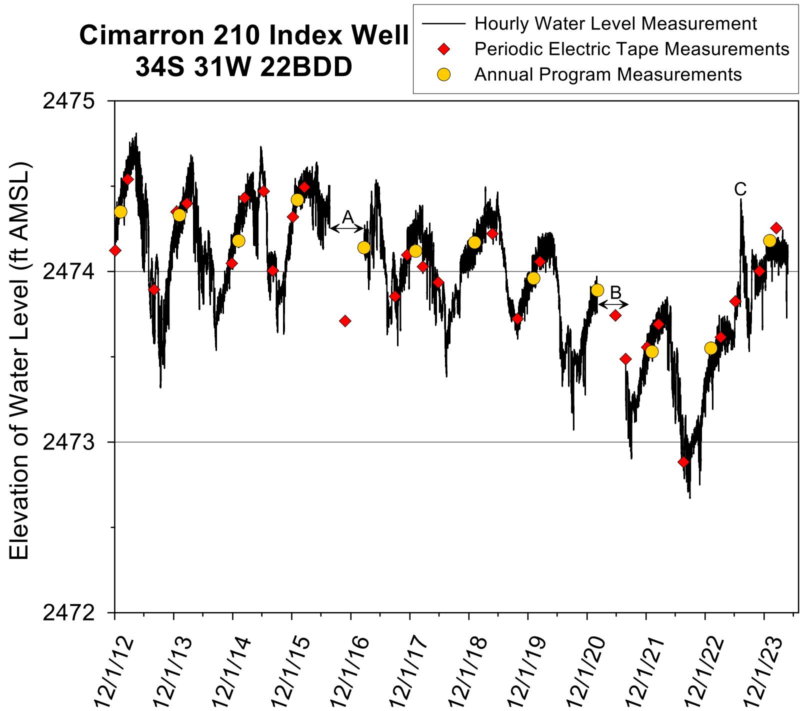

Figure 15—Cimarron 210 index well hydrograph—total data run to 4/26/24. A water-level elevation of 2,474 ft corresponds to a depth to water of 55 ft below lsf. The top of the 10 ft screen is 200 ft below lsf (elevation of 2,329 ft), and the bottom of the aquifer is 345 ft below lsf (elevation of 2,184 ft); A-C defined in text.

Major Points

- The hydrograph form and small response to pumping, despite a 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-level rise in early July 2023 (C) appears to be an episodic recharge event; this is the only definitive example of episodic recharge in GMD3 and only the second observed in the index wells of western Kansas.
- 2023 water use within a 2 mi radius of the well is the lowest of any of the index wells.
- Water level has declined 1.8 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

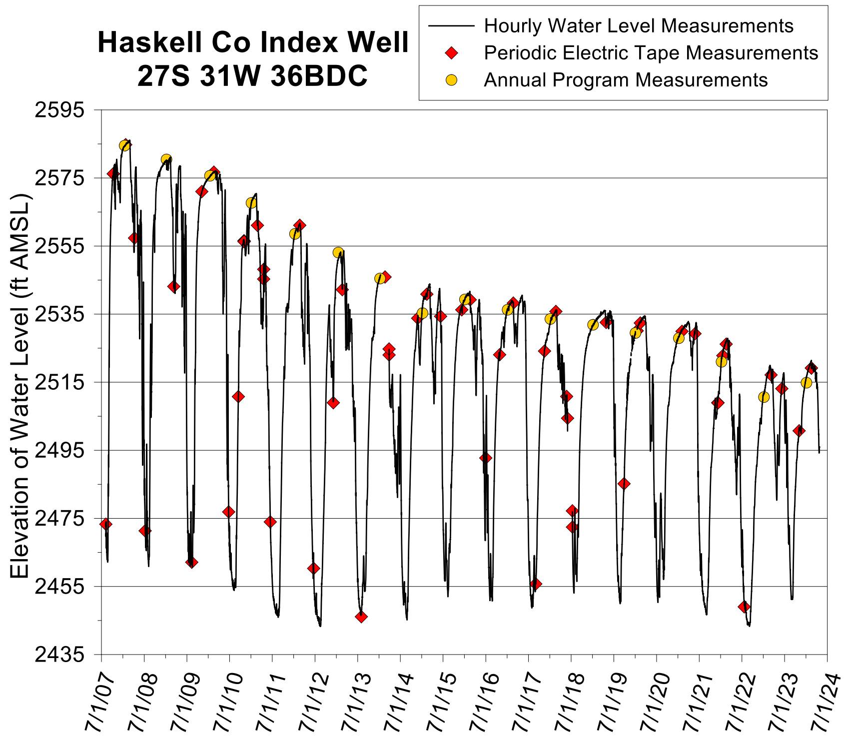

Figure 16—Haskell County index well hydrograph—total data run to 4/25/24. A water-level elevation of 2,455 ft corresponds to a depth to water of 382.8 ft below lsf. The top of the screen is 420 ft below lsf (elevation of 2,417.8 ft), and the bottom of the aquifer is 433 ft below lsf (elevation of 2,404.8 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 (70–120 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 (2020–2022) 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 2023 annual water-level change (+4.22 ft) was the second, and largest, annual water-level increase since the start of monitoring (2007) at the Haskell index well.
- 2023 irrigation water use (2 mi radius centered on well) was the highest of any of the index wells.
- Transducer readings are in reasonable agreement with manual measurements.

3.3.3 Hugoton Site

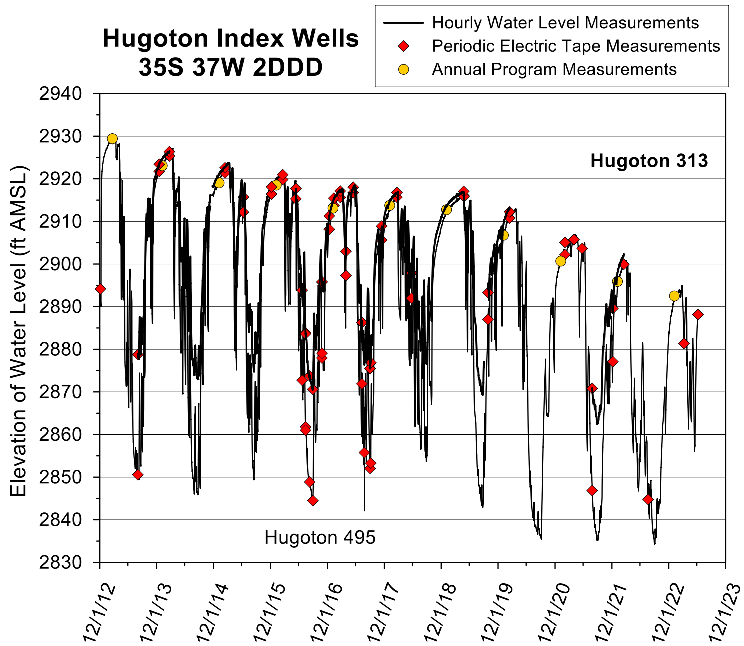

Figure 17—Hydrographs of Hugoton index wells—total data run to 4/25/24 for both wells. A water-level elevation of 2,900 ft corresponds to a depth to water of 200 ft below lsf. For the Hugoton 495 well, the top of the 10 ft screen is 485 ft below lsf (elevation of 2,615 ft). For the Hugoton 313 well, 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 was replaced on 11/9/23.

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 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 76.0 ft since January 2000 (decline rate of 3.2 ft/yr); see 2016 annual report (Butler, Whittemore et al., 2017) for further details.
- The 2023 annual water-level change (+1.02 ft) was the second, and largest, annual water-level increase since the start of monitoring (2012) at the Hugoton 495 index well.
- Transducer readings are in good agreement with manual measurements.

3.3.4 Kearny-Finney Index Well

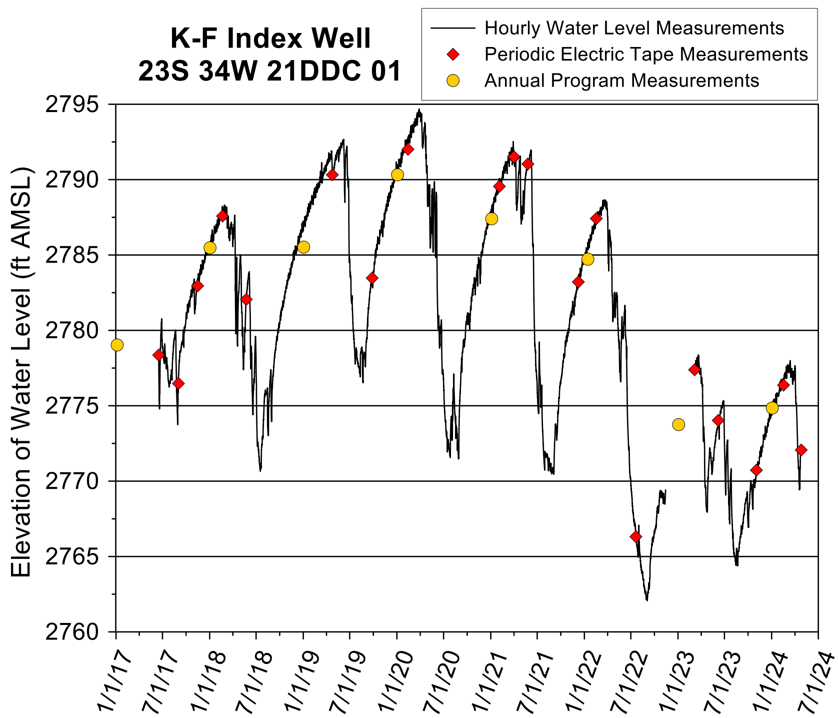

Figure 18—Kearny-Finney (K-F) index well hydrograph—total data run to 4/25/24. A water-level elevation of 2,775 ft corresponds to a depth to water of 186 ft below lsf. Nominal bottom of well is 300 ft below lsf (elevation of 2,661 ft), but the well is currently filled with sediments to 266 ft below lsf (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 63.8 ft since January 2008 (-4.0 ft/yr); the 2023 water-level rise (+1.1 ft) was the third largest since 2008.
- Minimum water-level elevation for 2023 was 2.3 ft higher than that of 2022, which was the second increase since the start of monitoring (2017).
- 2023 irrigation water use (1 mi radius centered on well) was the highest of any of the index wells.
- 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

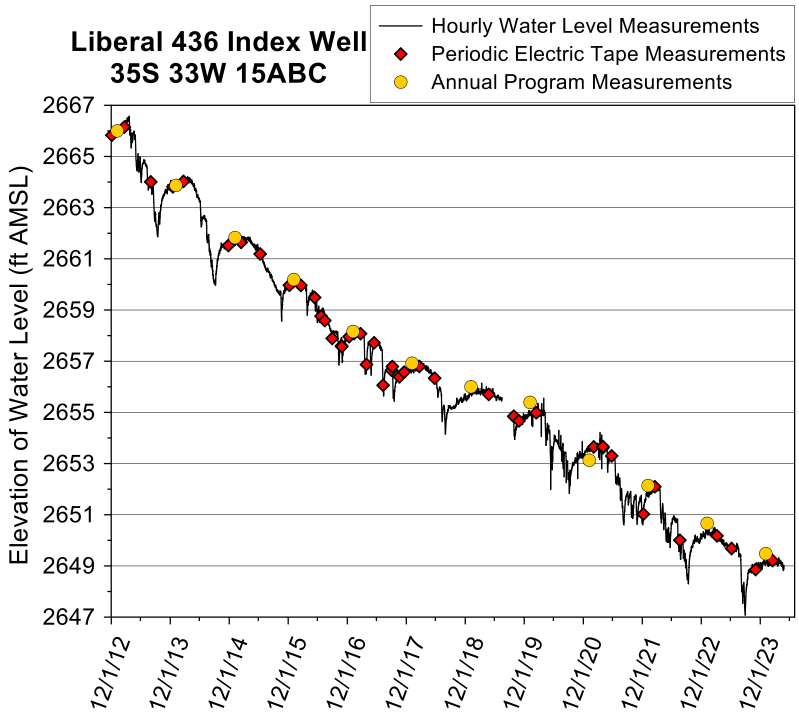

Figure 19— Liberal 436 index well hydrograph—total data run to 4/26/24. A water-level elevation of 2,649 ft corresponds to a depth to water of 172 ft below lsf. The top of the 10 ft screen is 426 ft below lsf (elevation of 2,395 ft). Sensor failed on July 6, 2019; a new sensor was installed on September 27, 2019.

Major Points

- One well is monitored in a four-well nest. Formerly, Liberal 160 well also was monitored but that stopped on 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 dropped every year since January 2000 for a total of 33.8 ft (decline rate of 1.4 ft/yr).
- 2023 total water use (1 mi radius centered on well) was the lowest of any of the index wells.
- 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

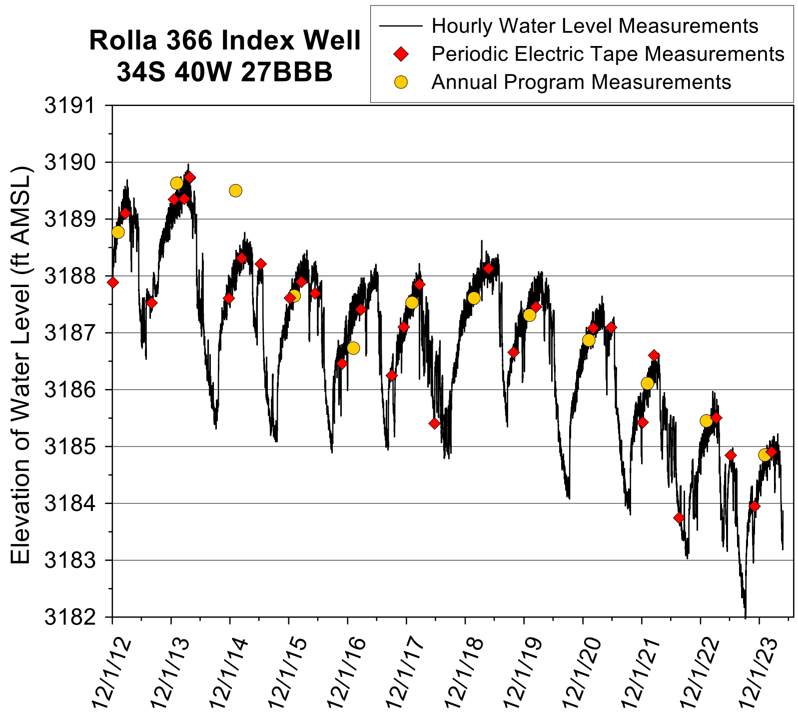

Figure 20—Rolla 366 index well hydrograph—total data run to 4/25/24. A water-level elevation of 3,185 ft corresponds to a depth to water of 190 ft below lsf. The top of the 10 ft screen is 356 ft below lsf (elevation of 3,019 ft), and the bottom of the aquifer is 399 ft below lsf (elevation of 2,976 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 2023 was the lowest since monitoring began in late 2012.
- The water level has declined 12.0 ft since January 2000 (decline rate of 0.5 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

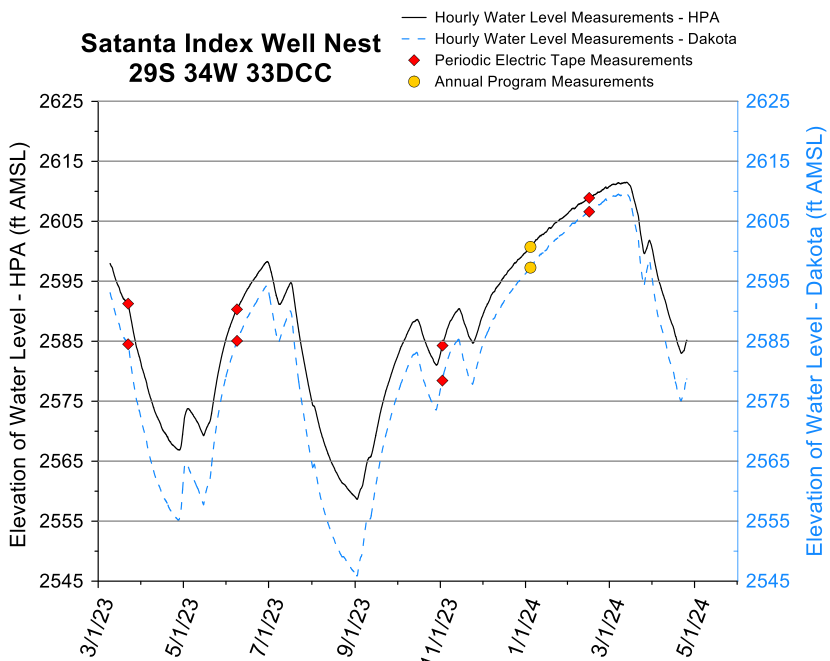

Figure 21—Satanta site hydrographs—total data run to 4/25/24. A water-level elevation of 2,580 ft corresponds to a depth to water of 400 ft below lsf. The top of the 20 ft screen in the HPA is 500 ft below lsf (elevation of 2,480 ft), and the top of the 20 ft screen in the Dakota is 600 ft below lsf (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 effect of nearby pumping wells. Additional work will be done later this year to further assess conditions in both 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

