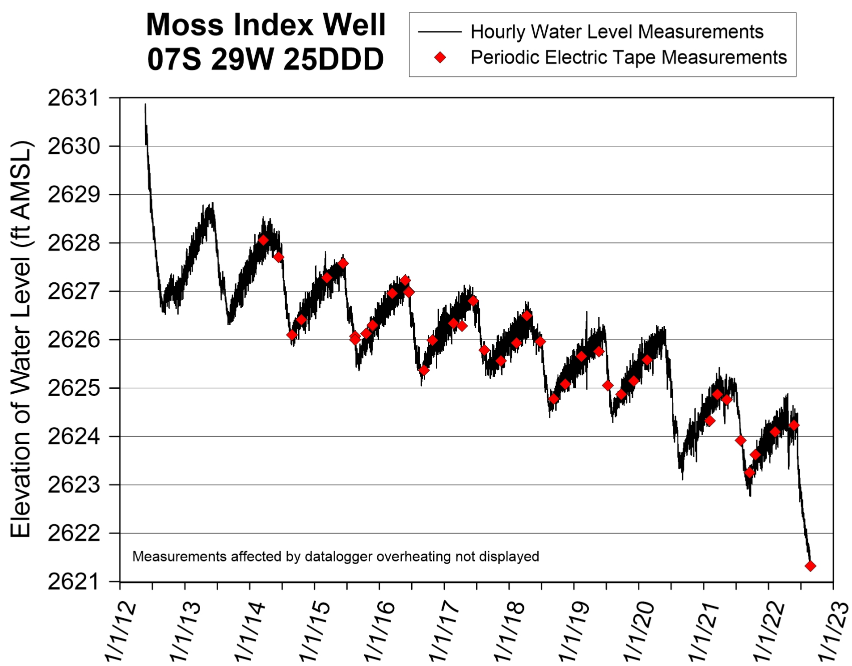
Kansas Geological Survey

High Plains Aquifer Index Well Program: 2021 Annual Report

J. J. Butler, Jr., D. O. Whittemore, E. Reboulet,
S. Knobbe, B. B. Wilson, and G. C. Bohling
Kansas Geological Survey
University of Kansas



Impact of Droughts at SD-6 Moss Index Well

Kansas Geological Survey Open-File Report No. 2022-27
December 2022

GEOHYDROLOGY

KU KANSAS GEOLOGICAL SURVEY The University of Kansas

The University of Kansas, Lawrence, KS 66047 (785) 864-3965; www.kgs.ku.edu

KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 2022-27

Acknowledgments

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

Executive Summary

The index well program 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 2021 and in the spring of 2022 by the installation of real-time monitoring equipment at an existing well in GMD1, an existing well in GMD4, and two existing wells in GMD5. The network now consists of 25 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 mid-summer 2022. 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, to a lesser extent, 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.
4. The standardized precipitation index and radar precipitation data are good indicators of the climatic conditions that drive pumping in the High Plains aquifer in Kansas. In addition, these quantities can be used in precipitation versus water use relationships to identify changes in pumping produced by management decisions or storm-induced crop damage.

In addition to the concise description in this report, these findings are discussed in previous program reports, a KGS publication (Whittemore et al., 2018), 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). In summer 2022, a scientific journal article related to recent program work was accepted for publication (Butler et al., 2023). That article is provided as an appendix to this report.

The focus of activities for the remainder of 2022 and the first half of 2023 will be on the continuation of monitoring at all program wells; continued analysis of hydrographs from all wells; installation of equipment for real-time monitoring at an existing well in GMD5; the drilling and installation of equipment at two well nests in GMD3 to monitor the relationship between the Dakota and High Plains aquifers in that area; and further assessment of the relationships among radar-determined precipitation, annual water-level change, and water use.

Table of Contents

List of Figures

List of Tables

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., 2015; Butler et al., 2023). The index well program, 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 criteria or methods to evaluate the effectiveness of management strategies at the local scale. Changes in water level—or the rate at which the water level is changing—are considered the most direct and unequivocal measures of the effect of management strategies. Because of the economic, social, and environmental importance of water in western and south-central Kansas, the effects of any modifications in patterns of water use need to be evaluated promptly and accurately. The program has focused on identifying and reducing the uncertainties and inaccuracies in estimates of year-to-year changes in water level, so that the effects of management decisions can be assessed as rapidly as possible. In addition, the program 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 enhance the information provided by the annual water-level measurement program.

At the time of this report, monitoring data (hourly frequency) from up to fourteen full recovery and pumping seasons and one additional ongoing or completed pumping season, depending on location, 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.
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 2021 by the installation of real-time monitoring equipment in one existing well in GMD1 (Wichita County 2 index well), one existing well in GMD4 (Sherman County 2 index well), and two existing wells in GMD5 (Rozel and Trousdale index wells). Note that the term “index well” is used here to designate a dedicated, non-pumping well at which monitoring is anticipated to continue for many years. There are additional wells, designated here as “expansion wells,” at which monitoring is not likely to continue over the long term because of constraints imposed by well depth (i.e., water level is anticipated to drop below the bottom of the well screen), logistics, or management issues. Both types of wells are considered in this report.

This report provides a concise description of conditions as of mid-summer 2022. 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, to a lesser extent, three additional wells and the implications of those relationships for efforts to moderate water-level declines by pumping reductions. In mid-summer 2022, a scientific journal article related to recent program work was accepted for publication (Butler et al., 2023). That article is provided as an appendix to this report.

2 Program History

The index well program began in summer 2007 with the installation of three transducer- and telemetry-equipped wells, designed and sited to function as HPA monitoring wells (hereinafter, original index wells). One well was installed in each of the three western GMDs, with locations deliberately chosen to represent different water use and hydrogeologic conditions and to take advantage of related past or continuing studies (blue 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 right to left (east to west), Cimarron, Liberal, Hugoton, and Rolla sites). These monitoring locations were important additions to the index well network because they provide valuable information about responses in the areas of thick aquifer intervals in southernmost GMD3.

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

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

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

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

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

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

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

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

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

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

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

In the second half of 2021, we converted two existing GMD5 monitoring wells to index wells. On August 11, 2021, an integrated pressure transducer-datalogger unit and telemetry equipment were placed in the Trousdale index well. On December 2, 2021, an integrated pressure transducer-datalogger unit and telemetry equipment were placed in the Rozel index well. 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.

Figure 1 shows the current state of the index well network. There are now 25 wells in the network with telemetry equipment and real-time data access from the KGS website and 6 wells without telemetry equipment (data downloaded approximately quarterly and displayed on the KGS website). The vast majority of these wells have been added to the annual water-level measurement network and are measured as part of the annual program. In addition, monitoring without telemetry equipment continues at three expansion wells in GMD1.

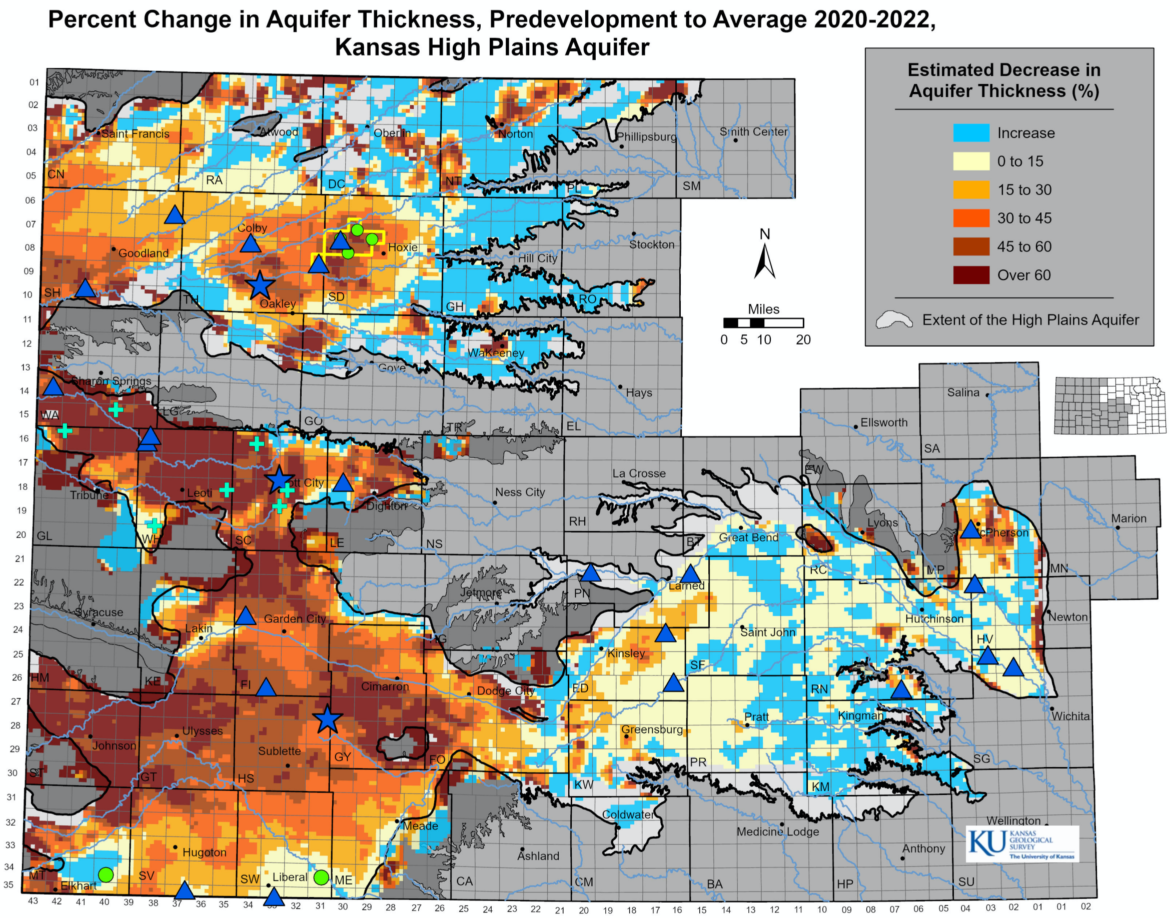


Figure 1—The Kansas portion of the High Plains aquifer, with aquifer and county boundaries shown. Each colored pixel represents one section (1 mi^2), coded for the degree of groundwater depletion from the beginning of large-scale development to the average of conditions in 2020–2022. The blue stars indicate the locations of the original three index well sites, the blue triangles indicate additional telemetry-equipped wells, the green circles are the index wells without telemetry equipment for which data are downloaded quarterly, and the yellow polygon indicates the Sheridan-6 Local Enhanced Management Area. The plus signs are seven expansion wells that have been or are being continuously monitored within GMD1.

3 Overview of Index Well Sites and Monitoring Data

This section provides a brief discussion of the hydrographs from the 31 index wells and additional GMD1 expansion wells currently in operation. The duration of monitoring ranges from more than 15 years of hourly measurements at the three original index wells to less than a year 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 second half of 2021 or early 2022, discussion of each well will be limited to one page. Further information can be found in previous reports and on the KGS website. In reports before 2017, two tables were presented for most wells: one provided information about the well hydrograph and the local water use, and the other provided comparisons between the manual annual water-level measurements and the transducer measurements. Those tables with data from all years of index well operation are now online at www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml.

3.1 GMD1 Index Wells

Five index wells are located in GMD1 (fig. 2). The Scott well was one of the original index wells drilled in 2007, whereas the Lane, Wallace, and Wichita County wells were drilled in the spring of 2016. The Wichita County 2 well was added to the network in early 2022. Table 1 summarizes the characteristics of these five wells. Further details concerning these wells are given in the 2016 annual report (Butler, Whittemore et al., 2017) and later in this section 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	2022 WL elev. (ft)[a]	2022 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2020 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Lane	2,768.7	34.7	118	105–115	513	1,381	3,046[b]
Scott	2,825.7	81.5	223	215–225	645	2,854[c]	15,483[d]
Wallace	3,551.2	117.2	394	375–385	887[e]	6,365[e]	20,003[f]
Wichita	3,287.6	29.6	190	175–185	312	2,293	8,574[g]
Wichita 2	3,277.4	39.4	221	[h]	913	3,434	8,123[g]

[a] 2022 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html). Wichita 2 is a manual measurement taken on 2/9/22.

[b] Includes 55 ac-ft of municipal water and 2 ac-ft of non-irrigation stock water.

[c] Includes 10 ac-ft of non-irrigation stock water.

[d] Includes 5 ac-ft of domestic water, 6 ac-ft of industrial water, 1,039 ac-ft of municipal water, and 417 ac-ft of non-irrigation stock water.

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

[f] Includes 66 ac-ft of municipal water and 7 ac-ft of non-irrigation stock water.

[g] Includes 91 ac-ft of non-irrigation stock water.

[h] Screened interval to be determined by downhole camera.