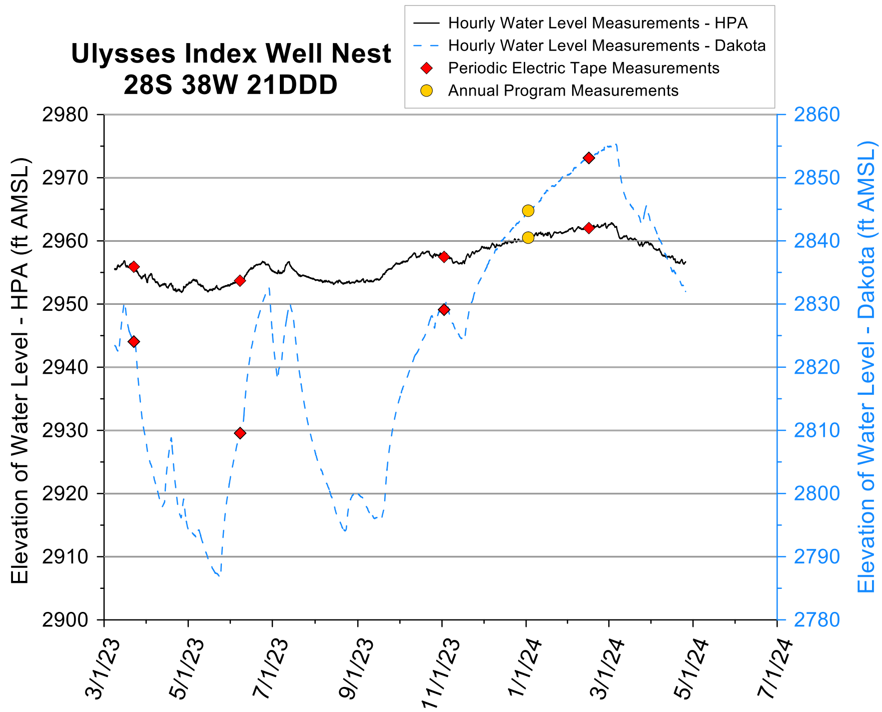

Figure 22—Ulysses site hydrographs—total data run to 4/25/24. For the HPA well, a water-level elevation of 2,955 ft corresponds to a depth to water of 225 ft below lsf. For the Dakota well, a water-level elevation of 2,800 ft corresponds to a depth to water of 380 ft below lsf. The top of the 20 ft screen 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 effect of nearby pumping wells. Additional work will be done later this year to further assess conditions in both 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

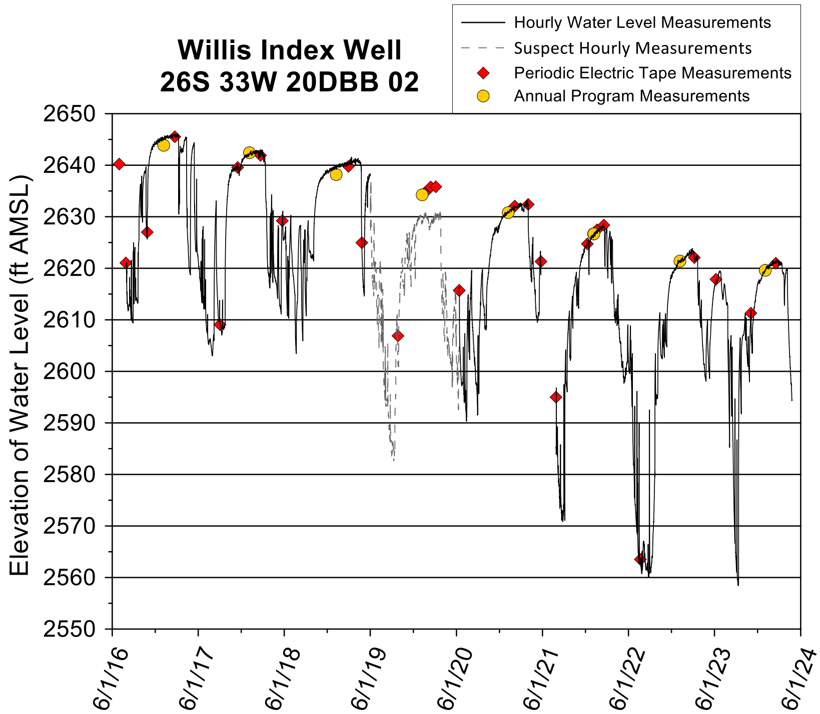

Figure 23—Willis Water Technology Farm index well hydrograph—total data run to 4/25/24. A water-level elevation of 2,620 ft corresponds to a depth to water of 320 ft below lsf. The top of the 220 ft screen is 262 ft below lsf (elevation of 2,678 ft), and the bottom of the aquifer is 502 ft below lsf (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 and sensor ceased operating on 5/25/21; repaired cable and sensor were installed on 7/28/21.

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 22.8 ft since January 2018, a rate of decline of approximately 3.8 ft/year. The minimum water level for 2023 was the lowest since the start of monitoring (2016).
- 2023 total water use (5 mi radius centered on well) was the highest of any of the index wells; virtually all of the water was used for irrigation (97.8%).
- 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

Ten index wells are located in GMD4, seven of which have telemetry equipment that allows real-time viewing of data (fig. 24). 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. The Brownville index well began operating in June 2024. Table 4 summarizes characteristics of these 10 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	2024 WL elev. (ft)[a]	2024 Saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2023 Water Use (ac-ft) 1 mi radius circle	2 mi radius circle	5 mi radius circle
Brownsville	3,210.0	111.0	260	202-262	730	1,652	2,732[b]
Colby	3,021.8	94.8[c]	250–300	156–175	433[d]	2,021[e]	8,596[f]
SD-6 Baalman	2,707.4	72.4	262	260–270	498	2,044	11,964[g]
SD-6 Beckman[h]	2,677.2[h]	[i]	[i]	[i]	785	2,278[j]	11,055[k]
SD-6 Moss[h]	2,622.7[h]	49.7	243	205–245	142	1,778	11,619[l]
SD-6 Seegmiller	2,737.0	69.0	265	225–265	560	2,041	12,482[m]
SD-6 Steiger	2,848.2[n]	60.2	177	145–185	133	1,028[o]	8,777[p]
Sherman	3,613.0	142.0	323	310–320	1,039	2,445	8,897[q]
Sherman 2[g]	3364.7	115.7	275	240-280	126	490	4,043[r]
Thomas	2,967.1	63.7	284	274–284	925	2,467	10,708

[a] 2024 annual tape water-level measurements from WIZARD database.
[b] Includes 16 ac-ft of non-irrigation stock water.
[c] Based on bedrock depth of 250 ft below lsf.
[d] Includes 281 ac-ft of municipal water.
[e] Includes 1,065 ac-ft of municipal water and 342 ac-ft of other water.
[f] Includes 1,216 ac-ft of municipal water, 342 ac-ft of other water, and 21 ac-ft of non-irrigation stock water.
[g] Includes 798 ac-ft of non-irrigation stock water.
[h] Not an annually measured index well; 2024 water-level measurements estimated from sensor data on 01/4/2024 from 0800 to 1700 at Beckman, Moss, and Sherman 2.
[i] Well construction information not available.
[j] Includes 312 ac-ft of non-irrigation stock water.
[k] Includes 753 ac-ft of non-irrigation stock water.
[l] Includes 639 ac-ft of non-irrigation stock water, 4 ac-ft of industrial water, and 336 ac-ft of municipal water.
[m] Includes 641 ac-ft of non-irrigation stock water.
[n] Annual measurement on 1/2/2024 is likely in error. Water-level elevation estimated from transducer data on 1/2/2024 from 0800 to 1700.
[o] Includes 34 ac-ft of non-irrigation stock water.
[p] Includes 55 ac-ft of non-irrigation stock water.
[q] Includes 93 ac-ft of recreational water.
[r] Includes 146 ac-ft of non-irrigation stock water.

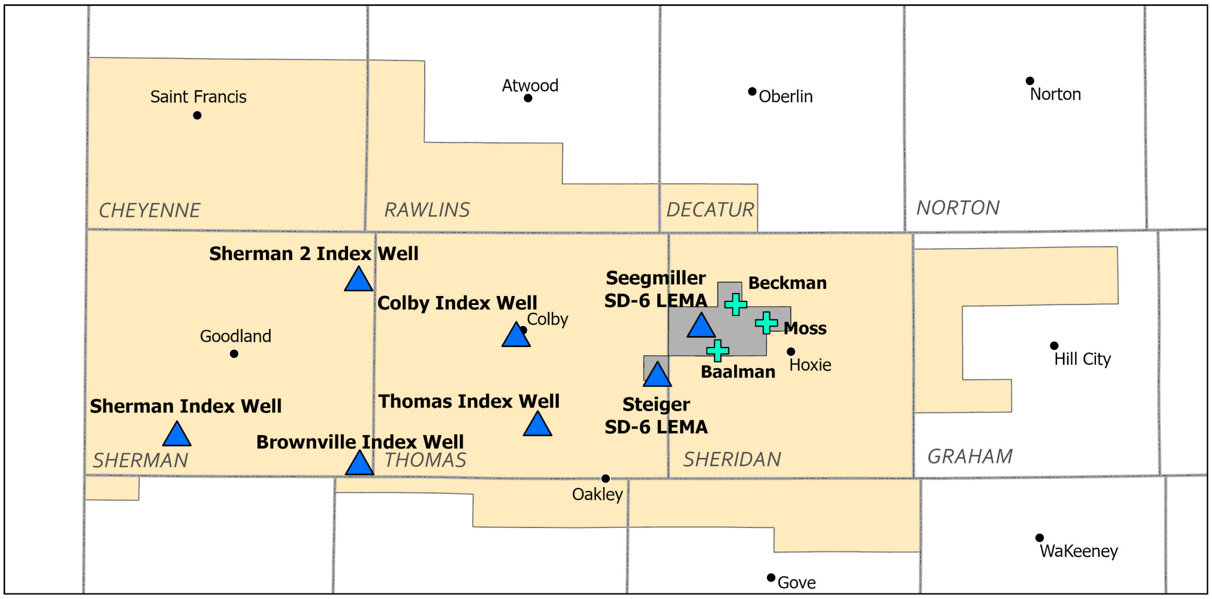

Figure 24—Map of index wells in GMD4. Triangles designate wells with telemetry equipment, and plus signs designate wells without telemetry equipment. Data from wells with telemetry equipment can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml); data from wells without telemetry equipment are periodically downloaded (typically quarterly) and posted on the KGS website. Gray shaded area is the Sheridan-6 LEMA.

3.4.1 Brownville Index Well

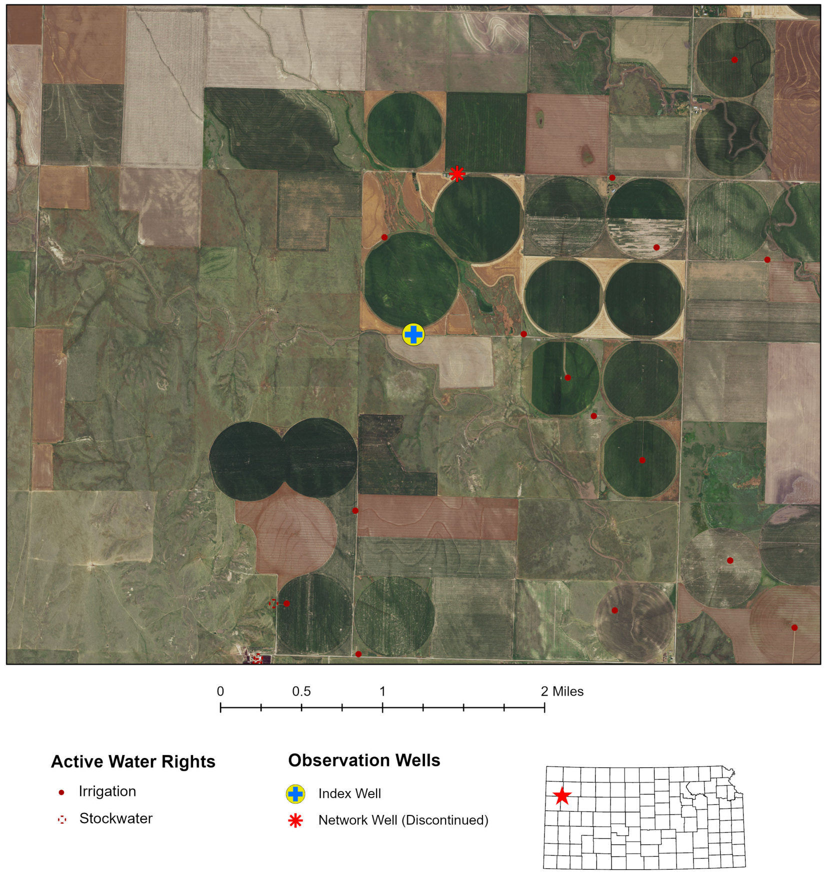

Figure 25—Aerial view of the Brownville index well and nearby points of diversion.

Figure 25 is an aerial view of the Brownville index well site (T. 10 S., R. 37 W., 23 CDD 01) at a scale that shows the site of the index well, nearby wells with active water rights, and tributaries to the North Fork of the Smoky Hill River.

An integrated pressure-transducer and datalogger unit and telemetry equipment were installed on June 25, 2024. Since 2013, the well has been part of the annual water-level measurement program. Figure 26 shows the annual program hydrograph for the Brownville index well.

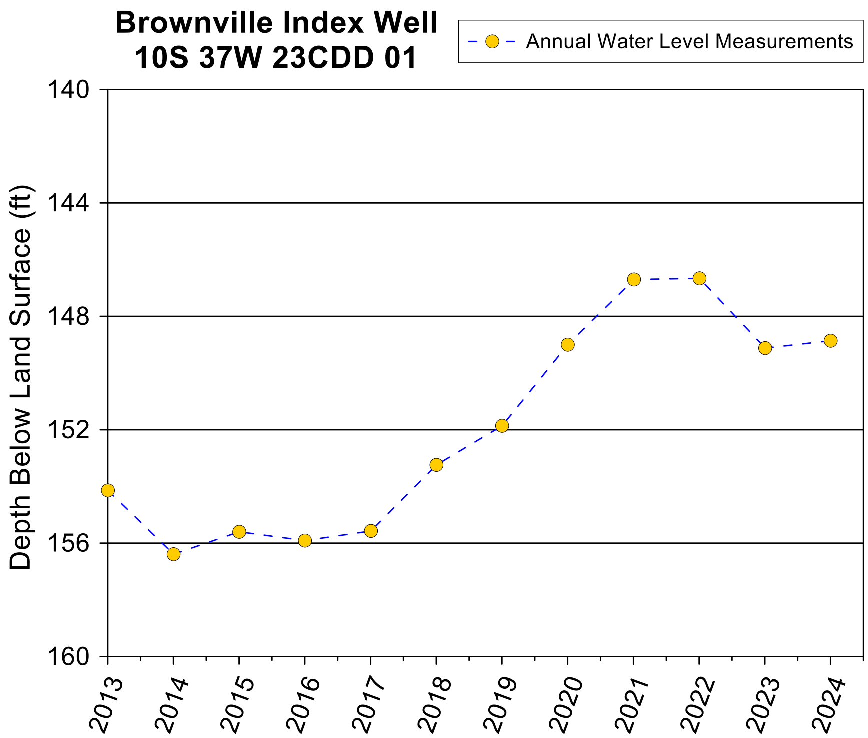

Figure 26—Brownville index well hydrograph—annual measurements since 2013. Measurements were taken each year between January 2nd and 4th. Total depth of well is 262 ft below lsf. The screened interval extends from 202 to 262 ft below lsf, and the base of the aquifer is 260 ft below lsf.

Major Points

- The 8.9 ft increase between 2017 and 2021 is the largest increase observed in any index well in western Kansas. Unlike the Steiger index well, which had a large increase (>7.5 ft in 2018 and 2019) but then declined to near starting conditions over the next two years, the Brownville index well has only declined 2.5 ft (all in 2022) since 2021.
- 2023 total water use (5 mi radius centered on well) was the lowest of any of the index wells.
- The driver of the large water-level rise has yet to be determined. Hourly monitoring should help clarify possible drivers.

3.4.2 Colby Index Well

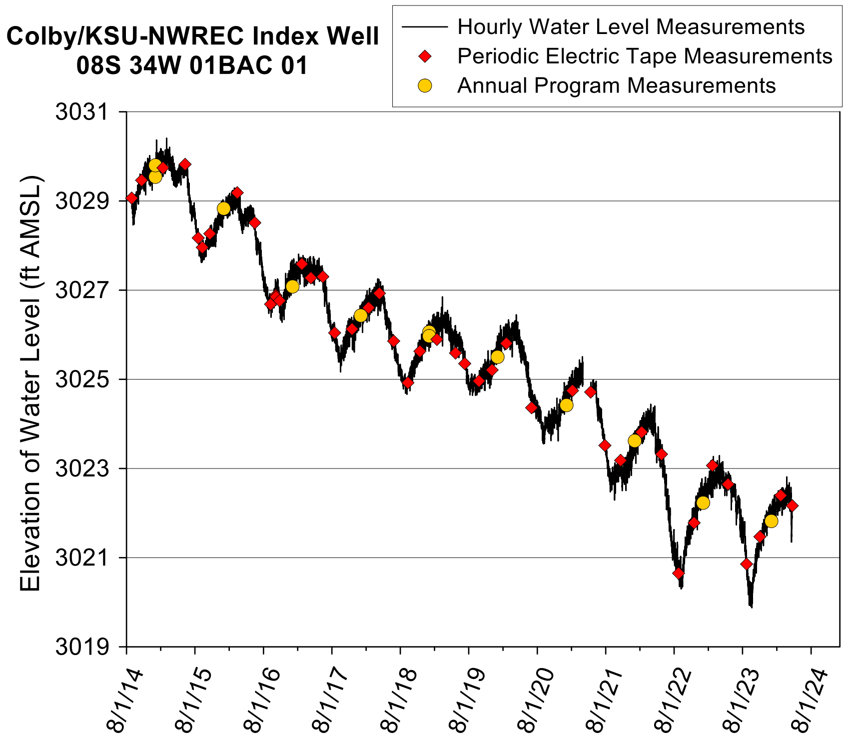

Figure 27—Colby index well hydrograph—total data run to 4/22/24. A water-level elevation of 3,021 ft corresponds to a depth to water of 156 ft below lsf. Total depth of the well is 175 ft below lsf (elevation of 3,002 ft). The screened interval extends from 156 to 175 ft below lsf. The base of the aquifer 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 41.1 ft since January 1948. The decline in 2022 was the largest during the monitoring period.
- Transducer readings are in good agreement with manual measurements.

3.4.3 SD-6 Baalman Index Well

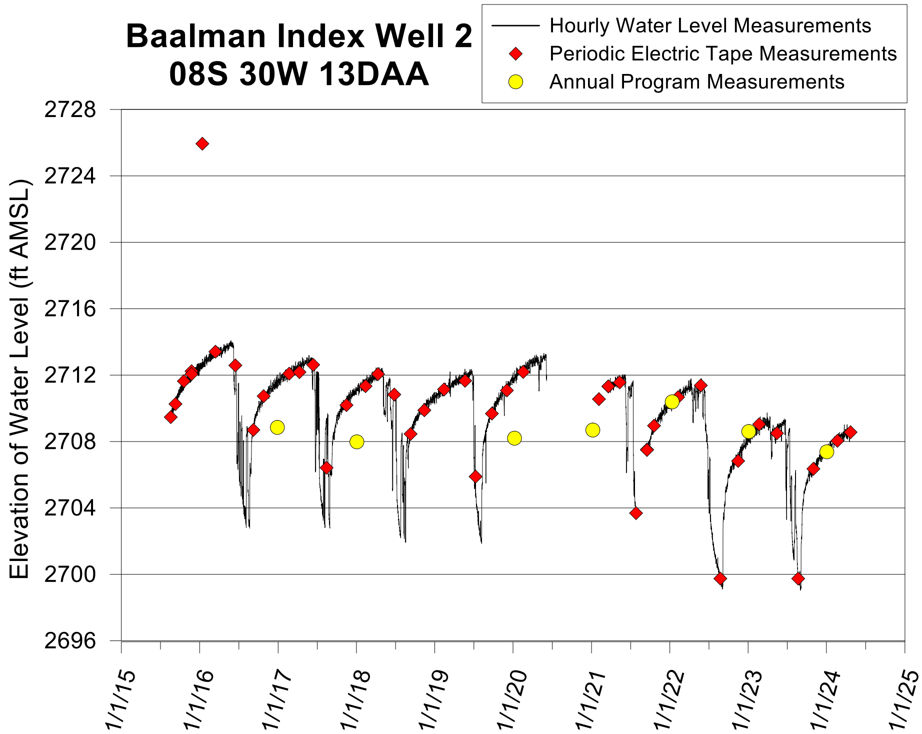

Figure 28—Baalman index well hydrograph—total data run to 4/22/24. A water-level elevation of 2,708 ft corresponds to a depth to water of 189 ft below lsf. The top of the 10 ft screen is 260 ft below lsf (elevation of 2,637 ft), and the bottom of the aquifer is 262 ft below lsf (elevation of 2,635 ft). 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 2023 was far lower than previous maxima during the monitoring period and the minimum water level in 2023 was the same as in 2022, which was far lower than previous minima during the monitoring period.
- In 2023, the water use per irrigated acre in the vicinity of the Baalman index well (2 mi radius) was 0.70 ft (8.4 inches)/acre. 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 early annual program measurements.

3.4.4 SD-6 Beckman Index Well

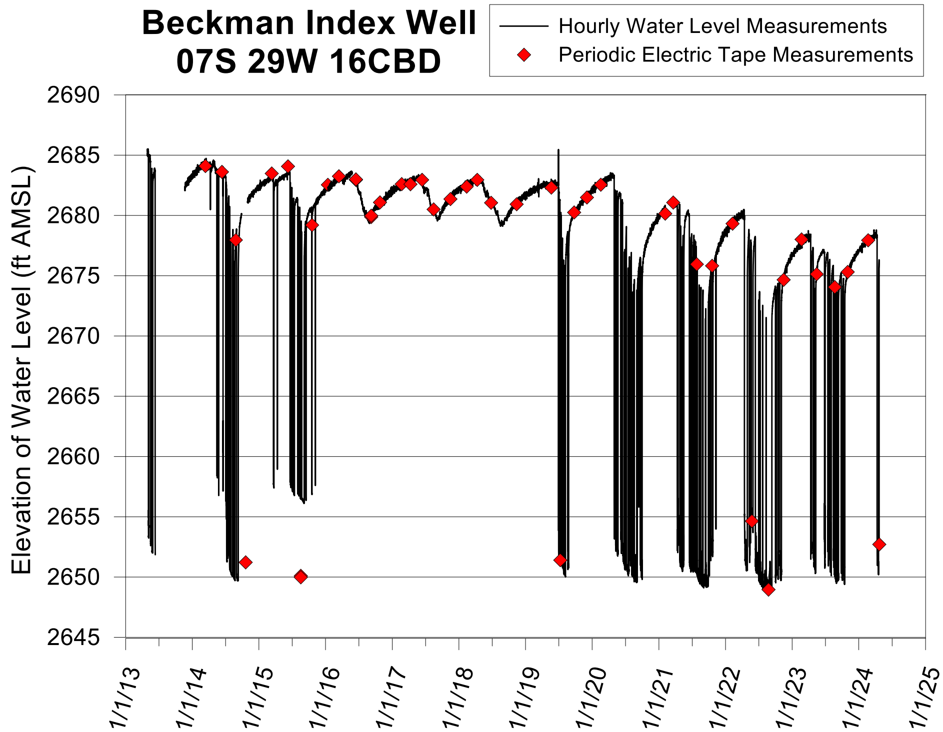

Figure 29—Beckman index well hydrograph—total data run to 4/22/24. A water-level elevation of 2,680 ft corresponds to a depth to water of 200.2 ft below lsf. The data gaps in 2013 and 2014 were caused by datalogger battery problems. The difference between the electric-tape measurement in the summer of 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. Measurements affected by datalogger overheating (mid-summer 2015 and earlier) are not displayed.

Major Points

- In 2023, the irrigation well adjacent to the Beckman index well was pumped for the fifth time in the last five irrigation seasons and the eighth 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 2023, the water use per irrigated acre in the vicinity of the Beckman index well (2 mi radius) was 0.52 ft (6.2 inches)/acre, the second lowest 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 0.75 ft (9.0 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.

3.4.5 SD-6 Moss Index Well

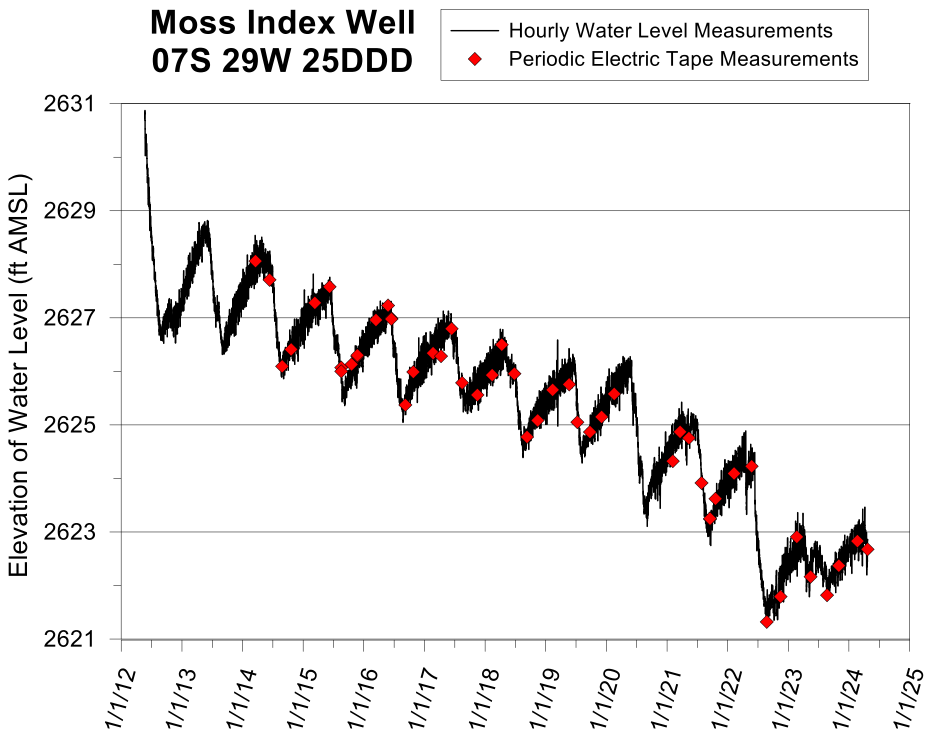

Figure 30—Moss index well hydrograph—total data run to 4/22/24. A water-level elevation of 2,623 ft corresponds to a depth to water of 193 ft below lsf. The top of the 40 ft screen is 205 ft below lsf (elevation of 2,611 ft), and the bottom of the aquifer is 243 ft below lsf (elevation of 2,573 ft). Measurements affected by datalogger overheating (mid-summer 2015 and earlier) are not displayed.

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 was above that of the preceding year for only the second time since the start of monitoring. Otherwise, the hydrograph displays a downward stepping pattern.
- In 2023, the water use per irrigated acre in the vicinity of the Moss index well (2 mi radius) was 0.65 ft (7.8 inches)/acre, the second lowest 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 0.85 ft (10.2 inches)/acre.
- Transducer readings are in good agreement with manual measurements.

3.4.6 SD-6 Seegmiller Index Well

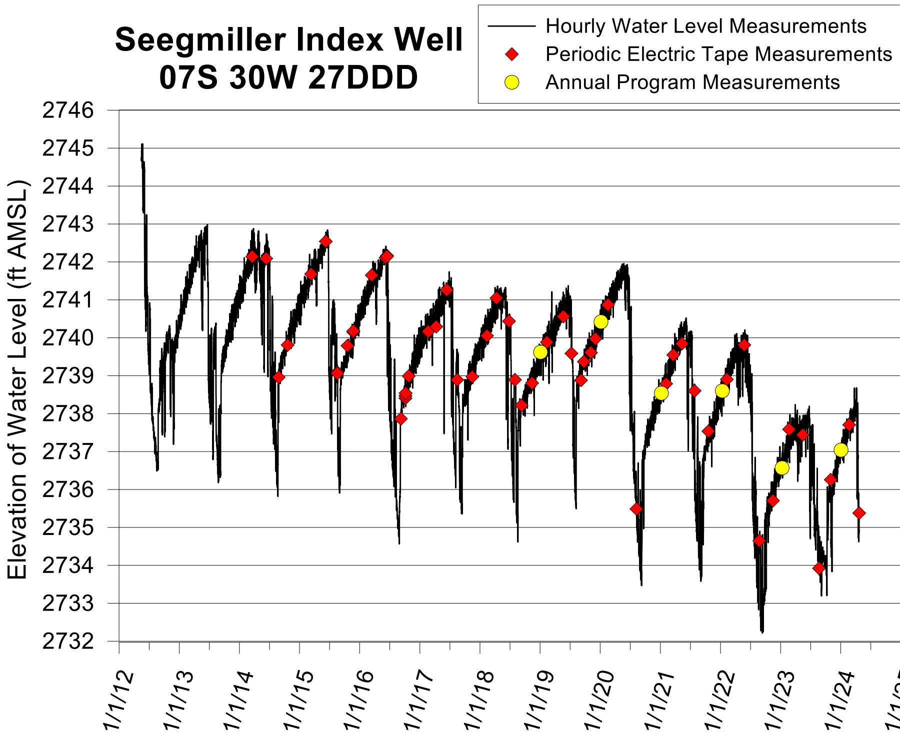

Figure 31—Seegmiller index well hydrograph—total data run to 4/22/24. A water-level elevation of 2,738 ft corresponds to a depth to water of 195 ft below lsf. The top of the 40 ft screen is 225 ft below lsf (elevation of 2,708 ft), and the bottom of the aquifer is 265 ft below lsf (elevation of 2,668 ft). Measurements affected by datalogger overheating (mid-summer 2015 and earlier) are not displayed.

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 2023 is 0.5 ft above that of 2022, which was the lowest observed during the monitoring period.
- In 2023, the water use per irrigated acre in the vicinity of the Seegmiller index well (2 mi radius) was 0.52 ft (6.2 inches)/acre, the second lowest 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 0.75 ft (9.0 inches)/acre.
- Transducer readings are in good agreement with manual measurements.

3.4.7 SD-6 Steiger Index Well

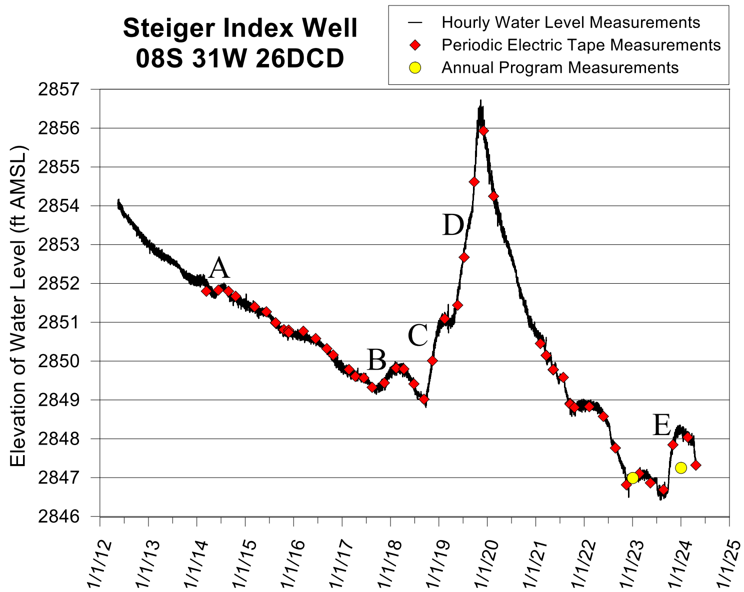

Figure 32—Steiger index well hydrograph—total data run to 4/22/24. A water-level elevation of 2,848 ft corresponds to a depth to water of 117 ft below lsf. The top of the 40 ft screen is 145 ft below lsf (elevation of 2,820 ft), and the bottom of the aquifer is 177 ft below lsf (elevation of 2,788 ft). A–E defined in text. Measurements affected by datalogger overheating (mid-summer 2015 and earlier) are not displayed.

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–E 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 is difficult to discern.
- 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 one of only two definitive examples of episodic recharge that we have observed in the index wells in western Kansas. The sharp decline since the peak in November 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 2023, the water use per irrigated acre in the vicinity of the Steiger index well (2 mi radius) was 0.80 ft (9.7 inches)/acre. 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 except for the 2024 annual measurement, which appears to be in error.