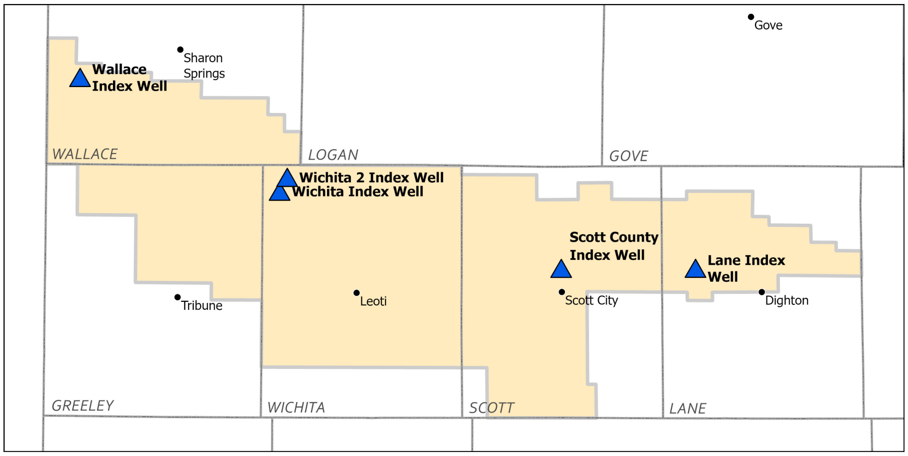


Figure 2—Map of index wells in GMD1; data from these wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

3.1.1 Lane County Index Well

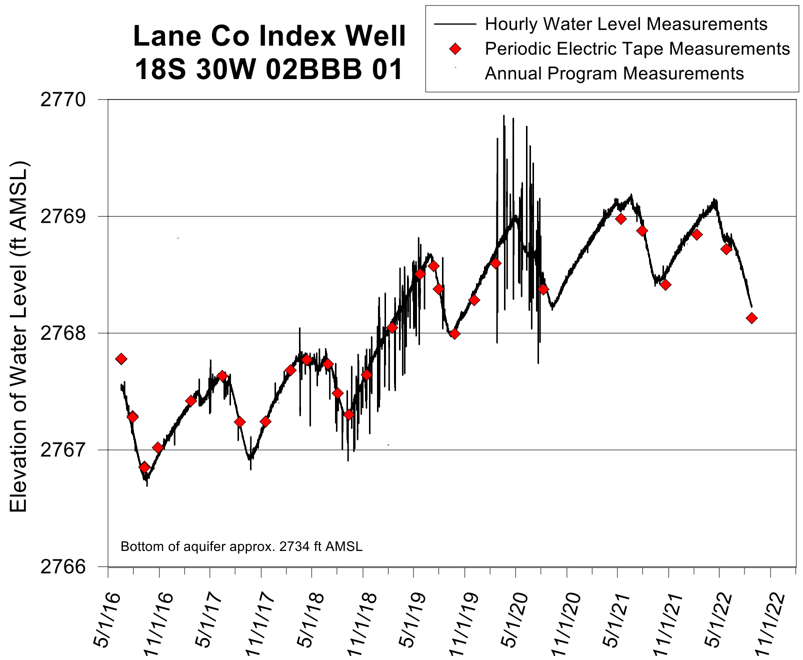


Figure 3—Lane County index well hydrograph—total data run to 8/25/22. A water-level elevation of 2,767 ft corresponds to a depth to water of 85 ft below land surface (lsf). The top of the screen is 105 ft below lsf (elevation of 2,747 ft), and the bottom of the aquifer is 118 ft below lsf (elevation of 2,734 ft). The screen terminates 3 ft above the bottom of the aquifer. The 2017 and 2019 annual water-level measurements appear to be in error. The agreement between electric-tape measurements and the transducer is beginning to lessen, indicating that the transducer likely needs to be recalibrated.

Major Points

- Very small amplitude fluctuations superimposed on the water levels are likely an indication of a relatively shallow unconfined aquifer overlain by a vadose zone with high air permeability.
- The influence of individual nearby pumping wells is not discernible; the water-level response appears to be a response to regional, more distant pumping, rather than a response to pumping at nearby wells as at most of the index wells (i.e., response is more integrated in nature).
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The maximum water level for 2021 was 0.2 ft above that of 2020, whereas the minimum water level for 2021 was also 0.2 ft above that of 2020; such year-on-year increases are rare in the index wells in western Kansas but have occurred every year during monitoring at the Lane County well.
- Many short-duration spikes appear on the hydrograph until mid-summer 2020; we suspect the origin of the spikes is related to air expansion and contraction in the desiccant tube of the gauge pressure sensor (Cain et al., 2004), which was located by the telemetry box and exposed to sunlight. On August 8, 2020, we replaced the telemetry system with a different vendor's system that did not expose the tubing to sunlight and the spikes disappeared.

3.1.2 Scott County Index Well

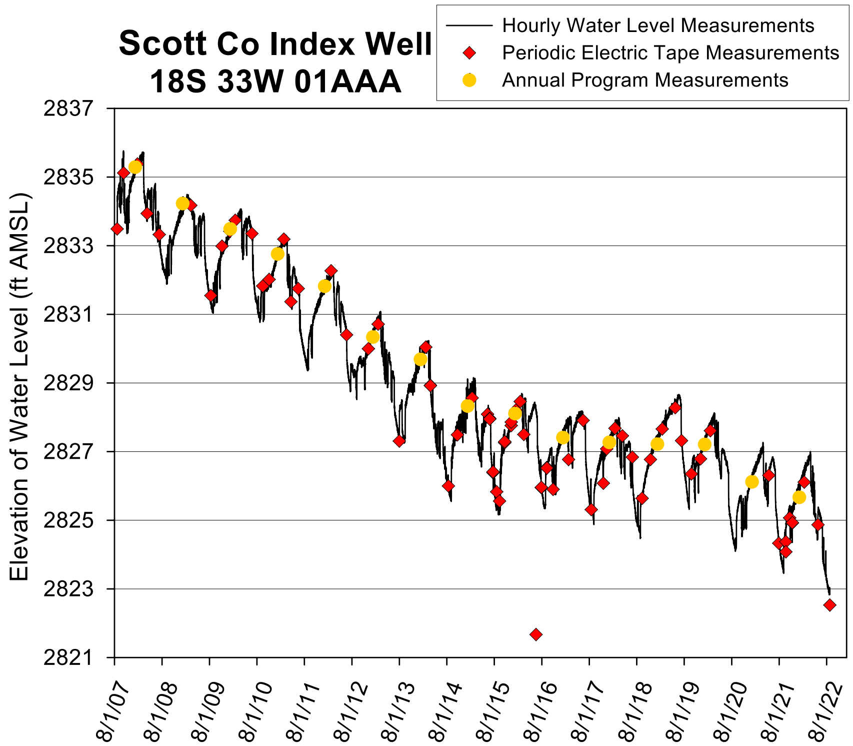


Figure 4—Scott County index well hydrograph—total data run to 8/25/22. A water-level elevation of 2,829 ft corresponds to a depth to water of 138.15 ft below lsf. The top of the screen is 215 ft below lsf (elevation of 2,752.15 ft), and the bottom of the aquifer is 223 ft below lsf (elevation of 2,744.15 ft). The screen terminates 2 ft below the bottom of the aquifer. Transducer data have been adjusted for change in position as described in a previous annual report (Butler, Whittemore, Reboulet et al., 2016).

Major Points

- The hydrograph form, the relatively small change and rate of change in water level during each pumping and recovery season (despite at least two high-capacity pumping wells within approximately a half mile of the index well), and the fluctuations superimposed on the water levels are all indications of an unconfined aquifer.
- The effect of individual pumping wells is discernible, indicating that one or more pumping wells are in relatively close proximity to and in good hydraulic connection with the index well.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The maximum water level has been below that of the preceding year for every year except 2019. The minimum water level for 2021 was the lowest of the monitoring period until that time and 0.6 ft below that for 2020. The minimum water level in 2022 will be the lowest on record.
- Transducer readings are in good agreement with manual measurements except for one anomalous electric-tape measurement that appears to be a transcription error.

3.1.3 Wallace County Index Well

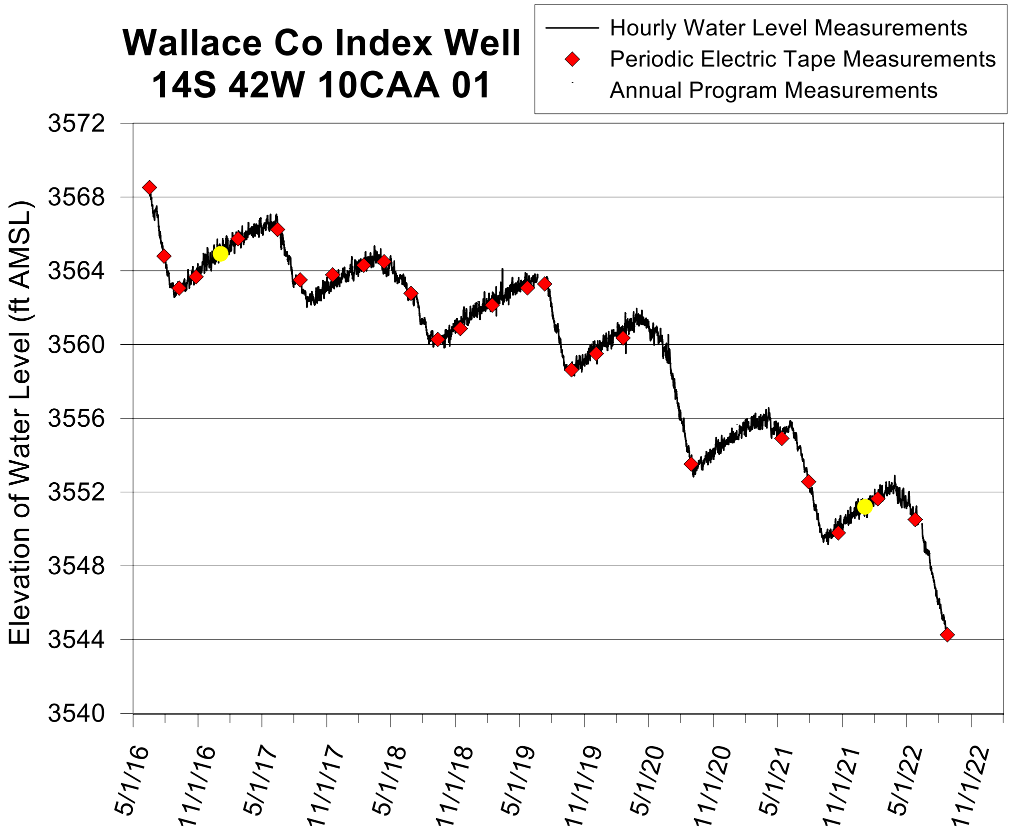


Figure 5—Wallace County index well hydrograph—total data run to 8/25/22. A water-level elevation of 3,564 ft corresponds to a depth to water of 264 ft below lsf. The top of the screen is 375 ft below lsf (elevation of 3,453 ft), and the bottom of the aquifer is 394 ft below lsf (elevation of 3,434 ft). The screen terminates 9 ft above the bottom of the aquifer.

Major Points

- The large amplitude fluctuations superimposed on the water levels, particularly evident during the recovery period, are an indication of unconfined conditions with a relatively deep water table.
- The effect of individual pumping wells is discernible, indicating that one or more pumping wells are in relatively close proximity to and in good hydraulic connection with the index well.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- Each year, the maximum and minimum water levels are below that of the preceding year, creating a downward stair-stepping pattern. The 2021 minimum water level was 3.6 ft below that of 2020. The difference between the 2021 and 2022 minimum water levels will likely be the largest of the monitoring period.
- Transducer readings are in good agreement with manual measurements. Similar to the Lane index well, many short-duration spikes appear on the hydrograph until mid-summer 2020. On August 29, 2020, we replaced the telemetry system with a different vendor's system and the spikes disappeared.

3.1.4 Wichita County Index Well

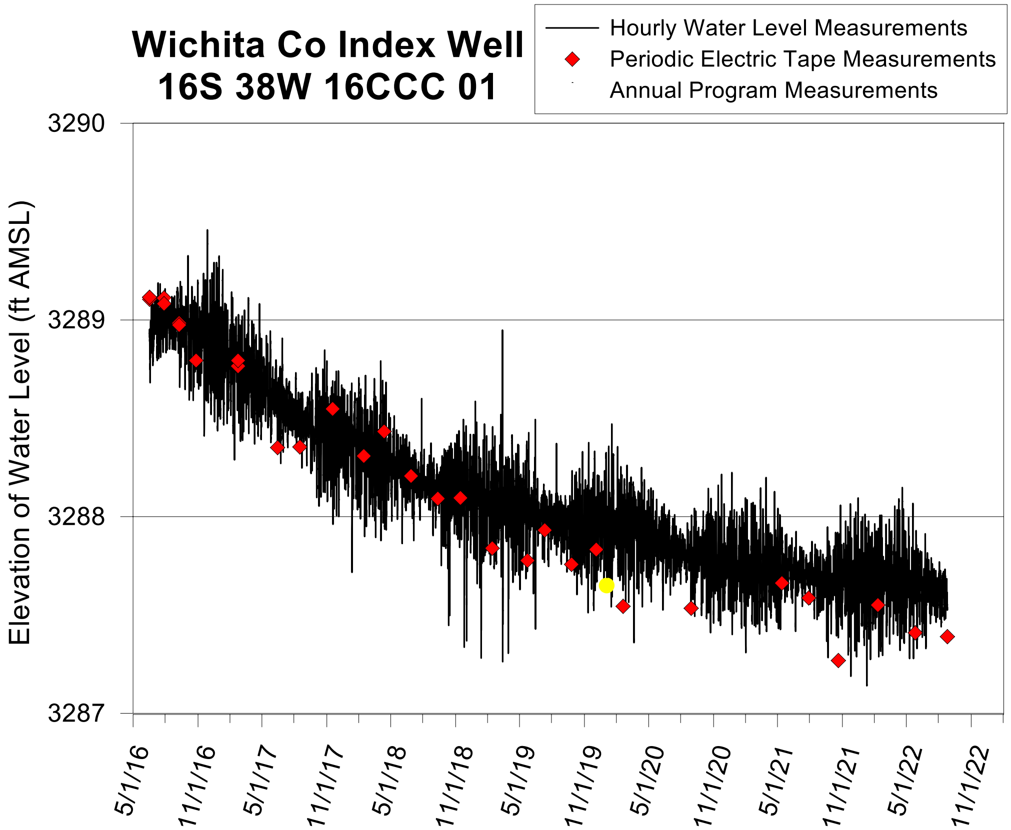


Figure 6—Wichita County index well hydrograph—total data run to 8/25/22. A water-level elevation of 3,288 ft corresponds to a depth to water of 160 ft below lsf. The top of the screen is 175 ft below lsf (elevation of 3,273 ft), and the bottom of the aquifer is 190 ft below lsf (elevation of 3,258 ft). The screen terminates 5 ft above the bottom of the aquifer.

Major Points

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

3.1.5 Wichita County 2 Index Well

Figure 7—Aerial view of the Wichita County 2 index well (center of figure) and nearby index and annual wells and points of diversion.

Figure 7 is an aerial view of the Wichita County 2 index well site (T. 16 S., R. 38 W., 10 BBC 01) at a scale that shows the site of the index well, the Wichita County index well, an additional annual program well, and the nearby wells with active water rights. The Wichita County 2 well is approximately 1.9 miles northeast of the Wichita County index well.

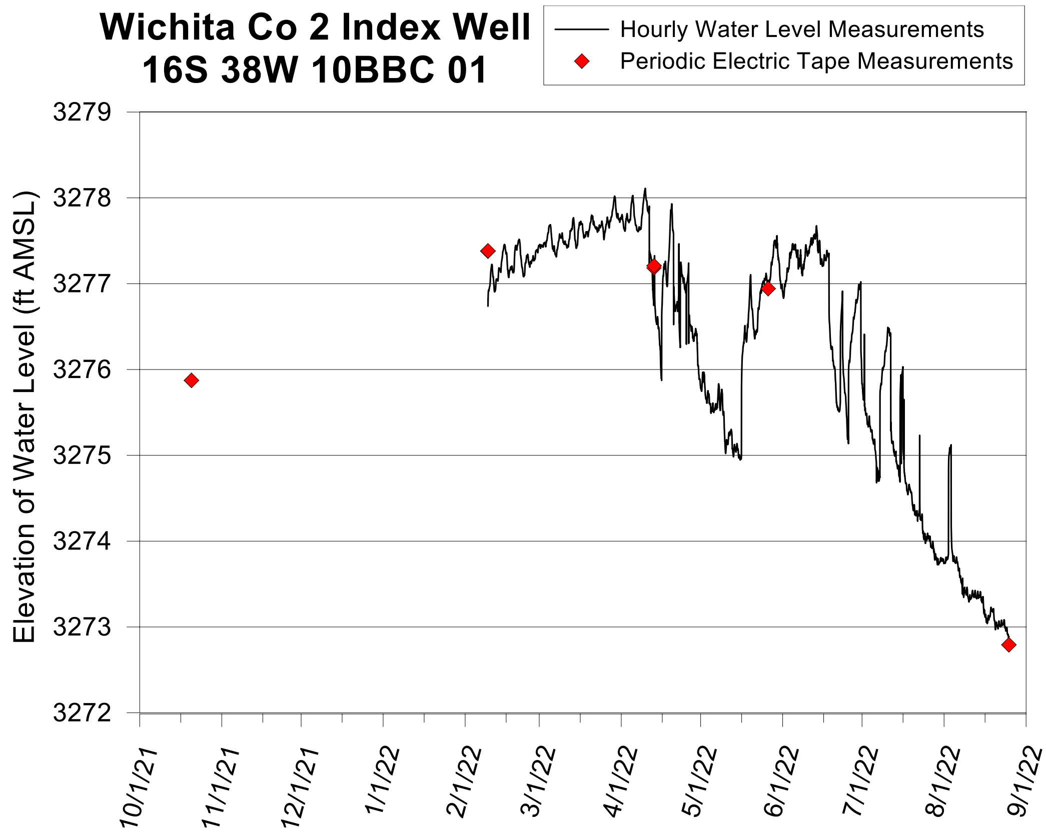


Figure 8—Wichita County 2 index well hydrograph—total data run to 8/25/22. A water-level elevation of 3,277 ft corresponds to a depth to water of 182 ft below lsf. The screened interval has yet to be determined. The aquifer bottom is estimated to be 221 ft below lsf (elevation of 3,238 ft); the well bottom is 226.2 ft below lsf.

Major Points

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

3.2 GMD2 Index Wells

There are currently five index wells in GMD2 (fig. 9), 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.

Site	2022 WL elev. (ft)[a]	2022 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2020 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Bentley	1,372.8	207.8	216	[b]	1,049	3,020[c]	24,115[d]
Harvey	1,416.5	167.5	206	198–208	638	3,304[e]	12,148[f]
McPherson	1,400.4	90.4	184	139–183	1,653[g]	6,642[h]	11,678[i]
Mount Hope	1,408.9	160.7	173	166–176	874	2,490[j]	18,855[k]
Pretty Prairie	1,547.2	49.2	71	61–71	756[l]	2,574[m]	8,564[m]

[a] 2022 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html); Bentley estimated from sensor data on 1/11/22 from 0800–1700.

[b] Screened interval to be determined by downhole camera.

[c] Includes 199 ac-ft of municipal water.

[d] Includes 10,369 ac-ft of municipal water and 681 ac-ft of industrial water.

[e] Includes 221 ac-ft of municipal water.

[f] Includes 221 ac-ft of municipal water and 140 ac-ft of non-irrigation recreation water.

[g] Includes 1,490 ac-ft of municipal water.

[h] Includes 2,975 ac-ft of municipal water, 2,547 ac-ft of industrial water, and 3 ac-ft of non-irrigation stock water.

[i] Includes 3,031 ac-ft of municipal water, 2,592 ac-ft of industrial water, 3 ac-ft of non-irrigation stock water, 171 ac-ft of non-irrigation recreation water, and 545 ac-ft of other water.

[j] Includes 25 ac-ft of non-irrigation recreation water.

[k] Includes 4,656 ac-ft of municipal water, 10 ac-ft of domestic water, 4 ac-ft of industrial water, 77 ac-ft of other water, and 236 ac-ft of non-irrigation recreation water.

[l] Includes 3 ac-ft of municipal water.

[m] Includes 87 ac-ft of municipal water.

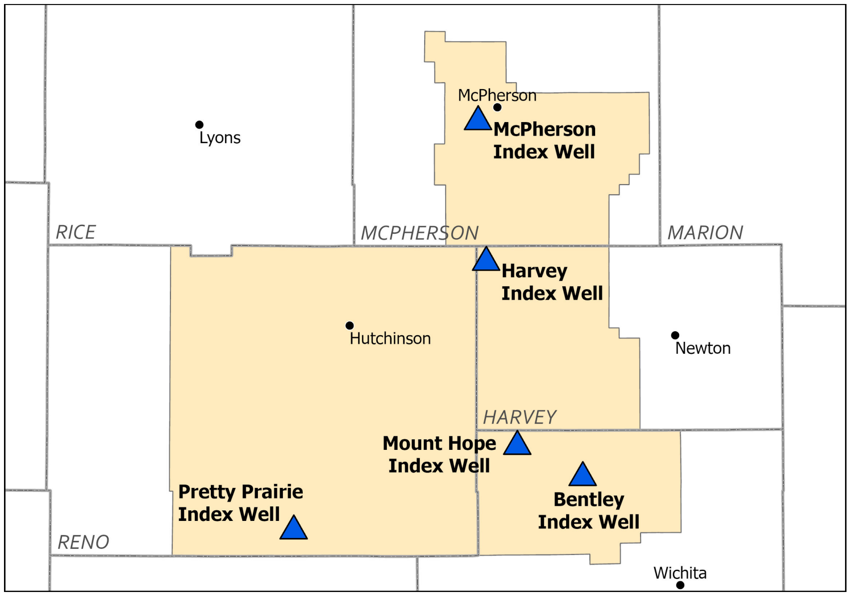


Figure 9—Map of index wells in GMD2; data from these wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_ program/index.shtml).

3.2.1 Bentley Index Well

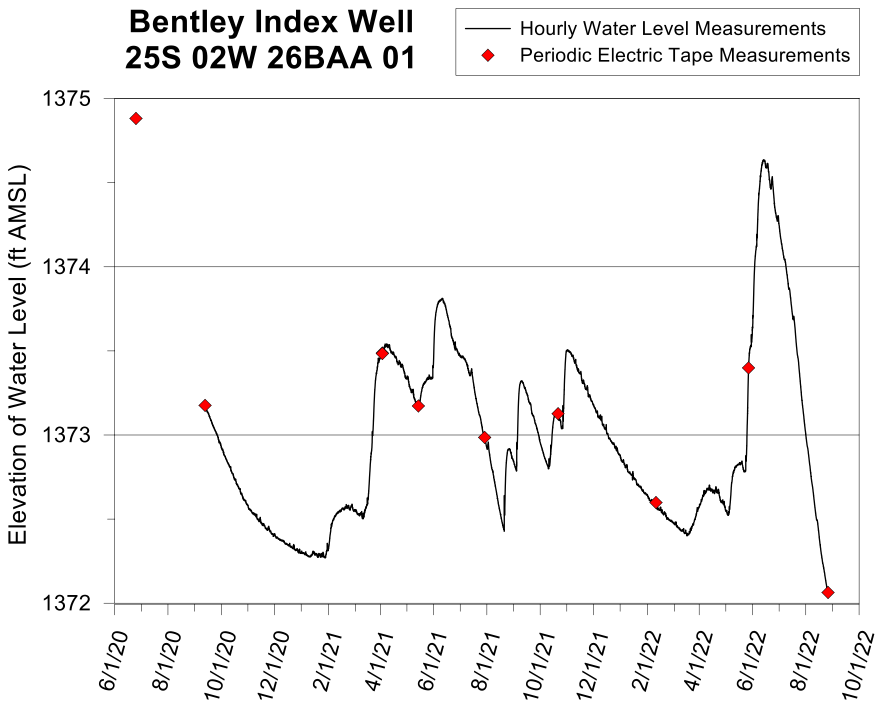


Figure 10—Bentley index well hydrograph—total data run to 8/26/22. A water-level elevation of 1,373 ft corresponds to a depth to water of 8.0 ft below lsf. The screened interval has yet to be determined. The bottom of the aquifer is approximately 216 ft below lsf (elevation of 1,165 ft), and the bottom of the well is 33.0 ft below lsf (elevation of 1,348.0 ft).

Major Points

- The hydrograph shows a small response to barometric pressure fluctuations as would be expected for shallow unconfined conditions.
- Large rapid rises are likely produced by stage changes in the nearby Arkansas River and precipitation.
- There is little indication of nearby pumping activity.
- Transducer readings are in good agreement with manual measurements.

3.2.2 Harvey County Index Well

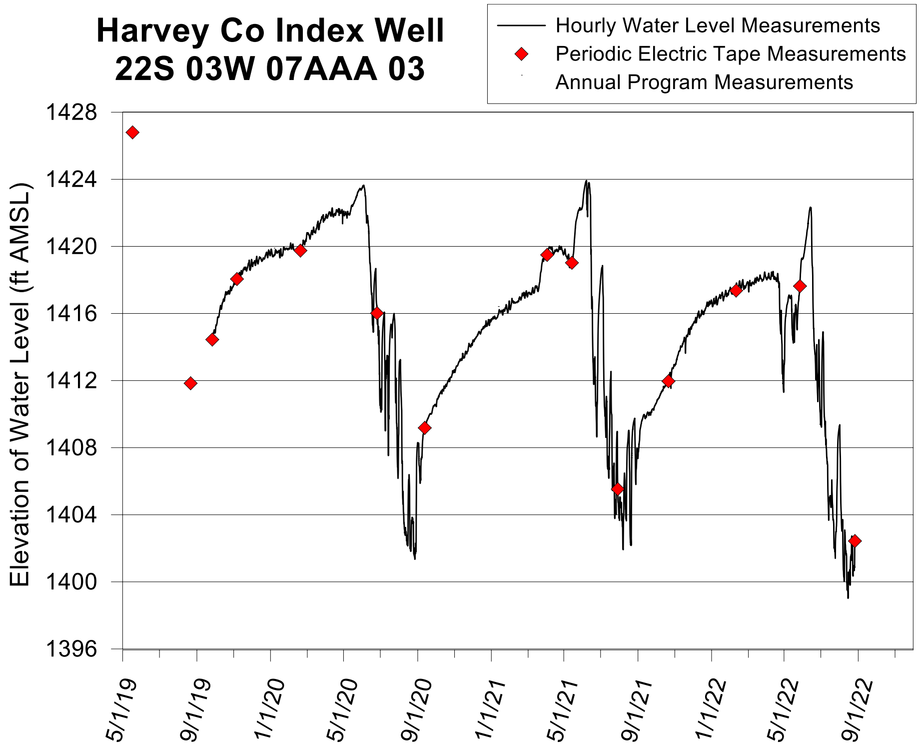


Figure 11—Harvey County index well hydrograph—total data run to 8/26/22. A water-level elevation of 1,416 ft corresponds to a depth to water of 39 ft below lsf. The top of the 10 ft screen is 198 ft below lsf (elevation of 1,257 ft), and the bottom of the aquifer is 206 ft below lsf (elevation of 1,249 ft).

Major Points

- The relatively large amplitude fluctuations superimposed on the water levels hint at unconfined conditions.
- After the end of the irrigation season, water levels continue to recover until the start of the next season.
- Abrupt rises in water level during the recovery period are likely produced by precipitation.
- Transducer readings are in good agreement with manual measurements.