3.4.8 Sherman County Index Well

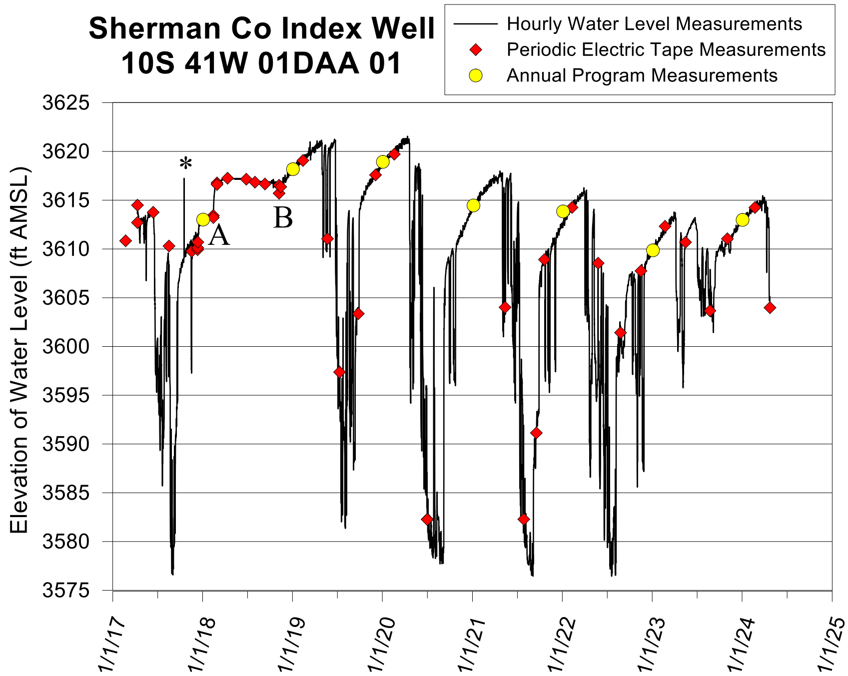

Figure 33—Sherman County index well hydrograph—total data run to 4/23/24. A water-level elevation of 3,615 ft corresponds to a depth to water of 179 ft below lsf. The top of the 10 ft screen is 310 ft below lsf (elevation of 3,484 ft), and the bottom of the aquifer is 323 ft below lsf (elevation of 3,471 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).
- The minimum water-level elevation for 2023 was 19.4 ft above that of 2022 and was the highest since the well was developed (B).
- 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).

3.4.9 Sherman County 2 Index Well

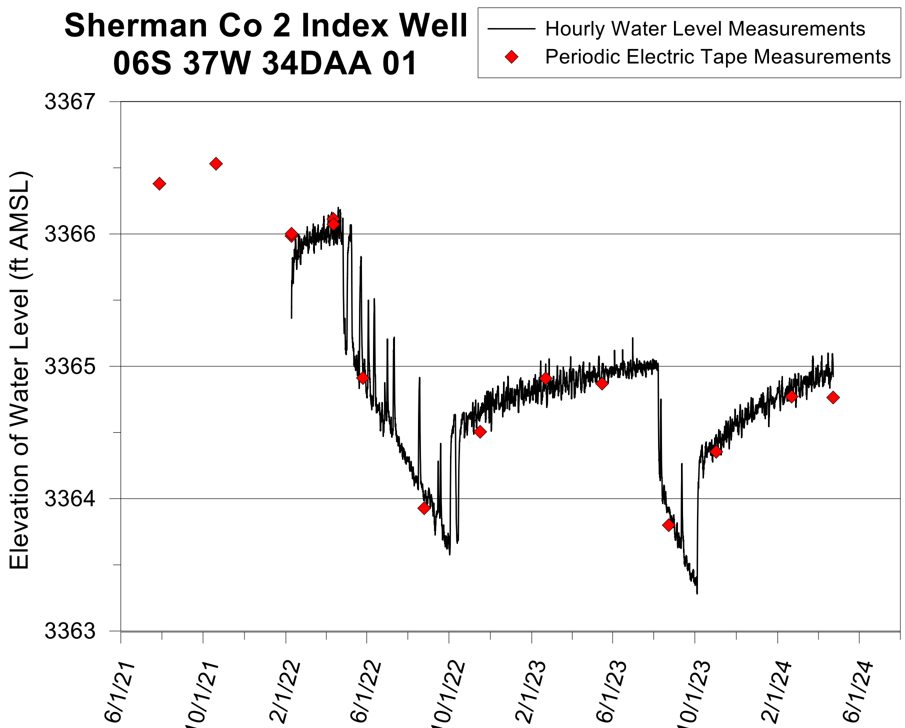

Figure 34—Sherman County 2 index well hydrograph—total data run to 4/23/24. A water-level elevation of 3,365 ft corresponds to a depth to water of 159 ft below lsf. The top of the 40 ft screen is 240 ft below lsf (elevation of 3,284 ft). The bottom of the aquifer is estimated to be 275 ft below lsf (elevation 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 and 2023 irrigation seasons 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.

3.4.10 Thomas County Index Well

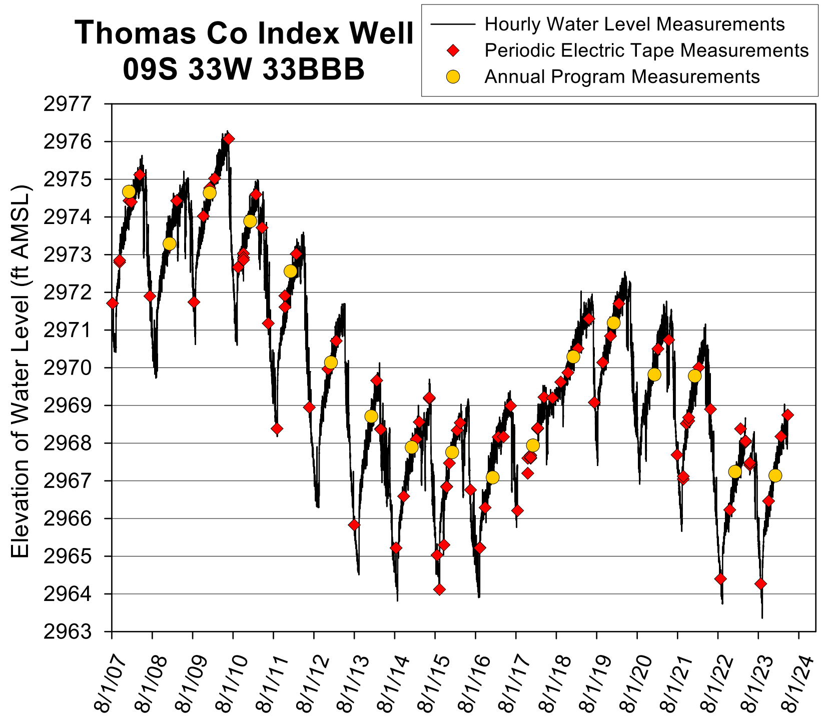

Figure 35—Thomas County index well hydrograph—total data run to 4/22/24. A water-level elevation of 2,967 ft corresponds to a depth to water of 220.6 ft below lsf. The top of the screen is 274 ft below lsf (elevation of 2,913.6 ft), and the bottom of the aquifer is 284 ft below lsf (elevation of 2,903.6 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. The in-field calibration approach described in Butler, Knobbe et al. (2021) has been applied to the transducer data to correct for sensor drift.

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 2023 was 0.4 ft lower than that in 2022, which had been the lowest since the start of monitoring (2007).
- 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 after in-field calibration.

3.5 GMD5 Index Wells

Five index wells, all of which have telemetry equipment that allows real-time viewing of data, are 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	2024 WL elev. (ft)[a]	2024 Saturated thickness (ft)	Bedrock depth (ft below land surface)	Screened interval (ft below land surface)	2023 Water Use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Belpre	2,040.12	134.4–160.1[b]	175–200[b]	89–109	781	2,819	17,221[c]
Larned	1,941.51	57.19	71	66-71	320[d]	2,494[e]	16,077[f]
Rozel	2,038.53	79.03	125.5[b]	40-59 109-129	539	3,535	13,262[g]
Trousdale	2,045.68	100.89	140[b]	47-57	1,013	3,688[h]	22,123[i]
St. John	1868.25	102.25	132[b]	65-75	525	1494	11,111[j]

[a] 2024 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 of municipal water.

[d] Includes 16 ac-ft of industrial water.

[e] Includes 139 ac-ft of non-irrigation stock water and 16 ac-ft of industrial water.

[f] Includes 234 ac-ft of non-irrigation stock water, 270 ac-ft of municipal water, and 16 ac-ft of industrial water.

[g] Includes 61 ac-ft of municipal water and 4 ac-ft of non-irrigation stock water.

[h] Includes 5 ac-ft of non-irrigation stock water.

[i] Includes 6 ac-ft of non-irrigation stock water.

[j] Includes 118 ac-ft of municipal water, 13 ac-ft of recreation water, 3 ac-ft of non-irrigation stock water, and 3 ac-ft of other use water.

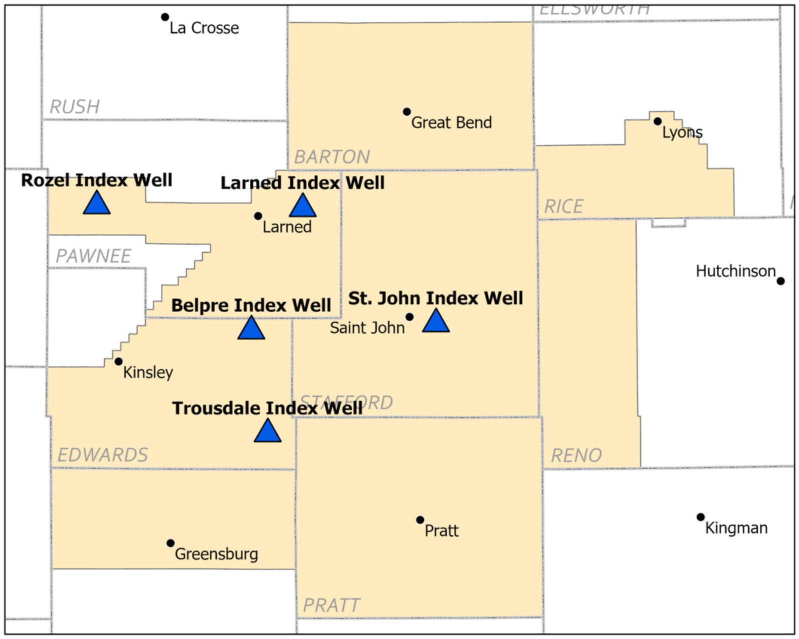

Figure 36—Map of index wells in GMD5 (blue triangles). Data from all five wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

3.5.1 Belpre Index Well

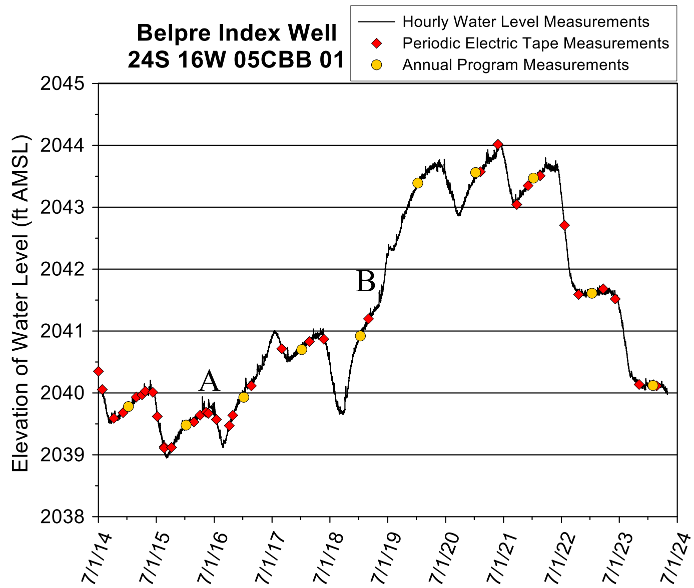

Figure 37—Belpre index well hydrograph—total data run to 4/29/24. A water-level elevation of 2,040 ft corresponds to a depth to water of 40 ft below lsf. The top of the 20 ft screen is 89 ft below lsf (elevation of 1,991 ft), and the bottom of the screen is 109 ft below lsf (elevation of 1,971 ft). The 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 and virtually non-existent after the end of the 2022 and 2023 irrigation seasons, respectively, because of drought conditions. This is an indication that vertical recharge is the primary driver of water-level rises at the well.
- 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 minimum and maximum water levels for 2023 were the lowest minimum and maximum values in the last four years.
- The water level has declined 10.4 ft since January 1988 (decline rate of 0.4 ft/yr) and 0.33 ft since January 2014 (decline rate of 0.03 ft/yr).
- Transducer readings are generally in good agreement with manual measurements.

3.5.2 Larned Index Well

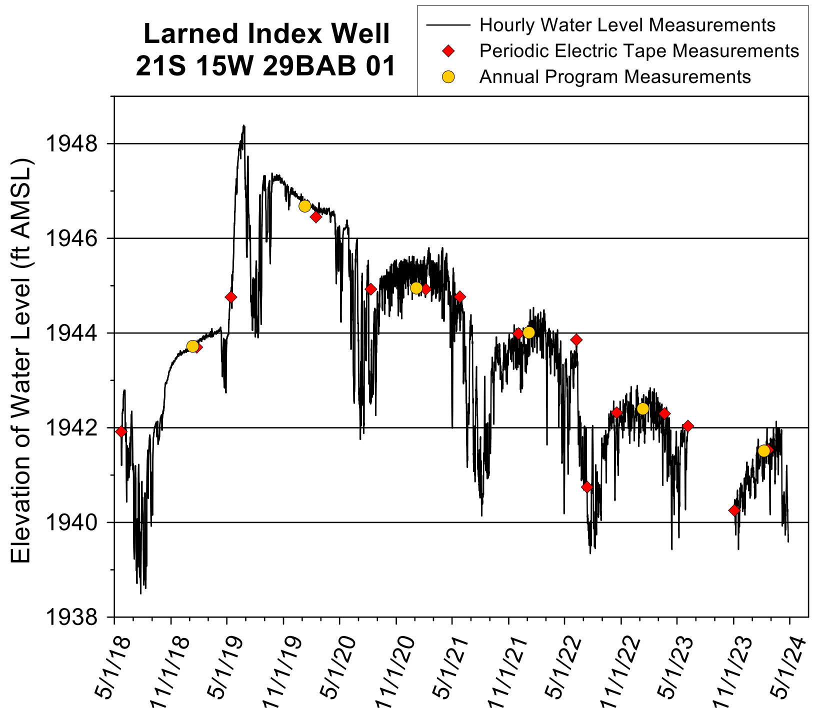

Figure 38—Larned index well hydrograph—total data run to 4/26/24. A water-level elevation of 1,942 ft corresponds to a depth to water of 13.3 ft below lsf. The top of the 5 ft screen is 66 ft below lsf (elevation of 1,889.3 ft), and the bottom of the screen, which is at the base of the aquifer, is 71 ft below lsf (elevation of 1,884.3 ft). Break in monitoring from 6/5/23 to 11/3/23 because of cable and transducer problems.

Major Points

- Hydrograph form and small amplitude fluctuations superimposed on water levels (until the summer of 2020) indicate confined conditions. Much larger amplitude fluctuations from 7/16/20 onward have apparently been introduced by the monitoring and telemetry equipment. Current equipment (including telemetry) will be replaced 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. The 2023 recovery continued until the start of the 2024 irrigation season.
- Transducer readings are in reasonable agreement with manual measurements.

3.5.3 Rozel Index Well

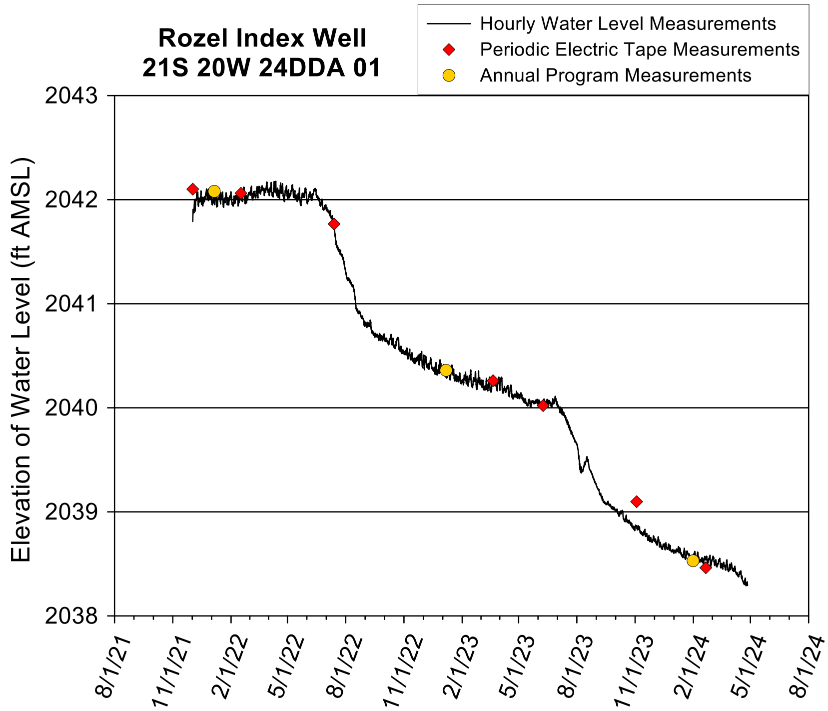

Figure 39—Rozel index well hydrograph—total data run to 4/26/24. A water-level elevation of 2,039 ft corresponds to a depth to water of 46 ft below lsf. There does not appear to have been a WWC5 form filed for this well so there are no well construction details. A camera survey found that the screen 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 continue to decrease after the 2022 and 2023 irrigation seasons. The reason for the continued decrease during the recovery period is not yet clear.
- Water levels have fallen 4.6 ft since late December 1984 for an average decline rate of -0.1 ft/yr. The decline rate over the last two years has been many times higher.
- Transducer readings are in good agreement with manual measurements except for one electric-tape measurement.