3.2.3 McPherson County Index Well

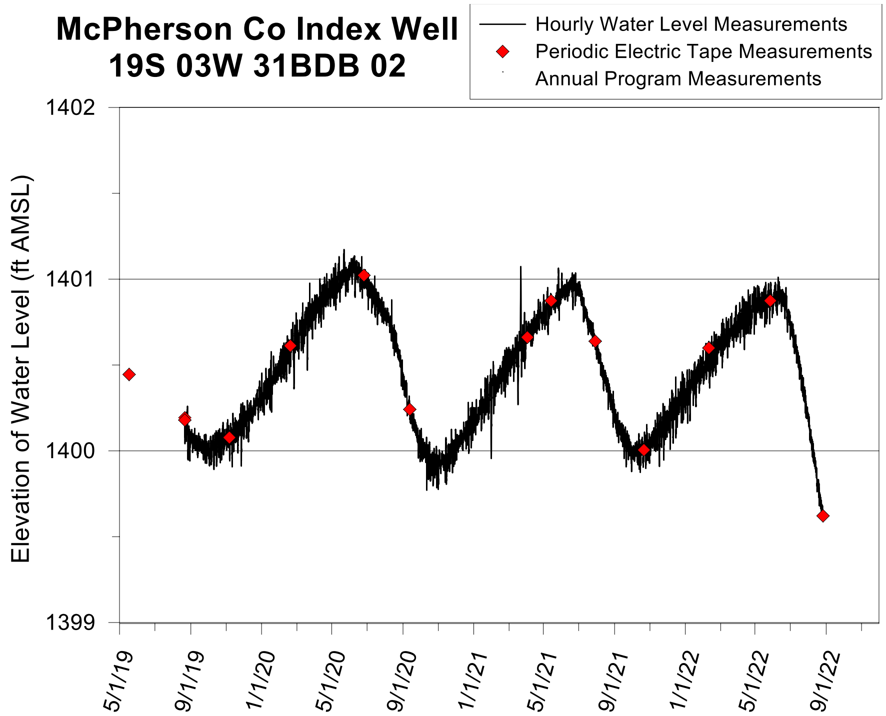


Figure 12—McPherson County index well hydrograph—total data run to 8/26/22. A water-level elevation of 1,400 ft corresponds to a depth to water of 94 ft below lsf. The top of the 44 ft screen is 139 ft below lsf (elevation of 1,355 ft), and the bottom of the screen is 183 ft below lsf (elevation of 1,311 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.
- 2020 water use (2 mi radius centered on well) was the highest of any of the index wells; the vast majority of the pumping was for municipal and industrial use.
- Transducer readings are in good agreement with manual measurements.
- The lack of water-level rises similar to that 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.

3.2.4 Mount Hope Index Well

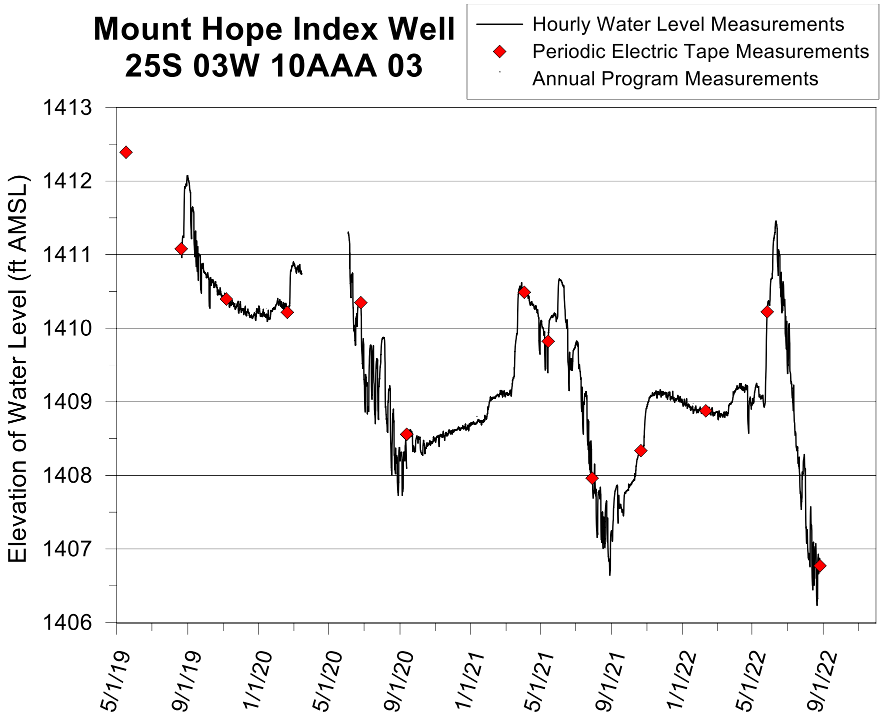


Figure 13—Mount Hope index well hydrograph—total data run to 8/26/22. A water-level elevation of 1,410 ft corresponds to a depth to water of 11.4 ft below lsf. The top of the 10 ft screen is 163 ft below lsf (elevation of 1,258.4 ft), and the bottom of the aquifer is 173 ft below lsf (elevation of 1,248.4 ft). Sensor failure produced the break of 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 following 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.
- Transducer readings are in good agreement with manual measurements.

3.2.5 Pretty Prairie Index Well

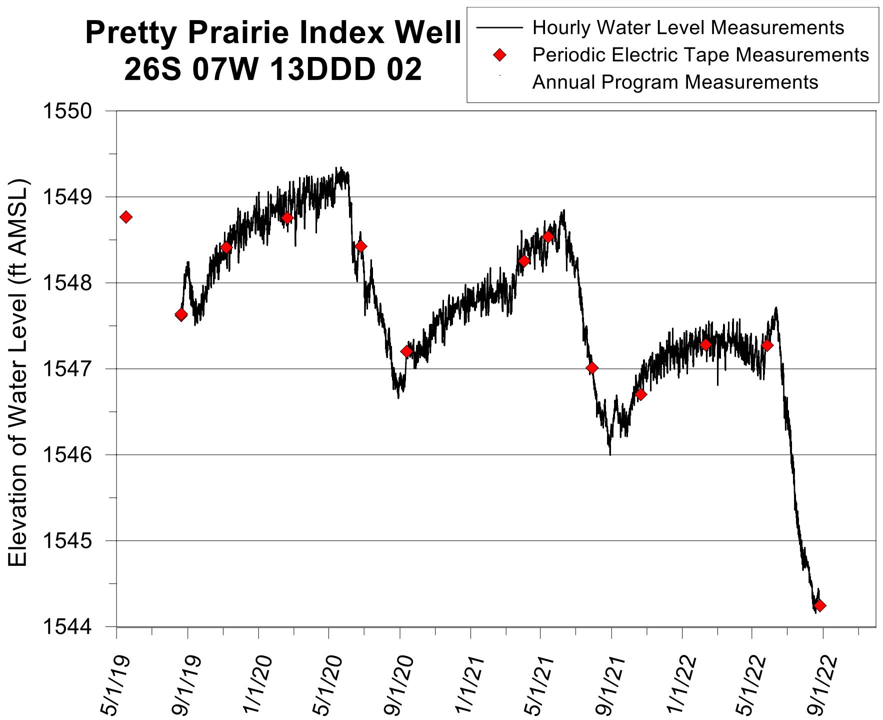


Figure 14—Pretty Prairie index well hydrograph—total data run to 8/26/22. A water-level elevation of 1,548 ft corresponds to a depth to water of 21 ft below lsf. The top of the 10 ft screen is 61 ft below lsf (elevation of 1,508 ft), and the bottom of the screen and aquifer is 71 ft below lsf (elevation of 1,498 ft).

Major Points

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

3.3 GMD3 Index Wells

Eight index wells are located in GMD3 (fig. 15). 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, and at the Kearny-Finney County index well in the summer of 2017. Table 3 summarizes characteristics of these eight wells. Further details concerning these wells are given in the 2016 annual report (Butler, Whittemore et al., 2017) 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.

Site	2022 WL elev. (ft)[a]	2022 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)[b]	Screened interval (ft below land surface)[b]	2020 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Cimarron 210	2,473.53	289.56	345	200–210	32	32	9,527[c]
Haskell	2,521.00	116.13	433	420–430	645	5,298[d]	33,380[e]
Hugoton 313[f,g]	2,899.97[f,h]	435.00	635	303–313	632	3,311	40,828[i]
Hugoton 495	2,894.90	429.96	635	485–495			
Kearny-Finney	2,784.72	183.70[e]	360[j]	70–266[k]	1,879	5,995[l]	39,686[m]
Liberal 436	2,653.14	407.14	576	426–436	0.01	1,728[n]	32,445[o]
Rolla 366	3,186.11	210.10	399	356–366	331[p]	1,248[q]	9,620[r]
Willis Tech Farm	2,626.68	188.69	502	262–482	947	5,519[s]	38,292[t]

[a] 2022 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html).
[b] Measurements for the Cimarron, Hugoton, Liberal, and Rolla wells from table 2 in McMahon (2001).
[c] Includes 34 ac-ft of non-irrigation stock water.
[d] Includes 3 ac-ft of industrial water and 5 ac-ft of municipal water.
[e] Includes 3 ac-ft of industrial water, 5 ac-ft of municipal water at 2 mile radius, and 9 ac-ft of stock water.
[f] Not part of the annual water-level measurement network.
[g] Well originally on a USGS telemetry system; the system was removed in 2017 because of a lack of funding.
[h] 2022 water-level measurement from hand measurements taken 2/15/22.
[i] Includes estimated 17,989 ac-ft of water use in Oklahoma based on "permitted" quantities.
[j] Based on logs of nearby wells to bedrock.
[k] Measurements estimated from borehole camera log.
[l] Includes 33 ac-ft of industrial water.
[m] Includes 108 ac-ft of industrial water, 275 ac-ft of municipal water, and 417 ac-ft of non-irrigation stock water.
[n] Includes 985 ac-ft of non-irrigation water for the city of Liberal and an estimated 675 ac-ft of water use in Oklahoma based on "permitted" quantities.
[o] Includes 7,785 ac-ft of non-irrigation water for the city of Liberal and an estimated 20,909 ac-ft of water use in Oklahoma based on "permitted" quantities.
[p] Includes 30 ac-ft of non-irrigation stock water.
[q] Includes 111 ac-ft of non-irrigation stock water.
[r] Includes 300 ac-ft of non-irrigation stock water and 98 ac-ft of municipal water.
[s] Includes 12 ac-ft of non-irrigation stock water.
[t] Includes 12 ac-ft of non-irrigation stock water and 563 ac-ft of industrial use water.

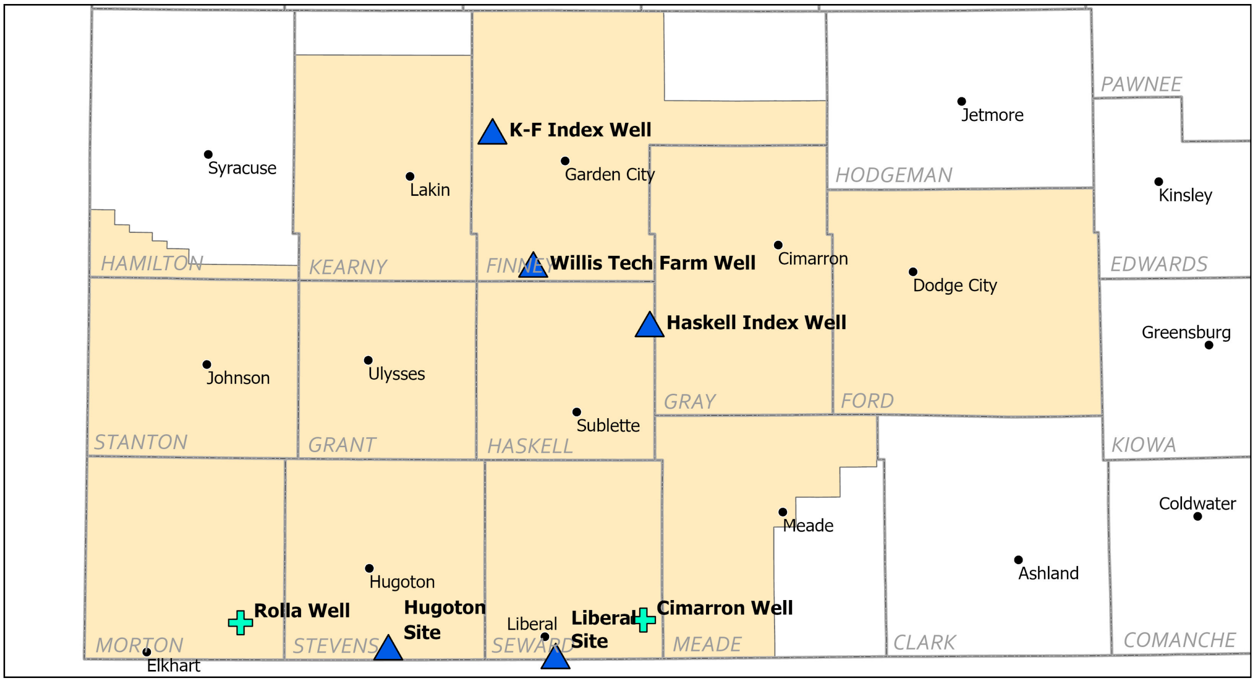


Figure 15—Map of index wells in GMD3. Triangles designate wells with telemetry equipment, whereas plus signs designate wells without telemetry equipment. Data from wells with telemetry equipment can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml); data from wells without telemetry equipment are periodically downloaded (typically quarterly) and posted on the KGS website. The 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

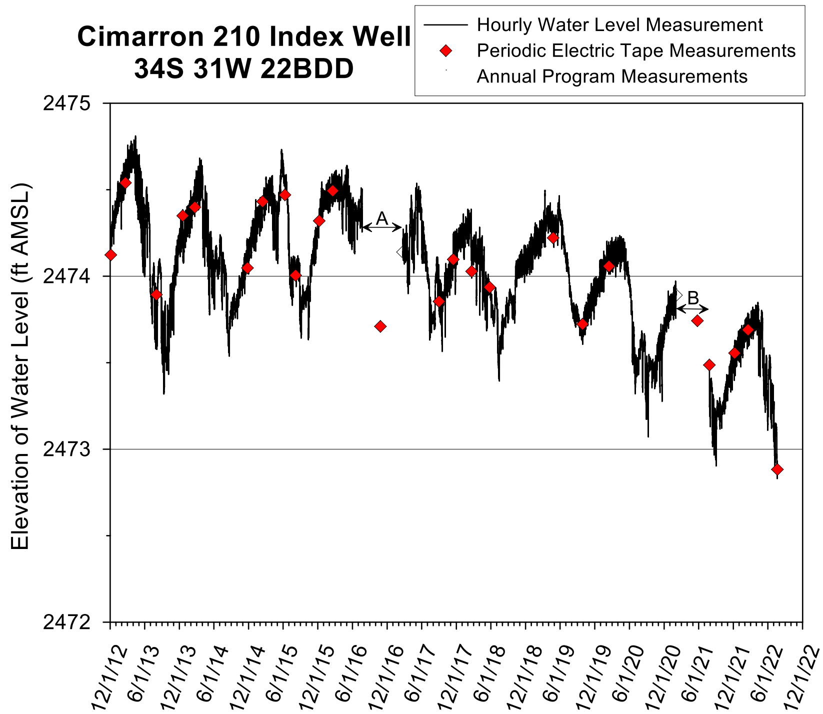


Figure 16—Cimarron 210 index well hydrograph—total data run to 7/21/22. A water-level elevation of 2,474 ft corresponds to a depth to water of 55 ft below lsf. The top of the 10 ft screen is 200 ft below lsf (elevation of 2,329 ft), and the bottom of the aquifer is 345 ft below lsf (elevation of 2,184 ft); A and B defined in text.