3.5.4 St. John Index Well

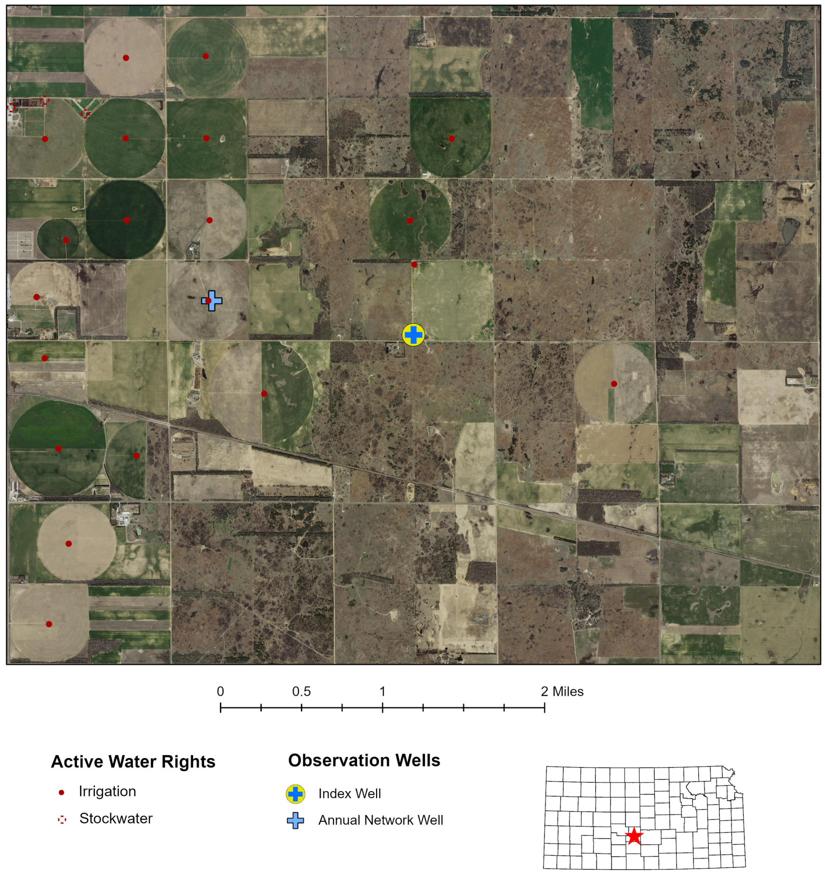

Figure 40—Aerial view of the St. John index well and nearby points of diversion.

Figure 40 is an aerial view of the St. John index well site (T. 23 S., R. 13 W., 36 DCC 02) at a scale that shows the site of the index well, nearby wells with active water rights, and an annual program well.

An integrated pressure-transducer and datalogger unit and telemetry equipment were placed in the well on November 9, 2023. Prior to that time, the well had been measured quarterly to monthly by GMD5 personnel since October 1978.

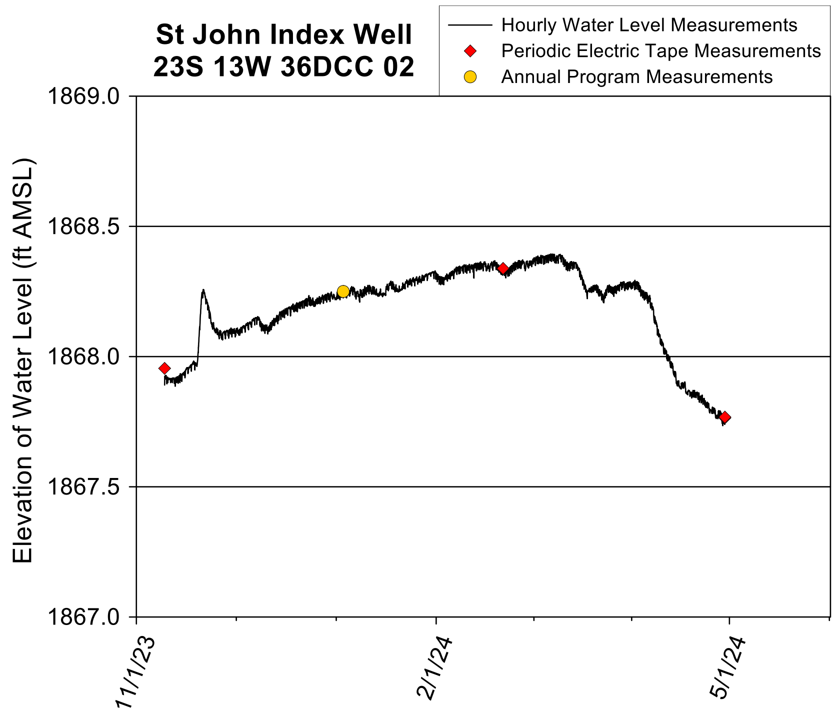

Figure 41—St. John index well hydrograph—total data run to 4/29/24. A water-level elevation of 1,868 ft corresponds to a depth to water of 30.0 ft below lsf. The top of the 10 ft screen is 65 ft below lsf (elevation of 1,833 ft). The bottom of the well is 75 ft below lsf (elevation of 1,823 ft); the base of the aquifer is 142 ft below lsf (elevation of 1,756 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.
- The low-amplitude and high-frequency undulations observed throughout the record are likely produced by a nearby domestic well.
- Based on manual measurements, the water level has dropped 6.0 ft since January 1, 1980 (0.1 ft/yr) and 3.1 ft in the last decade (0.3 ft/yr).
- Transducer readings are in good agreement with manual measurements.

3.5.5 Trousdale Index Well

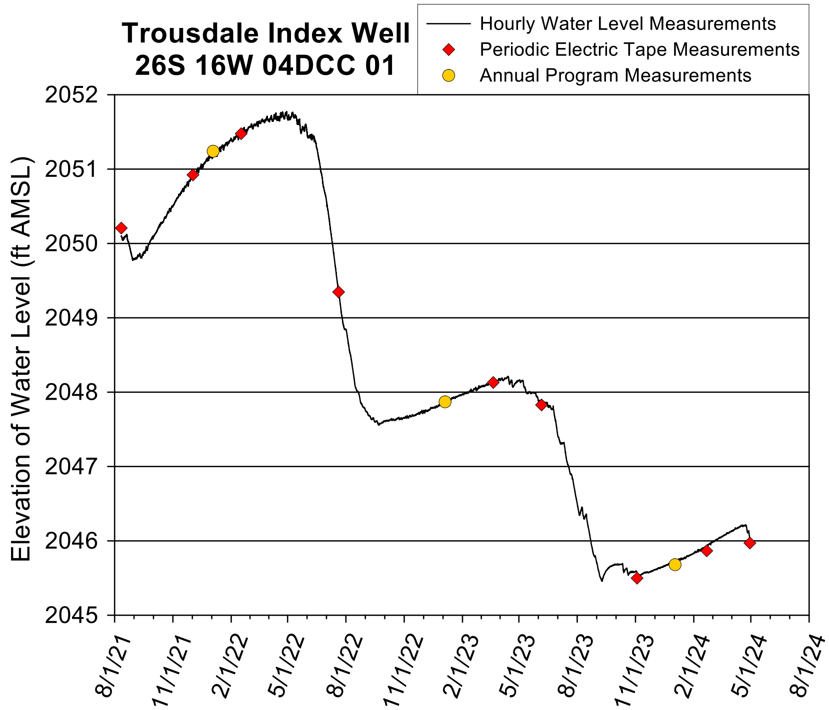

Figure 42—Trousdale index well hydrograph—total data run to 4/29/24. A water-level elevation of 2,046 ft corresponds to a depth to water of 38.8 ft below lsf. The top of the 10 ft screen is 47 ft below lsf (elevation of 2,037.8 ft). The bottom of the well is 57 ft below lsf (elevation of 2,027.8 ft); 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 end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize). The rise after the end of the 2022 and 2023 irrigation seasons was much smaller than the recovery after the 2021 irrigation season because of drought conditions.
- The water level has fallen 12.7 ft since January 2001 for a decline rate of 0.6 ft/yr. The decline rate has been close to five times higher over the last two years.
- Transducer readings are in good agreement with manual measurements for the first 18 months of monitoring, but the agreement is lessening. This is an indication that the transducer needs to be recalibrated.

3.6 Expansion Wells

3.6.1 GMD1 Expansion Wells

Five expansion wells (SC-8 and wells 1 and 3-5) are now operating in GMD1 (table 6 and fig. 43). There were originally seven wells, but the value of the information obtained from two of the wells did not merit continued participation in the index well program. 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 are not expected to be permanently monitored; sensors may be moved to other wells or 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, while expansion wells 3 and 5 are measured quarterly. Expansion wells 2 and 6 are measured as part of the annual cooperative network program and will no longer be considered as part of the index well program. The barometer that had been a short distance below land surface at expansion well 3 has been moved to the 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	2024 WL elev. (ft)[a]	2024 Saturated thickness (ft)[d]	Bedrock depth (estimated ft below land surface)[d]	Screened interval (ft below land surface)	2023 Water Use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
SC-8	2,846.1	83.1	174	c	973	1,767	7,839[m]
Site 1	2,928.5	25.5	195	c	349[e]	968[f]	4,054[g]
Site 3	3,424.1	21.1	220	c	26	636	7,894[h]
Site 4[b]	3,534.3	n	n	c	301	1,354	4,394[i]
Site 5[b]	2,843.3	NA	158	c	200[j]	1,781[k]	8,381[l]

[a] 2024 annual tape water-level measurements from WIZARD database.

[b] Not an annually measured index well; 2024 water-level measurements estimated from sensor data on 01/5/2024 from 0800 to 1700 at Site 4 and from 2/22/24 manual measurement at Site 5.

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

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

[e] Includes 95 ac-ft of non-irrigation stock water.

[f] Includes 179 ac-ft of non-irrigation stock water.

[g] Includes 414 ac-ft of non-irrigation stock water.

[h] Includes 17 ac-ft of municipal water and 45 ac-ft of non-irrigation stock water.

[i] Includes 794 ac-ft of non-irrigation stock water.

[j] Includes 17 ac-ft of non-irrigation stock water.

[k] Includes 431 ac-ft of municipal water, 3 ac-ft of industrial water, and 17 ac-ft of non-irrigation stock water.

[l] Includes 3 ac-ft of industrial water, 942 ac-ft of municipal water, and 244 ac-ft of non-irrigation stock water.

[m] Includes 942 ac-ft of municipal water, 3 ac-ft of industrial water, and 271 ac-ft of non-irrigation stock water.

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

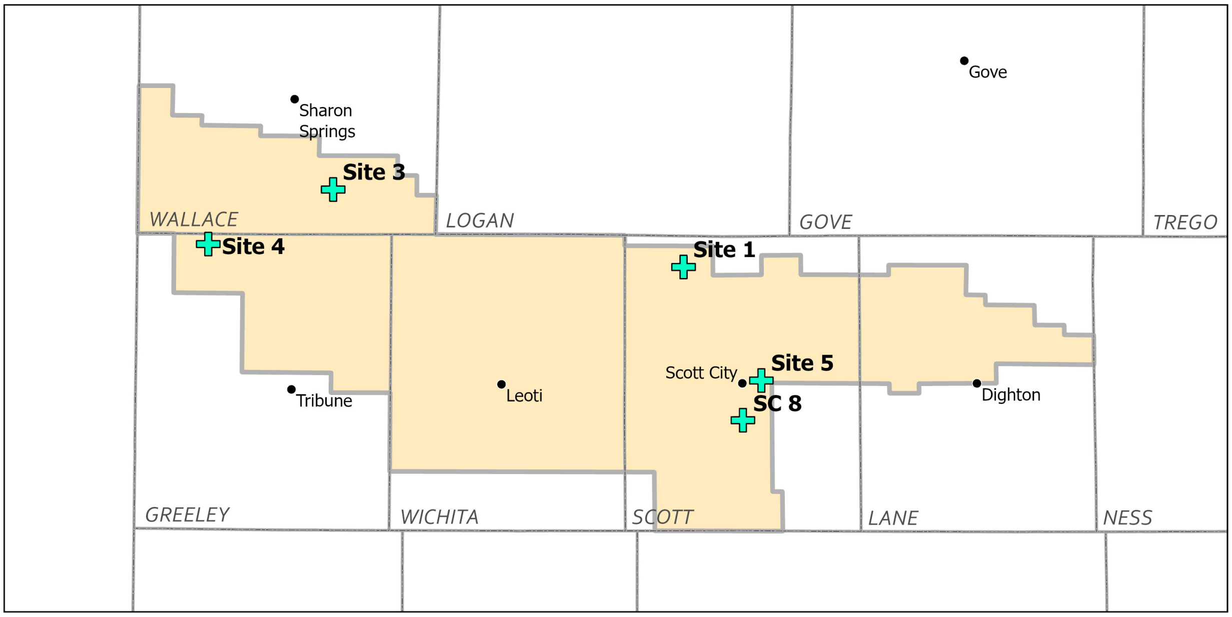

Figure 43—Map of GMD1 expansion wells.

3.6.1.1 SC-8 Site – Scott County

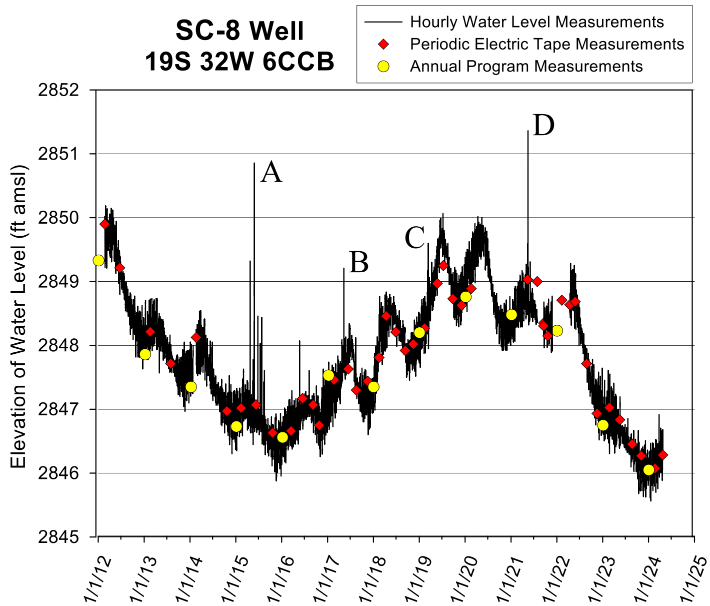

Figure 44—SC-8 well hydrograph—total data run to 4/23/24. A water-level elevation of 2,847 ft corresponds to a depth to water of 89 ft below lsf. Bottom of well is approximately 102 ft below lsf (elevation of 2,834 ft). Transducer measurements have been corrected from earlier reports for an incorrect 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.
- Transducer readings are generally in good agreement with manual measurements.

3.6.1.2 Expansion Site 1 – Scott County

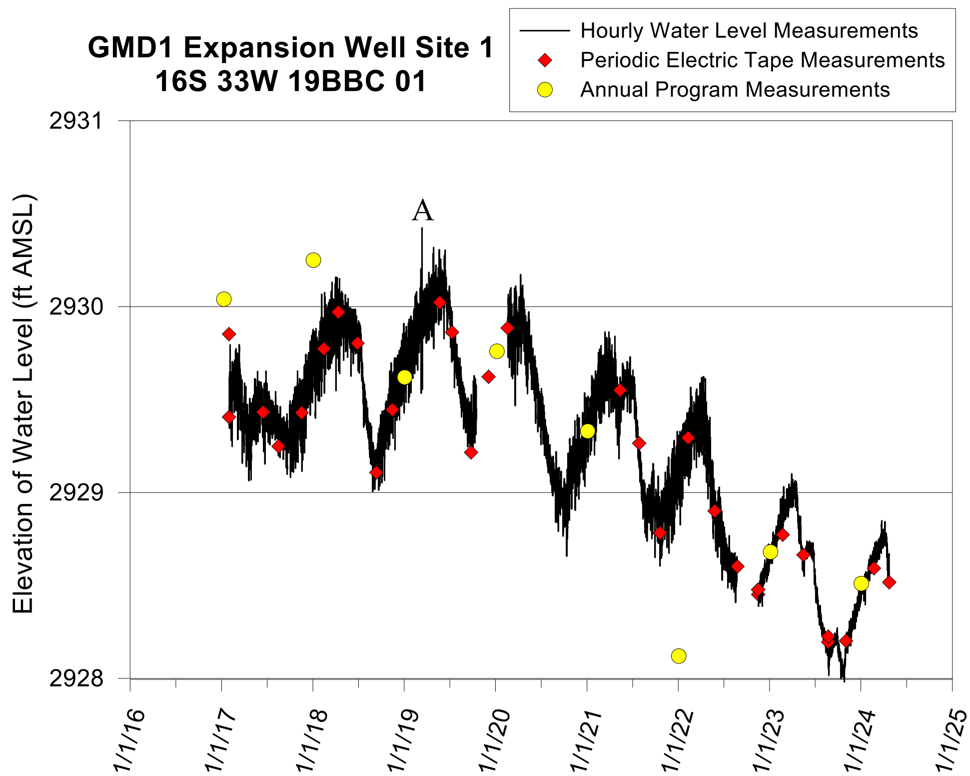

Figure 45—GMD1 Expansion Site 1 well hydrograph—total data run to 4/23/24. A water-level elevation of 2,930 ft corresponds to a depth to water of 168 ft below lsf. Bottom of well is 193.2 ft below lsf (elevation of 2,904.8 ft). A defined in text.