Major Points

- The hydrograph form and small response to pumping, despite the nearby (within 0.3 mi) irrigation well, indicate unconfined conditions.
- The relatively small (< 0.2 ft) fluctuations superimposed on the water levels, particularly evident during the recovery periods, indicate an unconfined aquifer with a relatively shallow depth to water.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- Sensor failure produced gaps (A [7/22/16–2/22/17] and B [2/3/21–7/27/21]) in hydrograph record.
- Water use within a 2 mi radius of the well is the lowest of any of the index wells.
- Water level has declined 2.5 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

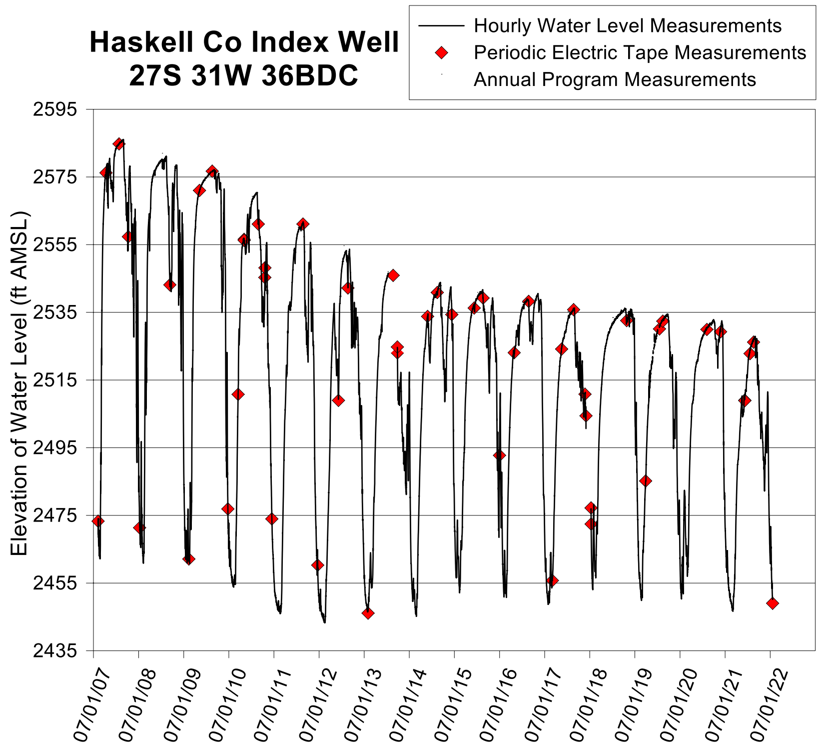


Figure 17—Haskell County index well hydrograph—total data run to 7/20/22. A water-level elevation of 2,455 ft corresponds to a depth to water of 382.85 ft below lsf. The top of the screen is 420 ft below lsf (elevation of 2,417.85 ft), and the bottom of the aquifer is 433 ft below lsf (elevation of 2,404.85 ft). The screen terminates 3 ft above the bottom of the aquifer. A sensor failure produced a break in monitoring from January to March 2014; a damaged cable produced a break in monitoring from early June to mid-July 2018; a malfunctioning sensor began producing many spurious values on 10/17/19 and was replaced on 1/16/20—only the sensor values deemed reasonable are plotted during that three-month period.

Major Points

- The hydrograph form and large response (80–120 ft) to pumping, despite the absence of nearby high-capacity wells (closest irrigation well about 0.5 mi away), indicate a confined aquifer.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- An increase in the minimum water-level elevation after 2013 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.
- The 2021 minimum water level was the lowest since 2014. The 2022 minimum is likely to be the lowest since the start of monitoring (2007) at the Haskell index well.
- Transducer readings are in reasonable agreement with manual measurements.

3.3.3 Hugoton Site

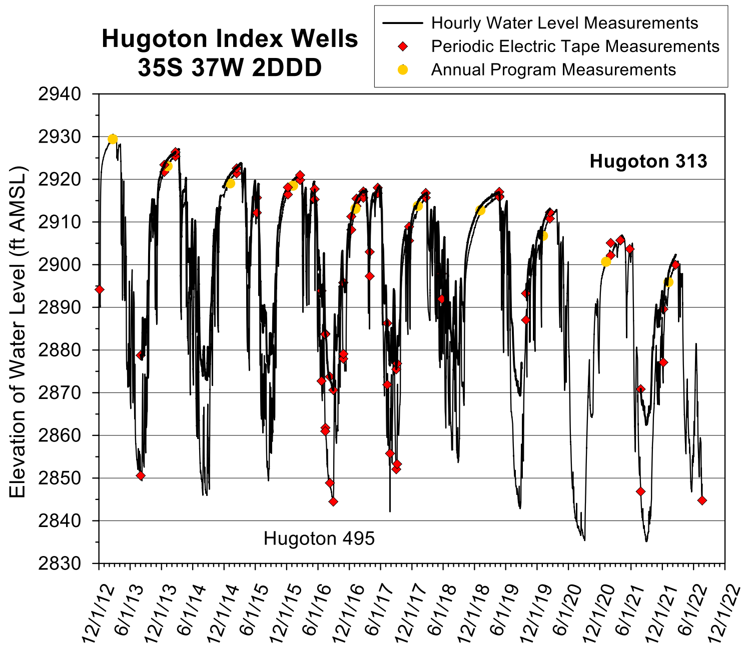


Figure 18—Hydrographs of Hugoton index wells—total data run to 7/21/22 for Hugoton 495 and 2/15/22 for Hugoton 313. A water-level elevation of 2,900 ft corresponds to a depth to water of 200 ft below lsf. For the Hugoton 495 well, the top of the 10 ft screen is 485 ft below lsf (elevation of 2,615 ft). For the Hugoton 313 well, the top of the 10 ft screen is 303 ft below lsf (elevation of 2,797 ft). Bottom of the aquifer is 635 ft below lsf (elevation of 2,465 ft). Three-hour downward spike (13–15 ft drop) on 7/26/17 in the Hugoton 495 well is associated with movement of the transducer in the well and is considered spurious. Sensor failed in Hugoton 313 on 5/19/20 but, because of pandemic-limited travel, the failure was not recognized until 2/2/21. Sensor was replaced on 7/27/21 and failed again on 2/15/22; sensor will be replaced in 2023.

Major Points

- Two wells are monitored in a four-well nest.
- Large rapid drops and rises of water level following commencement and cessation of pumping, respectively, are indicative of confined conditions in both monitored intervals.
- Hydrographs indicate both intervals are affected by the same pumping stresses; the larger response in Hugoton 495 shows that that interval is more heavily stressed, while the elevation difference between the water levels indicates that pumping has induced downward flow from the shallower interval.
- After the end of the irrigation season, water levels continue to recover until the start of the next season at both wells (water levels never stabilize).
- The water level in Hugoton 495 has declined 74.1 ft since January 2000 (decline rate of 3.4 ft/yr); see 2016 annual report (Butler, Whittemore et al., 2017) for further details.
- The 2021 minimum water level was the lowest since the start of monitoring (2012) at Hugoton 495.
- Transducer readings are in good agreement with manual measurements.

3.3.4 Kearny-Finney Index Well

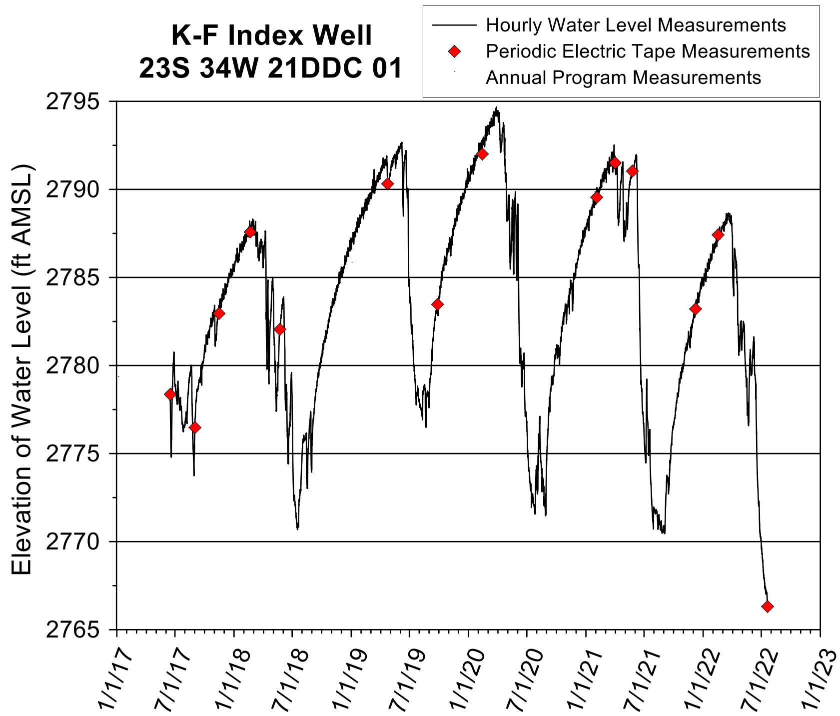


Figure 19—Kearny-Finney (K-F) index well hydrograph—total data run to 7/20/22. A water-level elevation of 2,785 ft corresponds to a depth to water of 176 ft below lsf. Nominal bottom of well is 300 ft below lsf (elevation of 2,661 ft), but the well is currently filled with sediments to 266 ft below lsf (elevation of 2,695 ft).

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 water-level elevation has dropped 53.5 ft since January 2008 (approximately half of that total decline occurred in 2011 and 2012).
- Minimum water-level elevation for 2021 was the lowest since start of monitoring and 1.0 ft lower than that of 2020 (the minimum for 2022 will be much lower); the apparent maximum recovered water level for 2022 was 3.9 ft below the maximum recovered level for 2021.
- 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

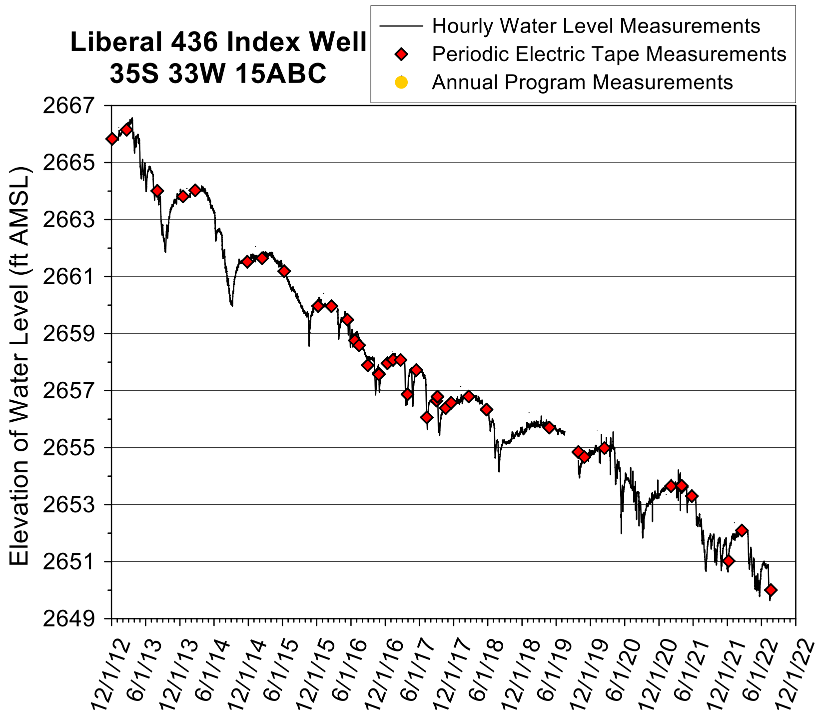


Figure 20—Hydrograph of Liberal 436 index well—total data run to 7/21/22. A water-level elevation of 2,651 ft corresponds to a depth to water of 170 ft below lsf. The top of the 10 ft screen is 426 ft below lsf (elevation of 2,395 ft). Sensor failed on July 6, 2019; a new sensor was installed on September 27, 2019.

Major Points

- One well is monitored in a four-well nest. Formerly, Liberal 160 well was also monitored but that stopped 12/26/18 as the monitoring provided very limited information.
- The hydrograph form and the relatively small (< 0.35 ft) amplitude fluctuations superimposed on water levels indicate confined conditions.
- After the end of the irrigation season, water levels recover to a near-stable value that is generally well below the level at the start of the pumping season; this pattern is an indication of limited lateral flow to the well (see Butler, Knobbe et al. [2021]).
- The water level in Liberal 436 has declined 31.1 ft since January 2000 (decline rate of 1.4 ft/yr).
- Transducer readings are in good agreement with electric tape measurements but annual program measurements recently appear to have greater error.