Major Points

- The amplitude of the fluctuations superimposed on the water levels, which are particularly prominent during the recovery period, changed after sensor replacement on 11/16/22, making it difficult to assess the degree of confinement.
- 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 with a more robust sensor on 11/16/22.
- The water level in this well has fallen 8.4 ft since January 1999 (0.3 ft/yr) and 2.7 ft since 2013 (0.3 ft/yr).
- Minimum water level on 10/27/23 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 3 – Wallace County

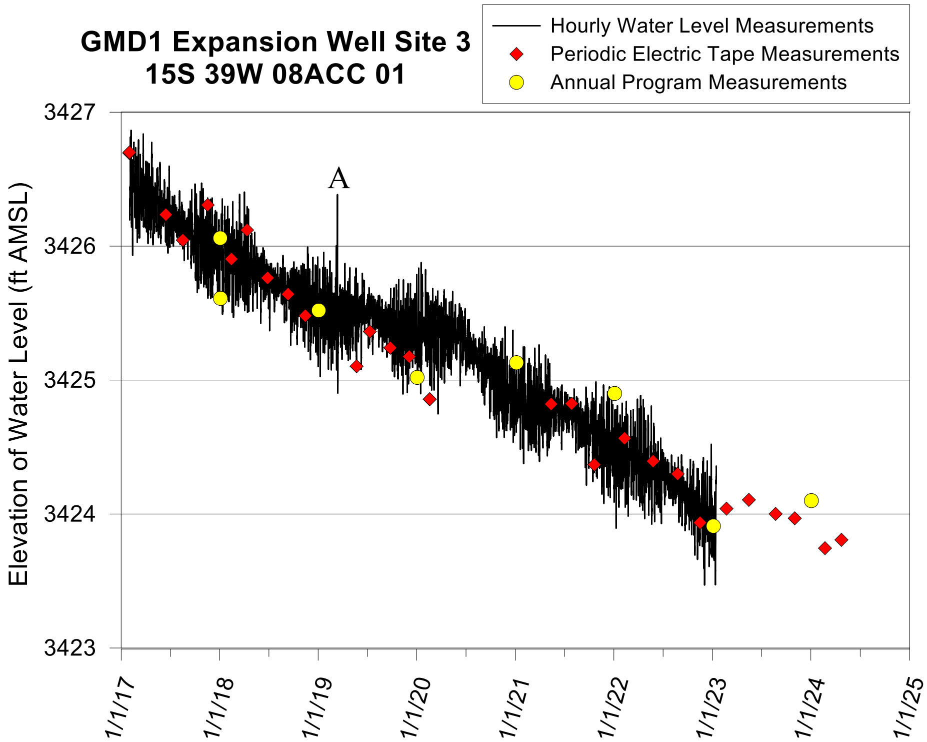

Figure 46—GMD1 Expansion Site 3 well hydrograph—total data run to 4/23/24. A water-level elevation of 3,424 ft corresponds to a depth to water of 199 ft below lsf. Bottom of well is 219.9 ft below lsf (elevation of 3,403.1 ft). A defined in text.

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 78.9 ft since 1964 (1.3 ft/yr) and 6.1 ft since 2014 (0.6 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.

3.6.1.4 Expansion Site 4 – Greeley County

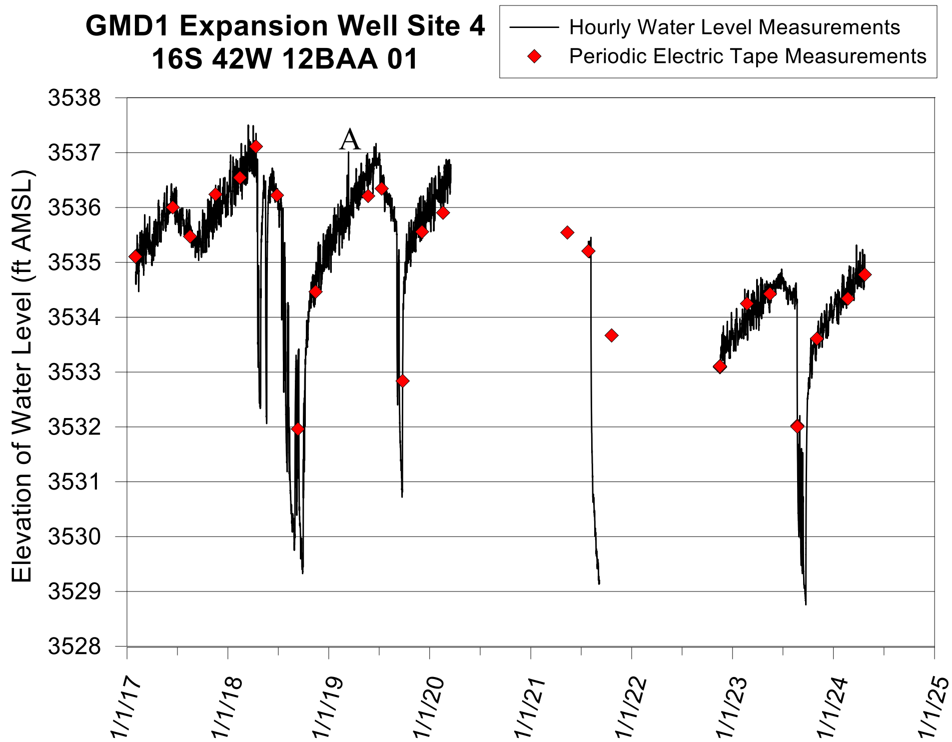

Figure 47—GMD1 Expansion Site 4 well hydrograph—total data run to 4/23/24, hourly measurements to 3/17/20, from 7/28/21 to 9/5/21, and from 11/16/22 on. A water-level elevation of 3,535 ft corresponds to a depth to water of 238 ft below lsf. Bottom of well is 264.5 ft below lsf (elevation of 3,508.5 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.

3.6.1.5 Expansion Site 5 – Scott County

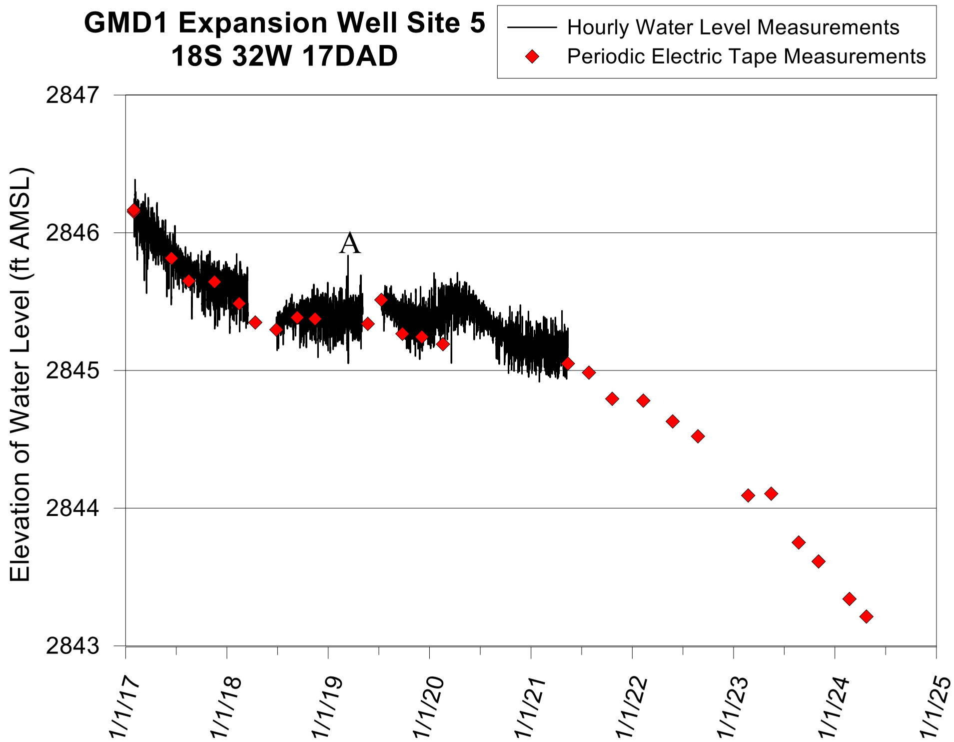

Figure 48—GMD1 Expansion Site 5 well hydrograph—total data run to 4/23/24. A water-level elevation of 2,845 ft corresponds to a depth to water of 131 ft below lsf. Elevation of well bottom is not known. A defined in text.

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 2014 (0.7 ft/yr) and 36.0 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.

3.6.2 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 Kansas HPA. In addition, the interpretation of water-level responses at these wells has helped to enhance 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**.** 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, Bohling et al., 2023). The components of net inflow are described in previous index well reports. Variations in irrigation water use across the HPA are primarily a function of 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 11 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, Butler, Bohling et al., 2023) that was provided as an appendix to last year's 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, Butler, Bohling 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 by enabling *Precipitation Estimate* on the map page at https://water.noaa.gov/). 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 (we also use station-based precipitation data called PRISM for certain applications). Figure 49 shows an image of the percent of normal annual precipitation during 2023 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 2023 was substantially above average over most of GMDs 1, 3, and 4, especially in the westernmost parts of these districts (between 25% and 200% above normal). This was in contrast to 2022, when precipitation was generally between 10% and 75% below normal for these districts. In comparison, precipitation over GMD5 in 2023 was mainly in the range of near average to 25% below normal and in GMD2 was primarily in the range 10% to 50% below normal. The map reveals that substantial spatial variation in precipitation existed within the GMDs; the precipitation ranged from 150–200% above normal to 25–50% below normal.

The mean spatial radar precipitation for March–October, which covers the extended irrigation season, ranged widely during 2005–2023 (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 2023 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 0.08, 0.04, 1.05, and -0.22, respectively, in comparison to -1.90, -2.16, -1.89, and -1.30 for 2022. 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 2023 climate for the irrigation season was within the normal range for GMDs 4, 1, 2, and 5 (although on the wet side of normal for GMDs 4 and 1 and on the dry side of normal for GMDs 2 and 5) and moderately wet in GMD3. In all five GMDs, the climate for the 2023 irrigation season was substantially wetter than in 2022.

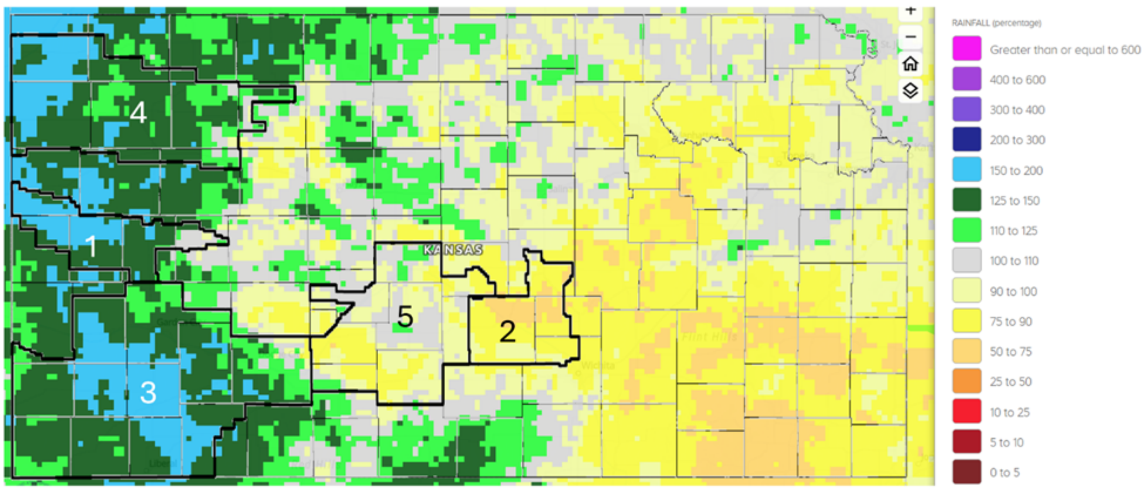

Figure 49—Percent of normal radar precipitation for Kansas in 2023. County lines are displayed and the GMD numbers and boundaries are bolded.

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 2005–2023 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 2024. 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–September sum), which are also displayed on fig. 50. The annual water-level changes in 2023 were relatively large in GMDs 1 and 4 (a rise from declines of -1.1 to -1.3 ft in 2022 to an increase of about 0.3 ft above zero); substantially greater in GMD3 (from a decline of -3.2 ft in 2022 to a decline of only -0.2 ft in 2023); and moderate in GMDs 2 and 5 (an increase from a decline of -2.3 ft to -1.6 ft in GMD 2 from 2022 to 2023 and from -2.3 ft to -1.1 ft in GMD5). The larger relative rises in the western GMDs compared to the south-central Kansas GMDs fit the precipitation pattern shown in fig. 49. The 2023 water-level change was the only increase during 2005–2023 in GMD1, tied for second for the largest positive change in GMD4, and was the smallest decline in GMD3 other than the increase in 2017 in GMD3.

a)

b)

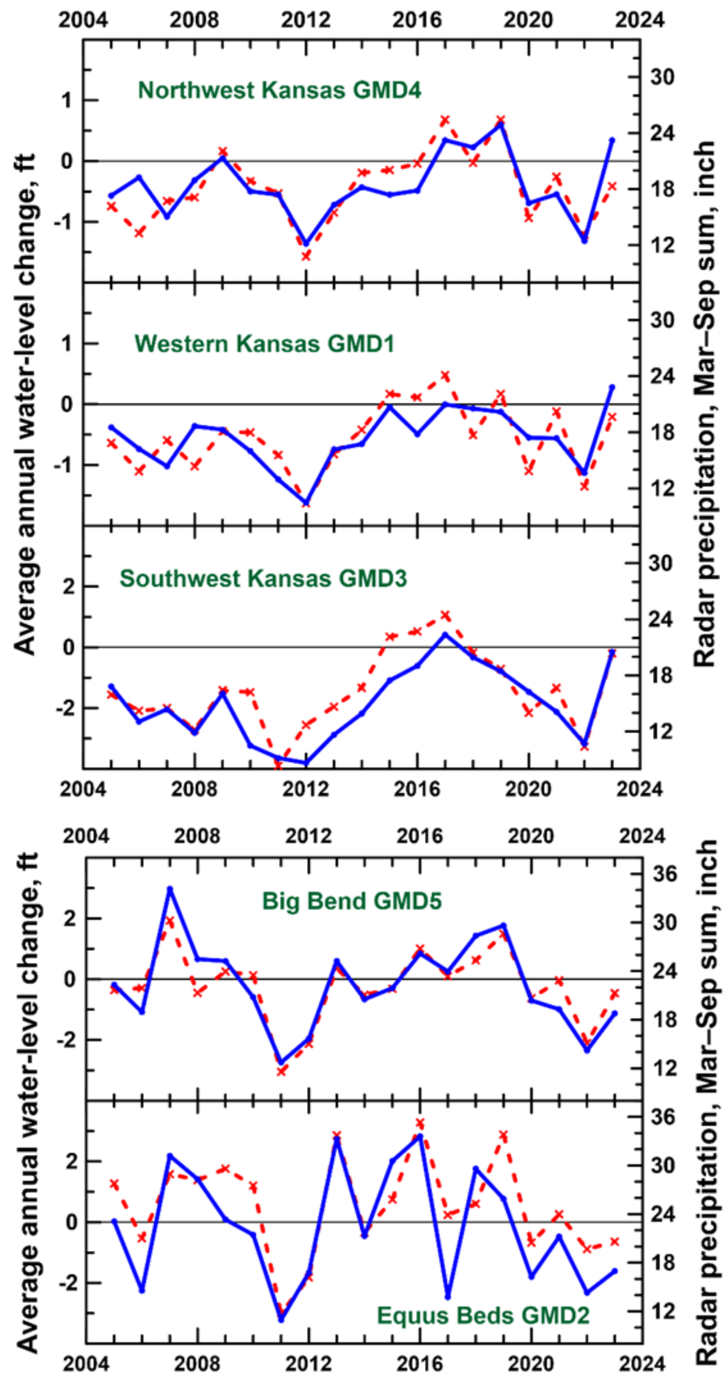

Figure 50—Mean annual water-level change (blue line) and radar precipitation (red dashed line, sum of March–October precipitation) during 2005–2022 for (a) GMDs 4, 1, and 3 and (b) GMDs 5 and 2. The water-level change for a particular year is the water-level difference between the following year and 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 2008–2024 (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 -0.02 and -1.48 ft for tape measurements; a total absolute range of 1.46 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 +4.2 and -10.4 ft for tape measurements; a total absolute range of 14.6 ft).