3.3.6 Rolla Index Well

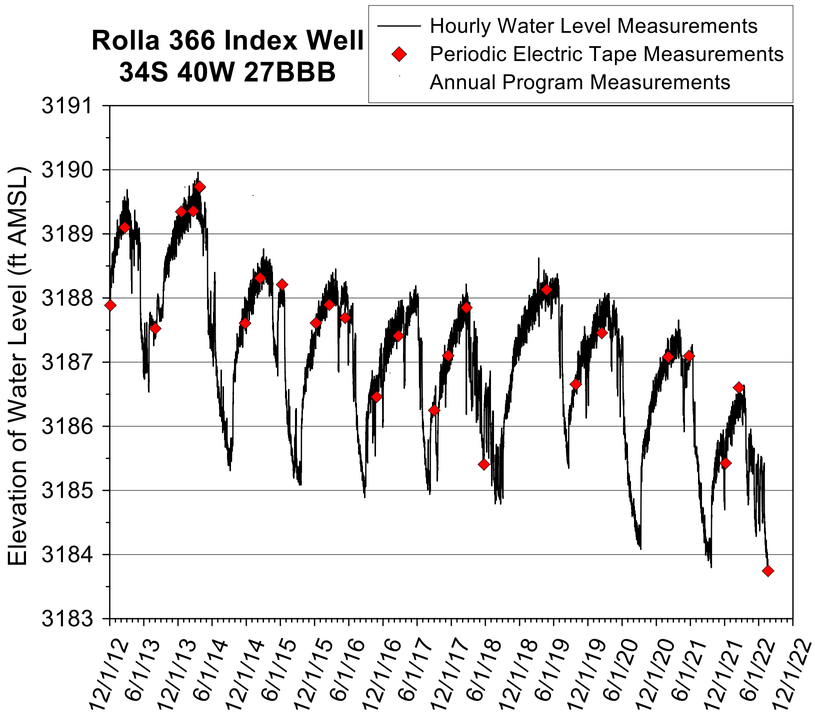


Figure 21—Rolla 366 index well hydrograph—total data run to 7/21/22. A water-level elevation of 3,188 ft corresponds to a depth to water of 187 ft below lsf. The top of the 10 ft screen is 356 ft below lsf (elevation of 3,019 ft), and the bottom of the aquifer is 399 ft below lsf (elevation of 2,976 ft). Note the suspect 2015 and 2017 annual program measurements.

Major Points

- The hydrograph form and the relatively large (up to 0.7 ft) amplitude fluctuations superimposed on water levels indicate unconfined conditions.
- The effect of individual wells turning on and off is clearly visible on the hydrograph, indicating that pumping wells are in relatively close proximity to and in good hydraulic connection with the index well.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The minimum water-level elevation in 2021 and the apparent maximum water level in 2022 were the lowest since monitoring began in late 2012; the minimum water-level elevation in 2022 will be the lowest on record.
- The water level has declined 10.9 ft since January 2000 (decline rate of 0.50 ft/yr).
- Transducer readings are in good agreement with electric-tape measurements but poorer agreement with some of the annual measurements.

3.3.7 Willis Water Technology Farm Index Well

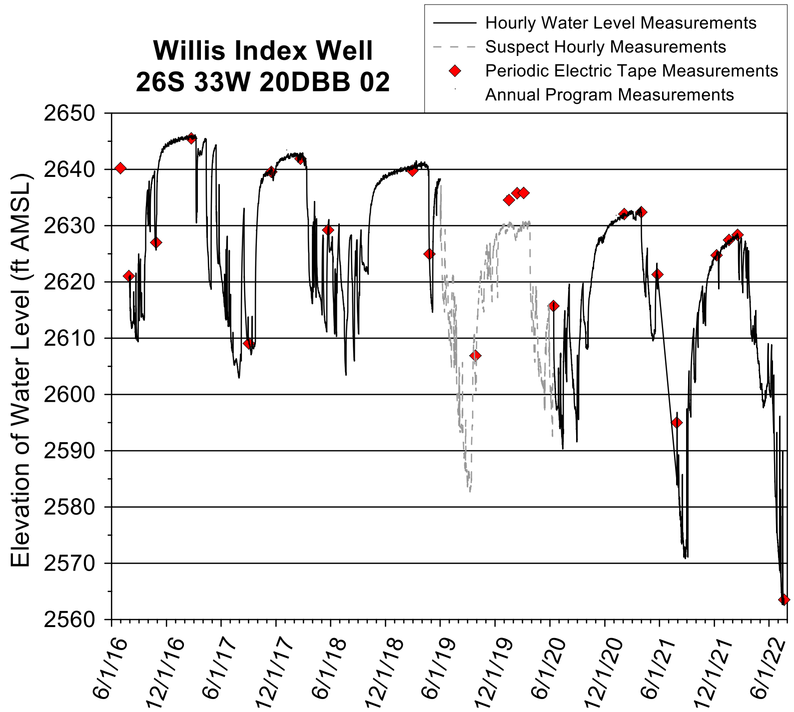


Figure 22—Willis Water Technology Farm index well hydrograph—total data run to 7/20/22. A water-level elevation of 2,620 ft corresponds to a depth to water of 320 ft below lsf. The top of the 220 ft screen is 262 ft below lsf (elevation of 2,678 ft), and the bottom of the aquifer is 502 ft below lsf (elevation of 2,438 ft). The first electric-tape measurement was taken before continuous monitoring began. The lack of agreement between manual and transducer measurements from September 2019 to June 2020 is a result of a miscalibrated transducer (dashed line indicates transducer data during this period). Telemetry ceased operating on 2/9/21 due to cable damage; repaired cable was installed on 7/27/21.

Major Points

- The relatively large amplitude fluctuations superimposed on the water levels, particularly evident during the latter stages of the recovery period, indicate unconfined conditions.
- The effect of individual wells turning on and off is clearly visible on the hydrograph, indicating pumping wells are in relatively close proximity to and in good hydraulic connection with the index well.
- Each year, the maximum water level is below that of the preceding year, creating a downward stair-stepping pattern. Some years, water levels recover to a near stable value while, in other years, the recovery continues until the start of the next irrigation season. The water level has fallen approximately 17.1 ft since February 2017, a rate of decline of approximately 3.4 ft/year.
- Transducer readings are in good agreement with manual measurements except for the 2017 and 2019 annual measurements and from 2/19 to 6/20 (dashed record).

3.4 GMD4 Index Wells

Nine index wells are located in GMD4, six of which have telemetry equipment that allows real-time viewing of data (fig. 23). The Thomas index well was one of the original 2007 index wells and had telemetry capabilities from the start. Monitoring with telemetry began at the Colby, Seegmiller Sheridan-6 (SD-6) LEMA, Sherman, Steiger SD-6 LEMA, and Sherman 2 index wells in 2015, 2016, 2017, 2021, and 2022, respectively. Table 4 summarizes characteristics of these nine wells. Further details concerning these wells are given in the 2016 annual report (Butler, Whittemore et al., 2017), this report, 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.

Site	2022 WL elev. (ft)[a]	2022 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2020 water use (ac-ft) 1 mi radius circle	2 mi radius circle	5 mi radius circle
Colby	3,023.6	96.6[b]	250–300	156–175	626[c]	2,256[d]	11,683[e]
SD-6 Baalman	2,710.4	75.4	262	260–270	724	2,459	16,578[f]
SD-6 Beckman[g,h]	2,678.9[g]				1,215	4,114[i]	16,556[j]
SD-6 Moss[g]	2,624.1[g]	51.1	243	205–245	390	2,783	16,150[k]
SD-6 Seegmiller	2,738.6	70.6	265	225–265	994	3,948	19,199[l]
SD-6 Steiger[g]	2,848.9[g]	60.9	177	145–185	237	1,351[m]	11,308[n]
Sherman	3,613.9	142.9	323	310–320	2,279	4,519	13,779[o]
Sherman 2	3,366.0	117.0	275	240–280	213	1,849	10,768[p]
Thomas	2,969.8	66.4	284	274–284	1,030	2,765	12,320

[a] 2022 annual tape water-level measurements from WIZARD database (www.kgs.ku.edu/Magellan/WaterLevels/index.html). Sherman 2 is a manual measurement taken on 2/9/22.
[b] Based on bedrock depth of 250 ft below lsf.
[c] Includes 341 ac-ft of municipal water.
[d] Includes 1,237 ac-ft of municipal water and 234 ac-ft of other water.
[e] Includes 1,392 ac-ft of municipal water, 234 ac-ft of other water, 1 ac-ft of industrial water, and 2 ac-ft of non-irrigation stock water.
[f] Includes 720 ac-ft of non-irrigation stock water.
[g] Not an annually measured index well; 2022 water-level measurements estimated from sensor data on 01/12/2022 from 0800 to 1700 at Beckman, Moss, and Steiger.
[h] Well construction information not available.
[i] Includes 367 ac-ft of non-irrigation stock water.
[j] Includes 636 ac-ft of non-irrigation stock water.
[k] Includes 555 ac-ft of non-irrigation stock water, 1 ac-ft of industrial water, and 325 ac-ft of municipal water.
[l] Includes 636 ac-ft of non-irrigation stock water.
[m] Includes 30 ac-ft of non-irrigation stock water.
[n] Includes 50 ac-ft of non-irrigation stock water and 3 ac-ft of recreational water.
[o] Includes 262 ac-ft of recreational water.
[p] Includes 76 ac-ft of non-irrigation stock water.

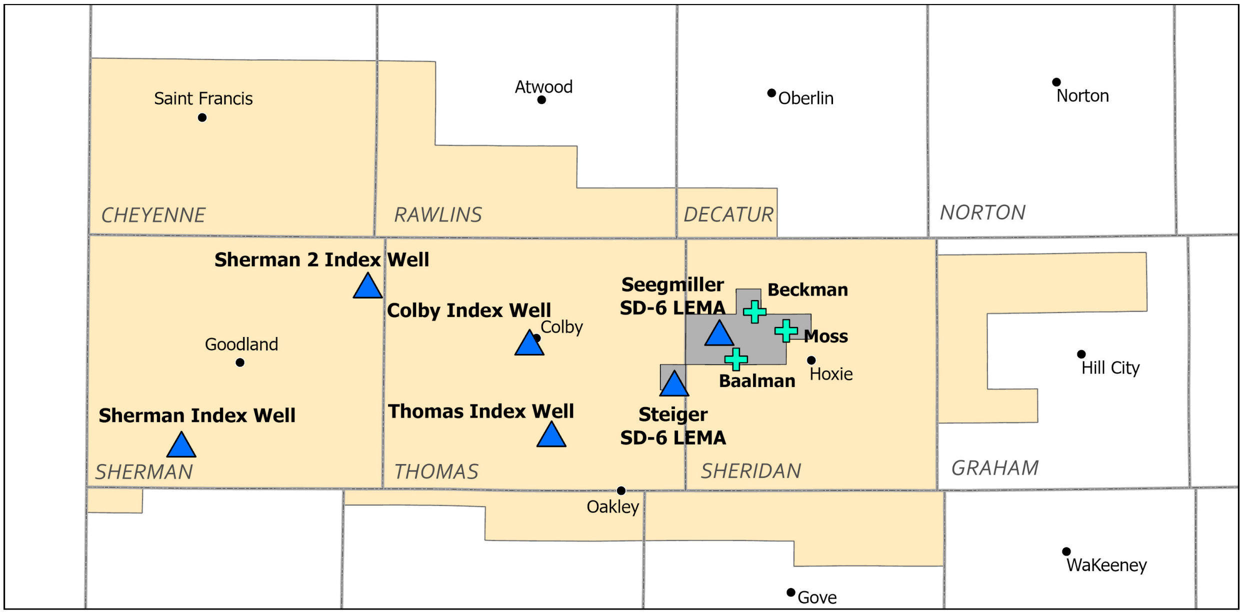


Figure 23—Map of index wells in GMD4. Triangles designate wells with telemetry equipment, and plus signs designate wells without telemetry equipment. Data from wells with telemetry equipment can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml); data from wells without telemetry equipment are periodically downloaded (typically quarterly) and posted on the KGS website. Shaded area is the Sheridan-6 LEMA.

3.4.1 Colby Index Well

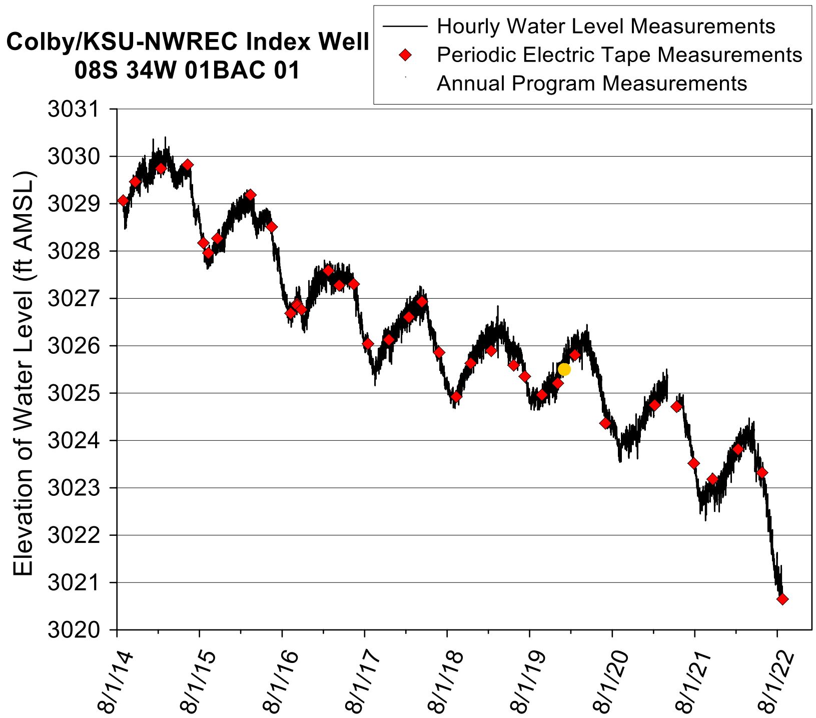


Figure 24—Colby index well hydrograph—total data run to 8/24/22. A water-level elevation of 3,024 ft corresponds to a depth to water of 153 ft below lsf. Total depth of the well is 175 ft below lsf (elevation of 3,002 ft). The screened interval extends from 156 to 175 ft below lsf. The base of the aquifer is estimated to be 250–300 ft below lsf (Butler, Whittemore et al., 2017). Sensor failed on 4/1/21 and was replaced on 5/12/21.

Major Points

- The relatively large amplitude fluctuations superimposed on the water-level record indicate unconfined conditions.
- After the end of the irrigation season, water levels continue to recover until the start of the next season; apparent stabilization of water levels in late winter and early spring of 2017 appears to be a product of nearby pumping.
- The maximum recovered water level has declined each year during the monitoring period, giving a distinct stair-step character to the hydrograph.
- Based on annual water-level measurements, the water level has declined approximately 0.86 ft/yr over the monitoring period and a total of 39.3 ft since January 1948. The decline in 2022 will likely be the largest during the monitoring period.
- Transducer readings are in good agreement with manual measurements.

3.4.2 SD-6 Baalman Index Well

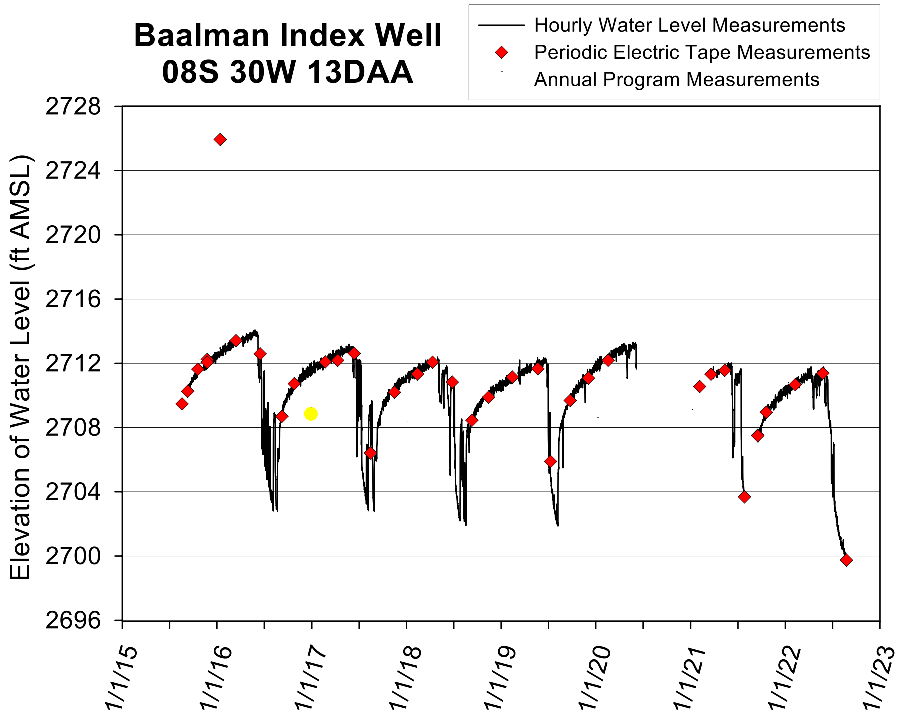


Figure 25—Baalman index well hydrograph—total data run to 8/24/22. A water-level elevation of 2,712 ft corresponds to a depth to water of 185 ft below lsf. The top of the 10 ft screen is 260 ft below lsf (elevation of 2,637 ft), and the bottom of the aquifer is 262 ft below lsf (elevation of 2,635 ft). The difference between the electric-tape and transducer measurements in January 2016 was caused by a malfunctioning electric tape.

Major Points

- The hydrograph form and the relatively large amplitude fluctuations superimposed on the water levels, particularly evident during the recovery period, are an indication of unconfined conditions.
- The effect of individual wells turning on and off is clearly visible, indicating pumping wells are in relatively close proximity to and in good hydraulic connection with the index well.
- The maximum water level in 2022 was the lowest in the monitoring period and the minimum water level in 2022 will be far lower than previous minima during the monitoring period.
- Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.71 ft (8.5 inches)/acre in the vicinity of the Baalman index well (2 mi radius).
- 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.
- Transducer readings are in good agreement with periodic electric-tape measurements, except for the January 2016 measurement, but in poor agreement with annual program measurements.

3.4.3 SD-6 Beckman Index Well

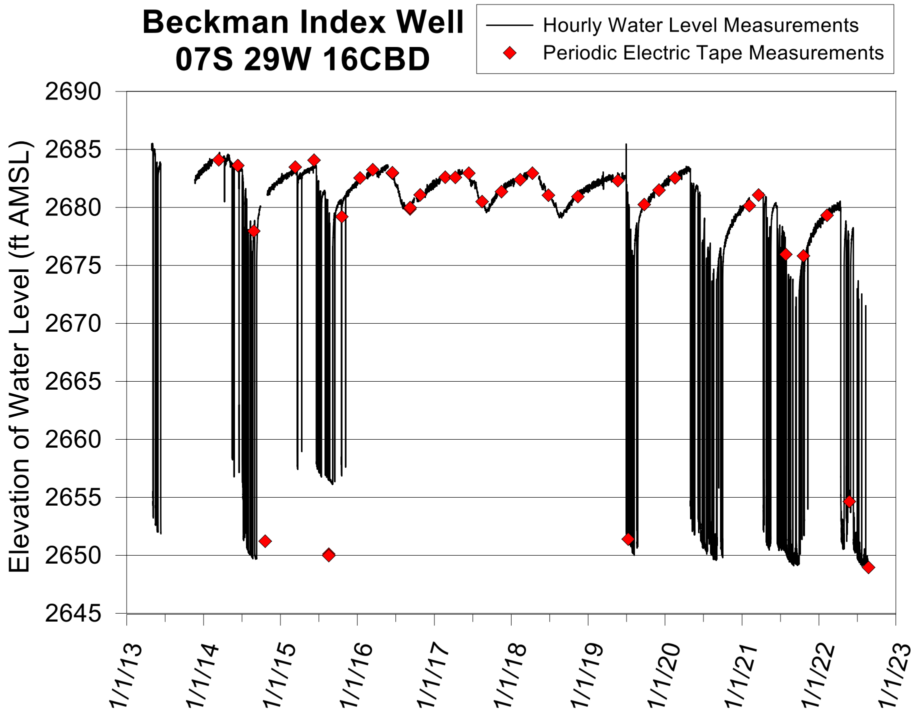


Figure 26—Beckman index well hydrograph—total data run to 8/24/22. A water-level elevation of 2,680 ft corresponds to a depth to water of 200.15 ft below lsf. The data gaps in 2013 and 2014 were caused by datalogger battery problems. The difference between the electric-tape measurement in the summer of 2015 and the hourly measurements from the transducer is thought to be caused by a change in transducer calibration specifications associated with the resumption of monitoring in late October 2014.

Major Points

- The irrigation well adjacent to the Beckman index well was pumped for the fourth time in the last four irrigation seasons and the seventh time since the establishment of the SD-6 LEMA.
- The hydrograph form and the relatively large amplitude fluctuations superimposed on the water levels, particularly evident during the recovery period, are an indication of unconfined conditions.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.73 ft (8.8 in)/acre in the vicinity of the Beckman index well (2 mi radius).
- Sensor failed on 2/4/21 and was replaced during site visit on 3/20/21.
- Transducer readings are in good agreement with manual measurements in the latter half of the monitoring period.

3.4.4 SD-6 Moss Index Well

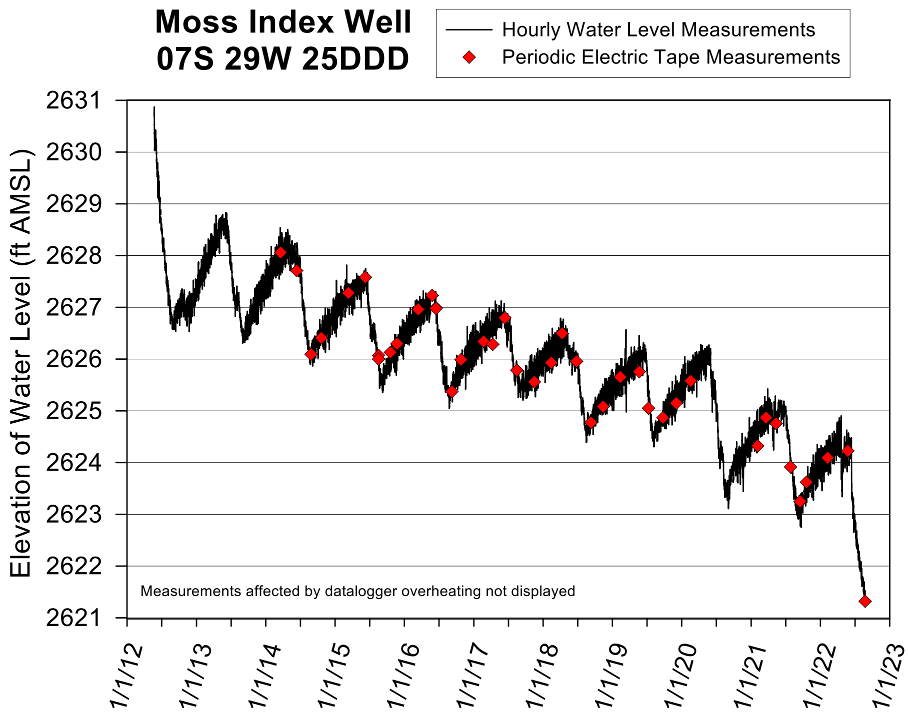


Figure 27—Moss index well hydrograph—total data run to 8/24/22. A water-level elevation of 2,625 ft corresponds to a depth to water of 191 ft below lsf. The top of the 40 ft screen is 205 ft below lsf (elevation of 2,611.0 ft), and the bottom of the aquifer is 243 ft below lsf (elevation of 2,573.0 ft).

Major Points

- The relatively large amplitude fluctuations superimposed on the water levels, particularly evident during the recovery period, are an indication of unconfined conditions.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The minimum water-level elevation has been above that of the preceding year once (2017, a wet year). Otherwise, the hydrograph displays a downward stepping pattern.
- Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.82 ft (9.8 in)/acre in the vicinity of the Moss index well (2 mi radius).
- Transducer readings are in good agreement with manual measurements.

3.4.5 SD-6 Seegmiller Index Well

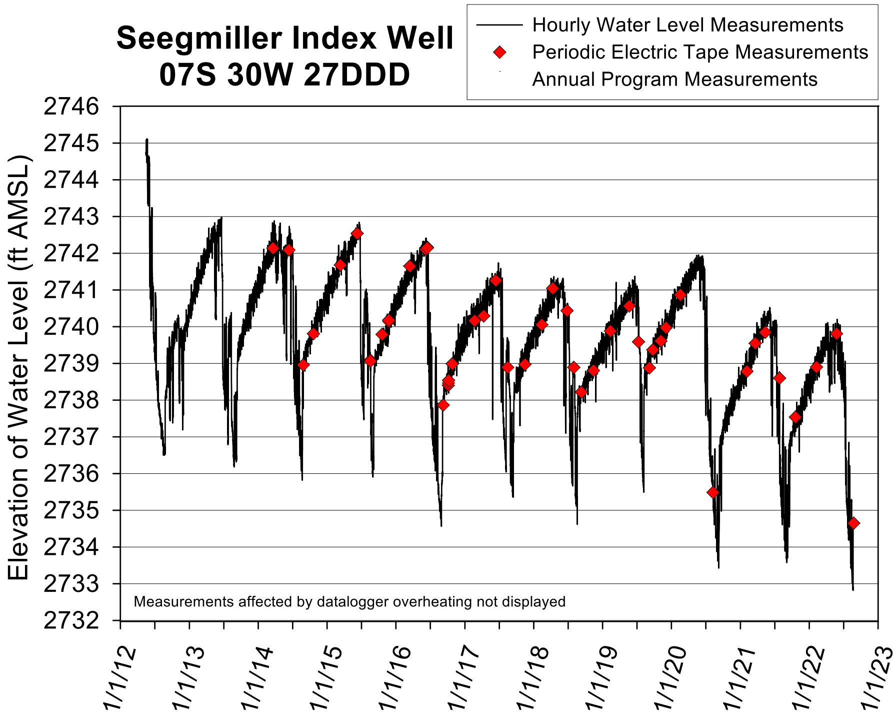


Figure 28—Seegmiller index well hydrograph—total data run to 8/24/22. A water-level elevation of 2,740 ft corresponds to a depth to water of 193 ft below lsf. The top of the 40 ft screen is 225 ft below lsf (elevation of 2,708 ft), and the bottom of the aquifer is 265 ft below lsf (elevation of 2,668 ft).

Major Points

- The hydrograph form and the relatively large amplitude fluctuations superimposed on the water levels, particularly evident during the recovery period, indicate unconfined conditions.
- The effect of individual wells turning on and off is clearly visible on the hydrograph, indicating pumping wells in relatively close proximity to and in good hydraulic connection with the index well.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The minimum water-level elevation for 2021 was 0.2 ft above that of 2020, which was the lowest observed during the monitoring period up to that time; the minimum for 2022 will be lower. The apparent maximum water-level elevation for 2022 is the lowest during the monitoring period.
- Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.74 ft (8.8 in)/acre in the vicinity of the Seegmiller index well (2 mi radius).
- Transducer readings are in good agreement with manual measurements.