The range in the annual water-level changes for the Scott index well is essentially the same as that for the mean annual water-level change for GMD1 during 2008–2023. 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 changes in the Thomas well and the 2016 and 2021 changes 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 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. The difference in changes from 2022 to 2023 was the greatest one-year difference for the 2008–2023 monitoring period, from -10.4 ft to 4.2 ft.

The 2023 water-level rise for all three index wells was relatively large and primarily resulted from the substantial change from a dry year in 2022 (see fig. 49 in the 2022 report) to wet conditions in 2023 at the well locations. The radar-estimated precipitation based on fig. 48 at the Thomas and Scott wells was in the range of 125–150% of normal and at the Haskell well about 150% of normal.

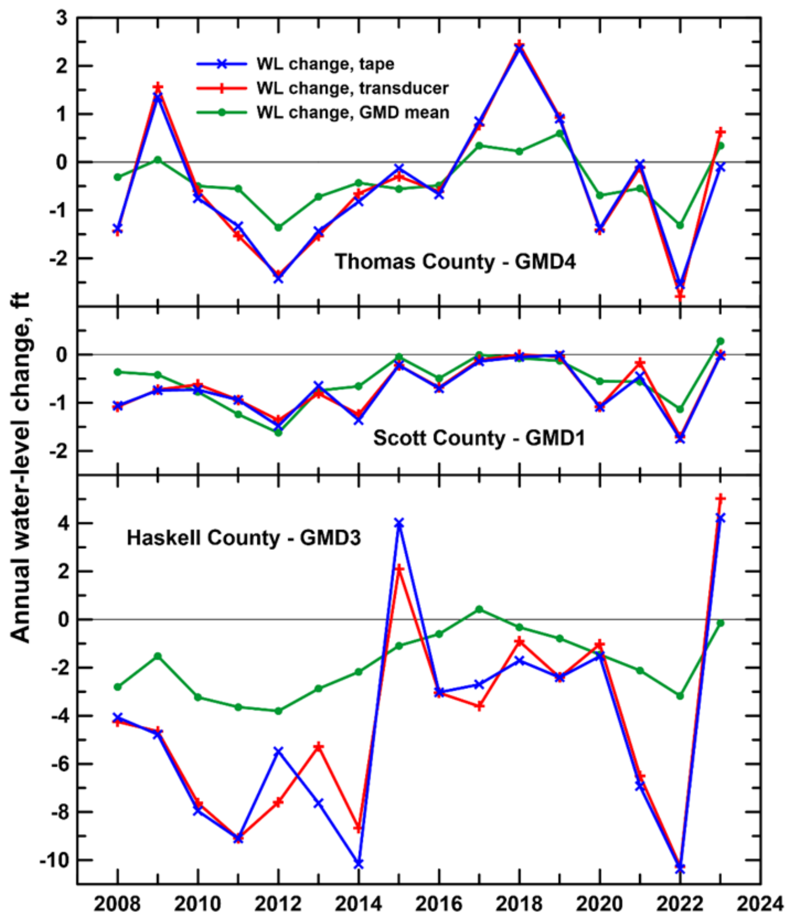

Figure 51—Annual winter (January) water-level changes in the original three index wells and the mean annual changes in the three GMDs in western Kansas in which they are located. Note the different y-axis range for Haskell County versus that for Thomas and Scott counties. Suspect 2013 tape measurement 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, Bohling 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 2008–2023. 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 11.1%, which is lower than the 16.3% for 2008–2017 that omits the hail year of 2018 and following years and the 15.0% for all of GMD4 for 2008–2022. The average annual water use during 2008–2023 was 3.9 in/yr for the 2 mi radius area centered on the well, which is substantially greater than the 1.4 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.

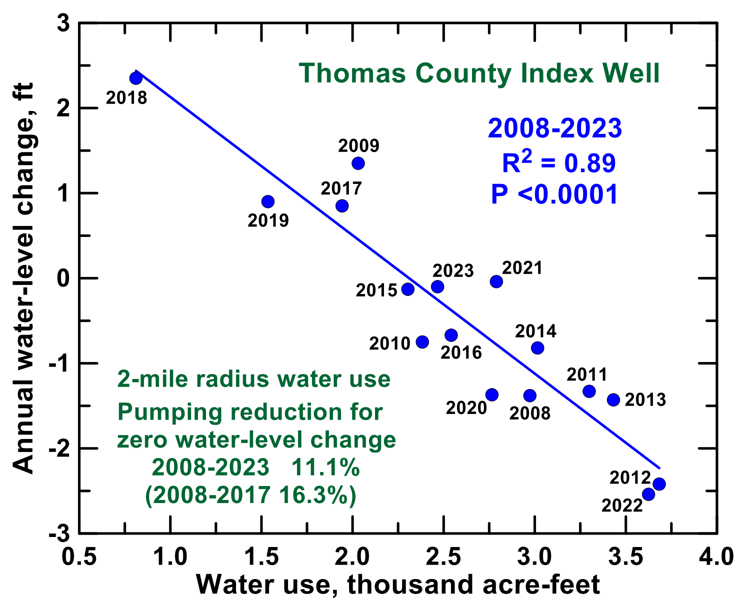

Figure 52—Correlation of annual water-level change based on manual measurements in the Thomas County index well with annual water use within a 2 mi radius centered on the well during 2008–2023.

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 2008–2023. The pumping reduction for stable water levels is 32%, which is above the 27% for all of GMD1 for 2008–2023. The average annual water use was 4.4 in/yr for the 2 mi radius area centered on the well, which is substantially greater than the 1.6 in/yr for all of GMD1. The water use for stable water levels (net inflow) was 3.0 in/yr for the 2 mi radius area, which again is substantially greater than the 1.2 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.

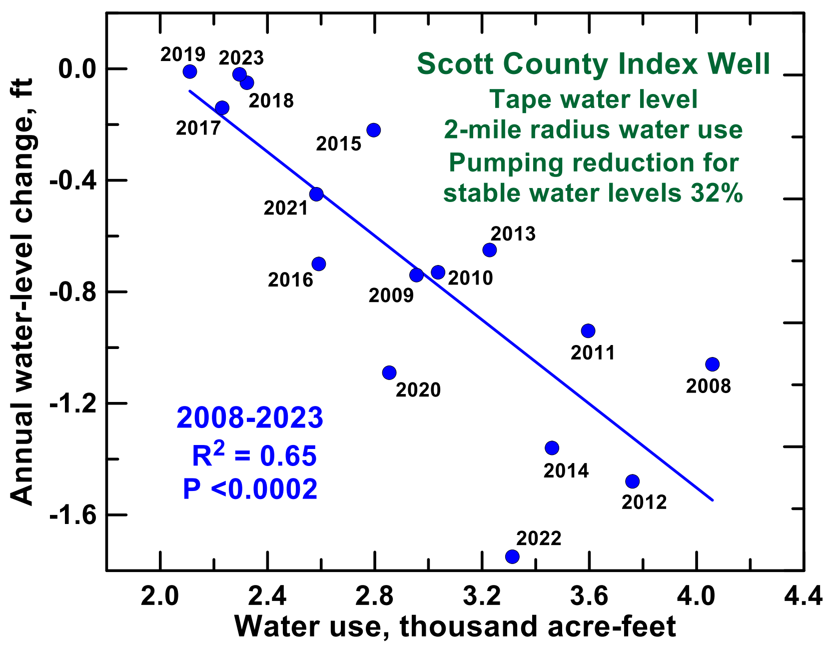

Figure 53—Correlation of annual water-level change based on manual measurements in the Scott County index well with annual water use within a 2 mi radius centered on the well during 2008–2023. The 2022 water-level change appears to have been affected by late-season pumping (recovery began on Nov. 9, 2022, while it typically begins in early to mid-September).

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 2008–2023. 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 2013–2023 (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 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 59% (using the linear regression for 2008–2023 and the average annual water use for 2008–2012), which is much larger than the 23% for all of GMD3 for 2008–2023. The pumping reduction for stable water levels for the average annual water use after the full shutdown (2015–2023; 2013 and 2014 were years of partial shutdown as described in section 3.3.2) is 25% (again using the linear regression for 2008–2023), which is similar to the reduction for all of GMD3 but appreciably less than for the period before the shutdowns. The average annual water-use rates were 14.3 in/yr and 7.7 in/yr for the 2 mi radius area centered on the well during 2008–2012 and 2015–2023, 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 5.8 in/yr for the 2 mi radius area based on the 2008–2023 data, which again is substantially greater than the 3.0 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.

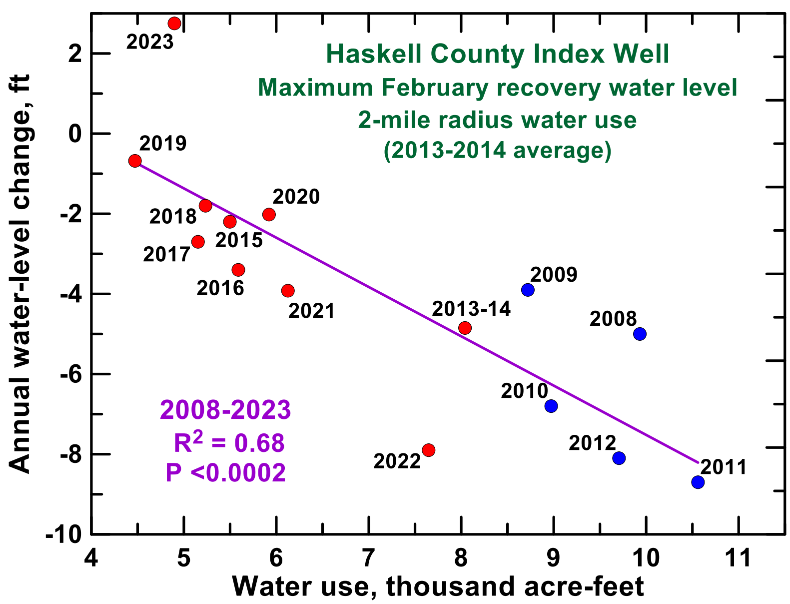

Figure 54—Correlation of change in maximum recovery water level during February based on transducer measurements in the Haskell County index well with annual water use within a 2 mi radius centered on the well during 2008–2023. Red points designate values after the court-ordered shutdowns (see section 3.3.2); 2013 and 2014 values are averaged because of equipment failure at the time of the 2013 maximum recovery. The 2022 value appears to have been affected by late-year (December) pumping; the result is that the 2022 value is more negative than would have been expected for the 2022 annual pumping and the 2023 value is more positive than would have been expected for the 2023 annual 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 (65% for 2023 for the 1 mi radius area centered on the well). The percent pumping reduction required to attain stable water levels (53%) 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 3.1 in/yr for the 1 mi radius area, which is less than that in the vicinity of the Thomas index well (3.9 in/yr for 2 mi radius) but substantially greater than the 1.4 in/yr for all of GMD4. The water use for stable water levels (net inflow) was 1.5 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 (27%) is less than that required in the vicinity of the Scott County index well (32% for 2 mi radius) and similar to that for all of GMD1 (27%). The average annual water use was 4.1 in/yr for the 1 mi radius area, which is somewhat less than that in the vicinity of the Scott index well (4.4 in/yr for 2 mi radius) but substantially greater than the 1.6 in/yr for all of GMD1. The water use for stable water levels (net inflow), however, was 3.0 in/yr for the 1 mi radius area, which is similar to that in the vicinity of the Scott index well (3.0 in/yr for 2 mi radius) but much greater than the 1.2 in/yr for all of GMD1.

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 2.4% and is close to the 3.4% 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.

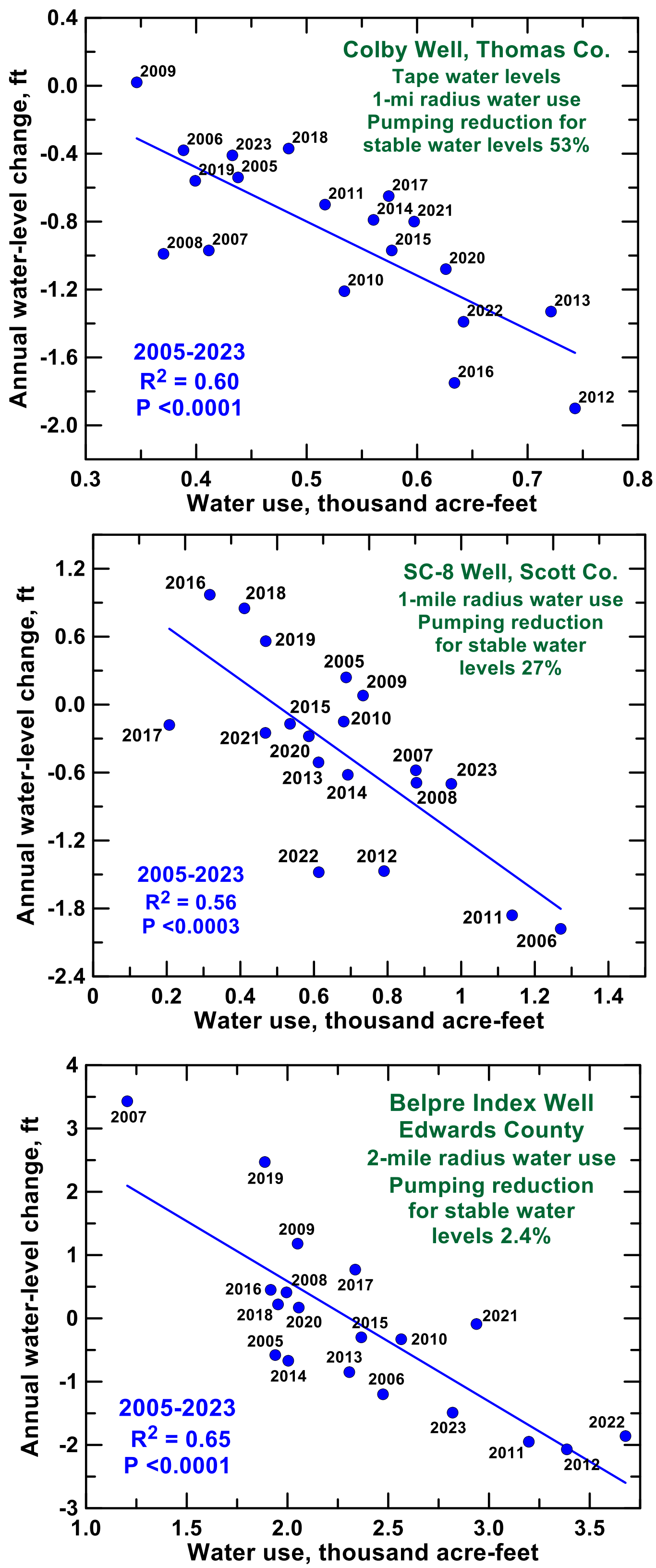

Figure 55—Correlation of annual water-level change in the Colby, SC-8, and Belpre wells with annual water use within a 1 or 2 mi radius centered on the wells during 2005–2023.

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 the extended irrigation season generally captures the precipitation that drives pumping in support of irrigated agriculture in the Kansas HPA. Figure 50 includes the variation in March–September radar precipitation versus time since 2005 for all five GMDs. This plot shows that 2017 was the wettest year experienced in GMDs 1, 3, and 4 since 2005 for this monthly range. The wettest year since 2005 in GMD5 was 2007, whereas the wettest year in GMD2 was 2016. The driest years were during the drought of 2011–2012; the lowest precipitation in GMDs 1, 3, and 4 occurred during 2012 and the lowest in GMDs 2 and 5 during 2011.

4.6.1 Correlation of Annual Water Use with Radar Precipitation

Based on earlier work in the index well program, we have found that water use and precipitation relationships can be used to identify where water use has been reduced and whether the reduction was achieved through a decrease in irrigated area or changes in pumping. In previous years' 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), and the monthly ranges for the irrigation season that give optimum correlations with water use vary among these wells. 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 over 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 (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, with the exception of 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 March–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 2008–2023 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; this 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 2019–2023 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). No significant water conservation is evident in the 2 mi circle around the well during 2008–2023. Irrigated area has actually increased several percent during the last few years and no substantial decrease has occurred in water use per irrigated area (water application rate).

The linear regression for 2018–2023 for the Scott County well is significantly offset to lower water use than for the regression for 2008–2017 (fig. 56), 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, Butler, Bohling 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 would show a significant difference in regression lines for 2008–2017 and 2018–2023 if irrigation efficiency were the main explanation, shows that the confidence intervals overlap for the two periods and indicate no significant difference. Thus, improvements in irrigation efficiency do not appear to be responsible for the offset in the total water use plot (fig. 56). Instead, a decrease in irrigated area during 2008–2023 (fig. 58) is the probable explanation for the decreased water use during 2018–2023 compared to 2008–2017. 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 better correlation for post-shutdown data. The plots show the much lower water use for a given precipitation after the well shutdowns compared to before. 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, 2023; Whittemore, Butler, Bohling 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 is not appropriate for plotting with the data after the complete shutdown.

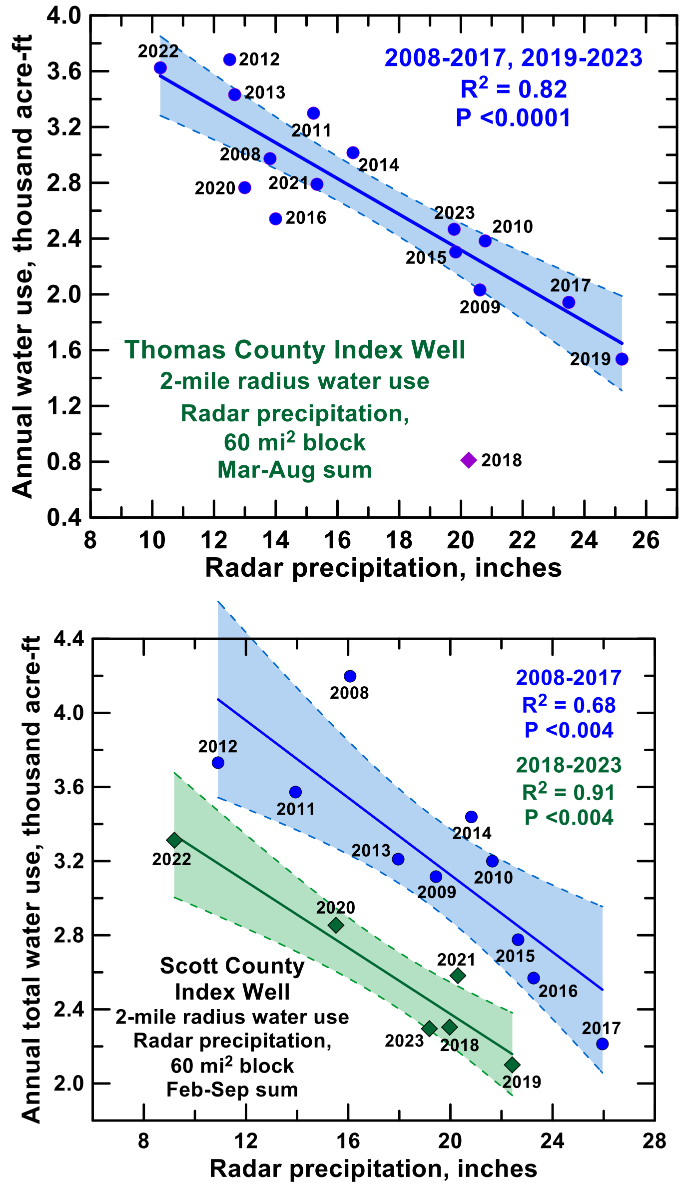

Figure 56—Correlation of annual total groundwater use with radar precipitation at the Thomas County and Scott County index wells for 2008–2017 and 2019–2023 (Thomas) and 2008–2023 (Scott). The shaded intervals represent 95% confidence intervals for the regressions.

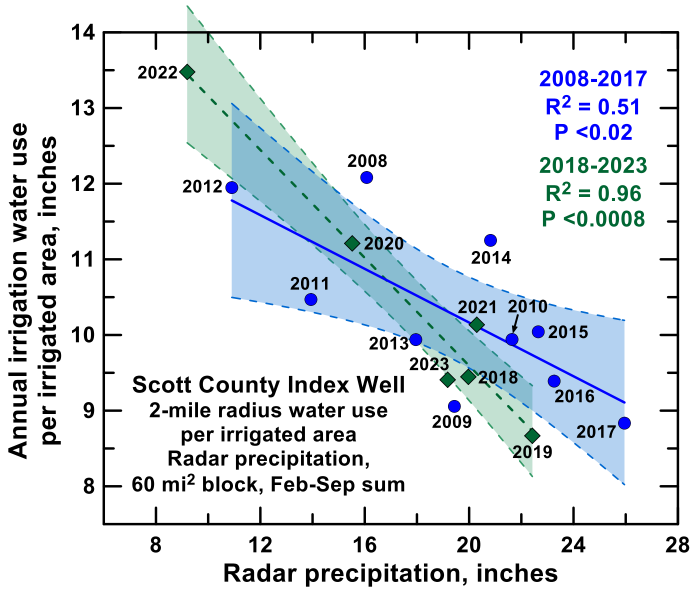

Figure 57—Correlation of annual irrigation groundwater use per irrigated area with radar precipitation at the Scott County index well for 2008–2023. The shaded intervals represent the 95% confidence interval for the linear regressions.

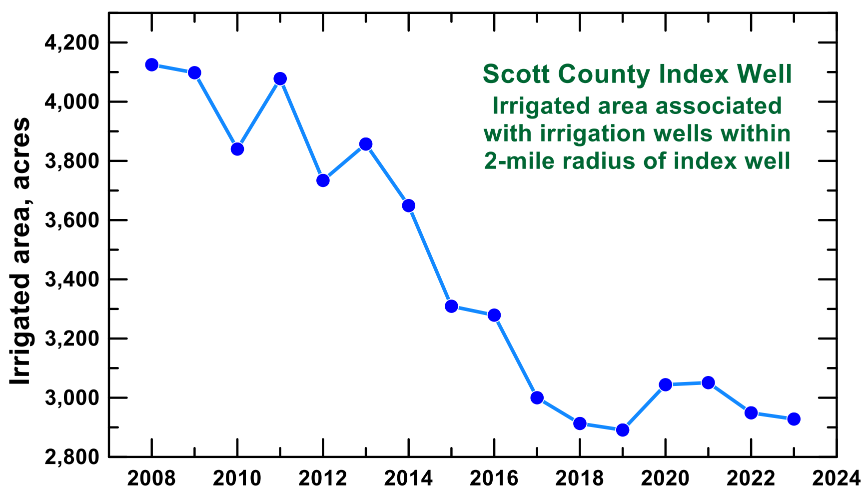

Figure 58—Change in irrigated area associated with the irrigation wells within the 2 mi radius of the Scott County index well for 2008–2023.

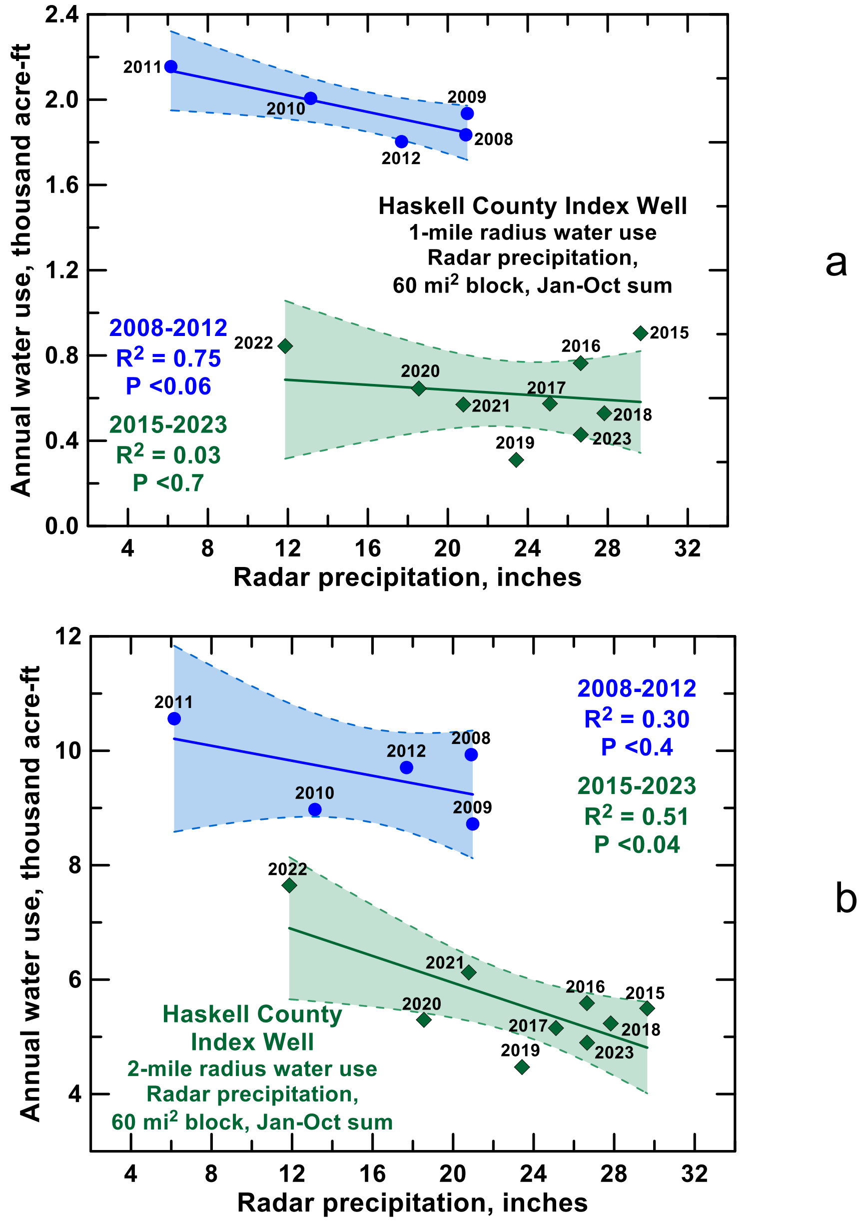

Figure 59—Correlation of annual total groundwater use with radar precipitation at the Haskell County index well for 2008–2023 for (a) a 1 mi radius and (b) a 2 mi radius of water use. The 2008–2012 and 2015–2023 periods represent years before and after the onset of a court-ordered shutdown of nearby irrigation well pumping; points for the 2013–2014 period, which was for a limited shutdown (see section 3.3.2), are not included.

Figure 60 shows the correlations between water use and radar precipitation for the three additional wells (Colby, SC-8, and Belpre). Groundwater is used for multiple purposes within the 2 mi radius around the Colby well, but the focus here is on water use for irrigation (fig. 60). The monthly range that gives the optimum correlation (March–October) is longer than that for the Thomas County well (March–August). The irrigation water use for 2018–2023 is significantly lower than 2008–2017 for a given precipitation. The irrigated area changed little between these periods (-0.1%), but the irrigation application rate changed substantially (-20.4%). It thus appears that irrigation conservation measures based on improved irrigation efficiency have been implemented since the establishment of the districtwide LEMA in GMD4 in April 2018. The greatest groundwater use within the 2 mi radius is for municipal supply, but municipal use changed little after establishment of the districtwide LEMA (-0.02%).

The water-use data for 2005–2007 for the SC-8 well appear to be too high, as a much better correlation (R^2 increasing from 0.55 to 0.81) is obtained using the 2008–2017 data (fig. 60). In this case, all the water use within the 2 mi radius of the index well is for irrigation. The monthly precipitation range for the SC-8 well optimum correlation is the same as for the Scott County index well. As with the Scott County and Colby wells, the water use during 2018–2023 was below that for 2008–2017 for a given precipitation. Although the SC-8 and Scott County index wells are relatively near one another, the irrigated area within the 2 mi radius of the SC-8 well did not decrease during 2008 to 2023. However, the irrigation application rate did decrease from 2008–2017 to 2018–2023. Thus, the decrease in water use between the two periods for the SC-8 well was achieved by increasing irrigation efficiency rather than by decreasing irrigated acreage as for the Scott County well.

The water-use data for the Belpre well during 2005–2007 fall within the band of variation of the 2008–2023 data; thus, the longer time span of 2005–2023 was used in the plot for this well (fig. 60; irrigation is the only use). As with the SC-8 well, the optimum monthly range for precipitation 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, only one regression line and confidence interval are shown. There is no evidence that conservation measures have decreased water use around the Belpre well during the 2005–2023 period.

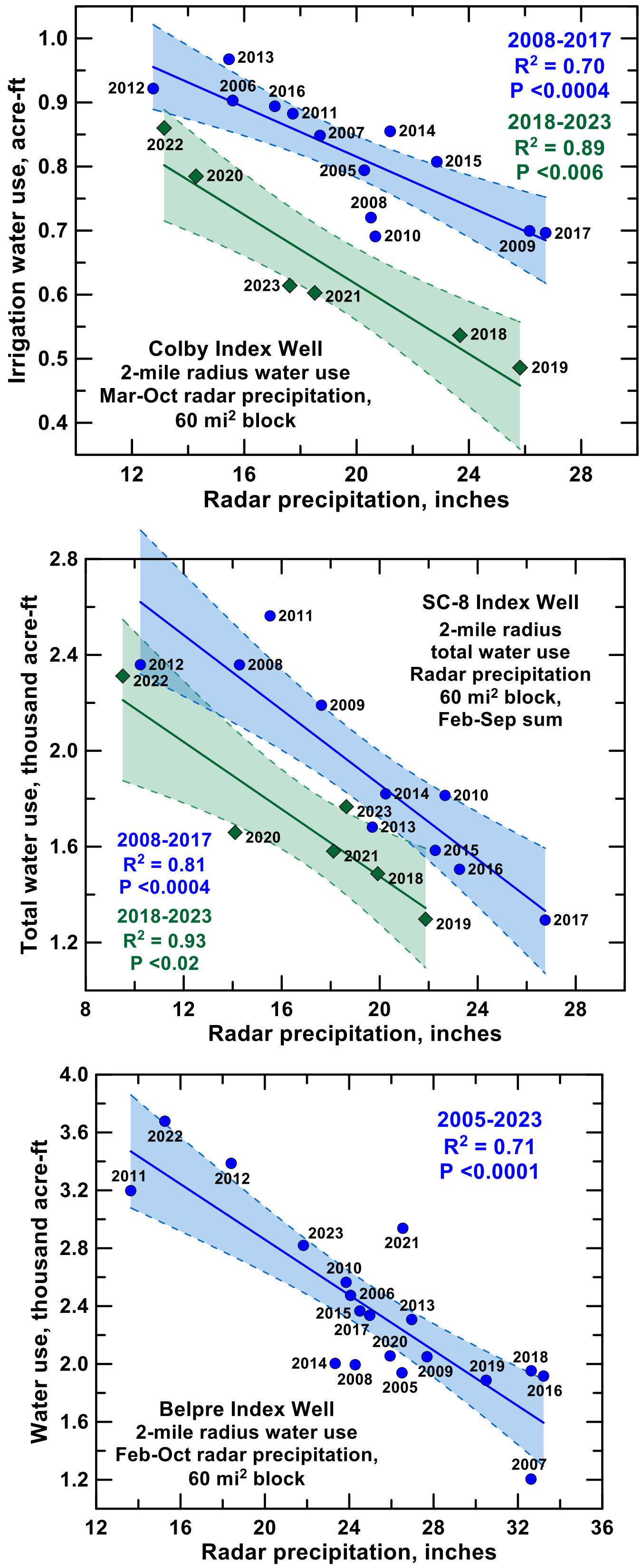

Figure 60—Correlation of annual groundwater use with radar precipitation at the Colby (irrigation use) and SC-8 and Belpre (total water use) wells for 2008–2023 (Colby and SC-8) and 2005–2023 (Belpre).

5 Summary of 2023–2024 Accomplishments and Plans for 2024–2025

5.1 Accomplishments, 7/2023–6/2024

- Collected and processed data from all wells currently involved in the index well program. Telemetered data from 31 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.
- Equipped two existing wells with transducers and telemetry equipment; one well is in GMD4 and the other is in GMD5.
- Equipped the Steiger well, which has a hydrograph that shows a clear signal of episodic recharge, with a camera to take daily photographs of the nearby impoundment to help develop a relationship between precipitation and recharge reaching the water table.
- Began to apply the in-field calibration approach developed through the index well program to transducer data to correct for sensor drift.
- 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.

5.2 Planned Activities, 7/2024–6/2025

- 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 in southeastern GMD3.
- Automate the in-field calibration approach developed through the index well program to account for sensor drift in all wells currently involved in the program.
- Sample water at as many index wells as possible
- 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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