3.4.6 SD-6 Steiger Index Well

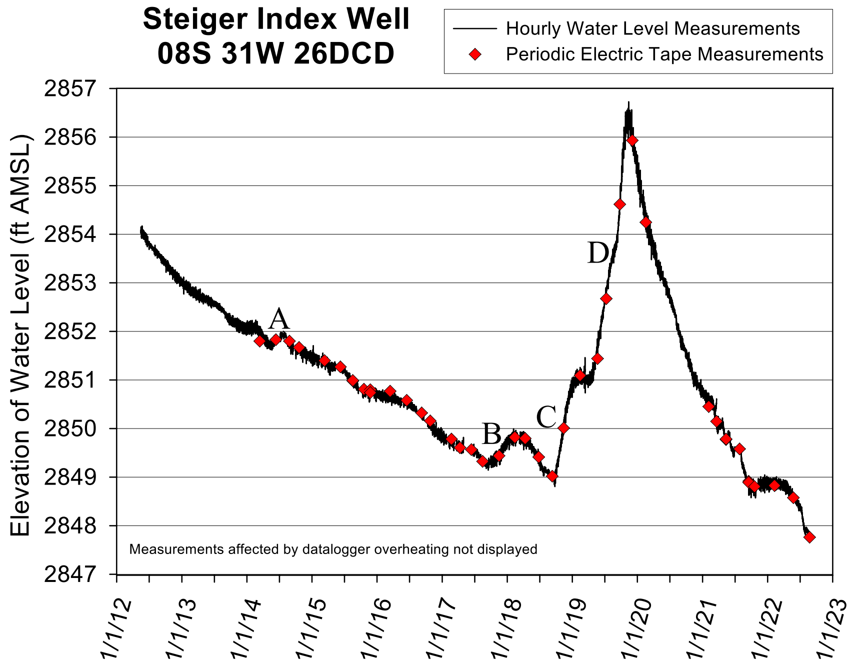


Figure 29—Steiger index well hydrograph—total data run to 8/24/22. A water-level elevation of 2,850 ft corresponds to a depth to water of 115 ft below lsf. The top of the 40 ft screen is 145 ft below lsf (elevation of 2,820 ft), and the bottom of the aquifer is 177 ft below lsf (elevation of 2,788 ft). A–D defined in text.

Major Points

- The fluctuations superimposed on the water levels are an indication of unconfined conditions but are of smaller magnitude than the other index wells in GMD4; this small magnitude typically indicates a relatively shallow depth to water.
- It is difficult to discern individual pumping seasons. The humps and troughs observed in the hydrograph at points marked A–D are likely related to a series of episodic recharge events and not pumping. The Steiger index well is located near an impoundment behind a small dam over an ephemeral stream channel; the impoundment appears to serve as a site of focused recharge.
- The effect of individual wells cutting on and off cannot be discerned.
- Except for a short decline early in the 2019 irrigation season, water levels rose continuously from the end of the 2018 pumping season to November 2019. This rise (>7.5 ft) is the only definitive example of episodic recharge that we have observed in the index wells in western Kansas. The sharp decline since the peak in November of 2019 indicates that the recharge was likely a localized event (i.e., water flows laterally to areas that did not receive the recharge) associated with the nearby impoundment (Butler, Knobbe et al., 2021). Comparison of the rise in water level with area rainfall indicates that the recharge pulse appears to have taken a little over a year to reach the water table.
- Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.82 ft (9.9 in)/acre in the vicinity of the Steiger index well (2 mi radius).
- Transducer readings are in good agreement with manual measurements.

3.4.7 Sherman County Index Well

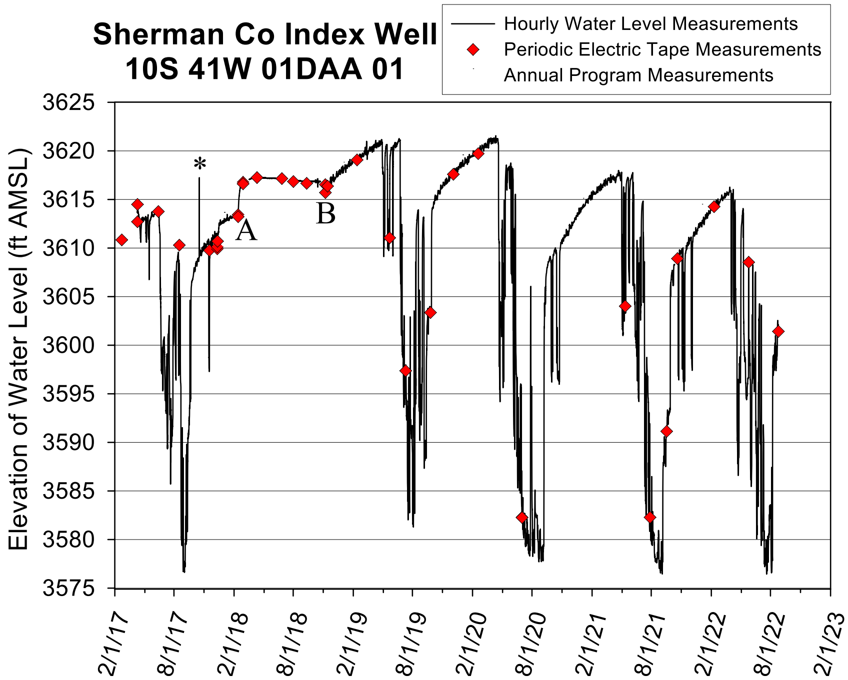


Figure 30—Sherman County index well hydrograph—total data run to 8/25/22. A water-level elevation of 3,615 ft corresponds to a depth to water of 179 ft below lsf. The top of the 10 ft screen is 310 ft below lsf (elevation of 3,484 ft), and the bottom of the aquifer is 323 ft below lsf (elevation of 3,471 ft). The well has a 10 ft sump that extends to 330 ft below lsf. The asterisk indicates a single spurious reading; A and B defined in text.

Major Points

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

3.4.8 Sherman County 2 Index Well

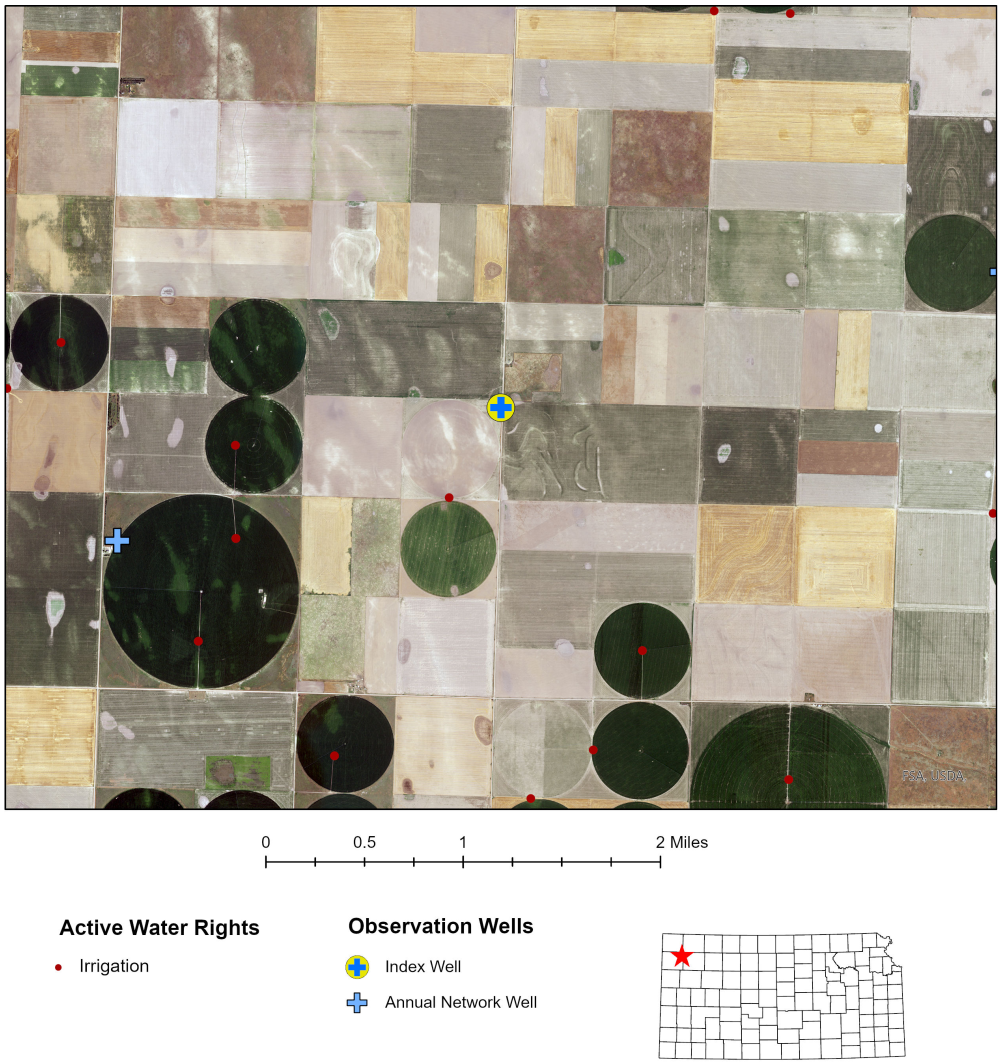


Figure 31— Aerial view of the Sherman County 2 index well and nearby annual well and points of diversion.

Figure 31 is an aerial view of the Sherman County 2 index well site (T. 6 S., R. 37 W., 34 DAA 01) at a scale that shows the site of the index well, an additional annual program well, and the nearby wells with active water rights.

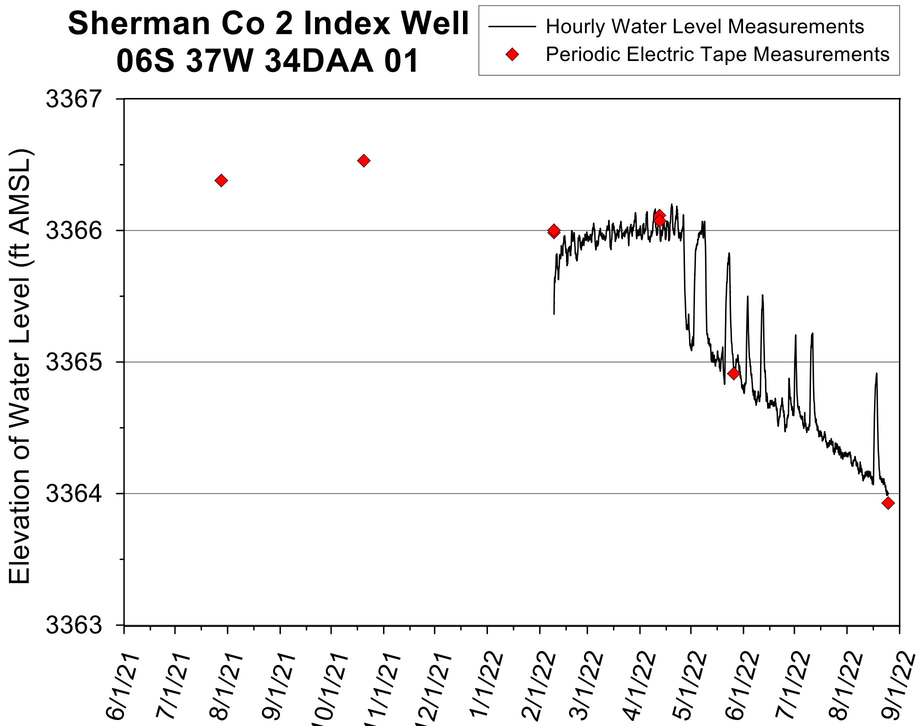


Figure 32—Sherman County 2 index well hydrograph—total data run to 8/25/22. A water-level elevation of 3,365 ft corresponds to a depth to water of 159 ft below lsf. The top of the 40 ft screen is 240 ft below lsf (elevation of 3,284 ft). The bottom of the aquifer is estimated to be 275 ft below lsf (elevation 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.
- Transducer readings become in good agreement with manual measurements a short time after start of monitoring.

3.4.9 Thomas County Index Well

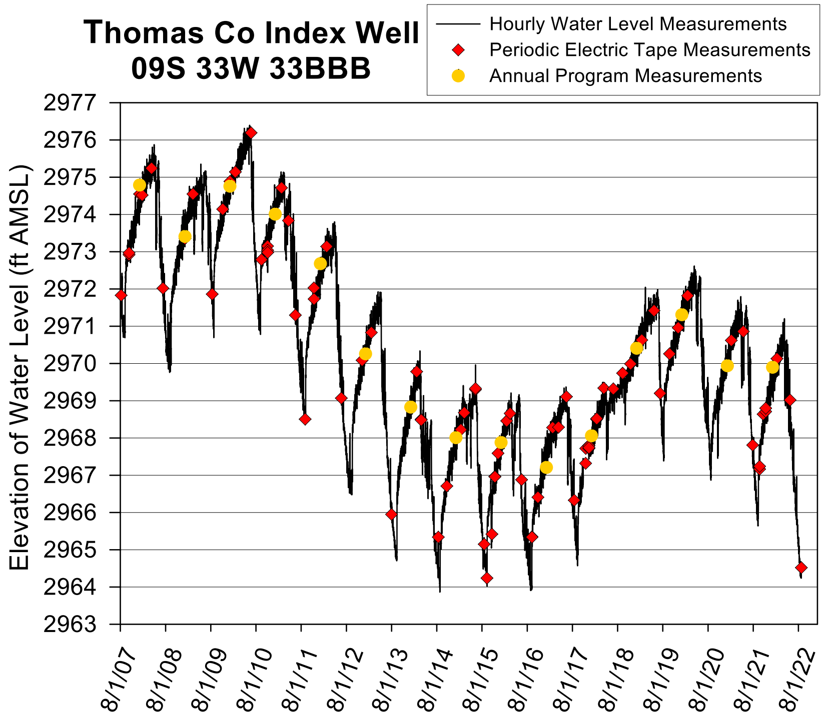


Figure 33—Thomas County index well hydrograph—total data run to 8/24/22. A water-level elevation of 2,967 ft corresponds to a depth to water of 220.56 ft below lsf. The top of the screen is 274 ft below lsf (elevation of 2,913.6 ft), and the bottom of the aquifer is 284 ft below lsf (elevation of 2,903.6 ft). The screen terminates at the bottom of the aquifer. No water-level data are available from 10/28/17 to 12/11/17 because of sensor failure.

Major Points

- The hydrograph form, the relatively small change and rate of change in water level during each pumping and recovery season (despite eight high-capacity pumping wells within a mile of the index well), and the relatively large amplitude fluctuations superimposed on water levels indicate unconfined conditions.
- The effect of individual wells turning on and off is clearly visible on the hydrograph, indicating pumping wells in relatively close proximity to and in good hydraulic connection with the index well.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The minimum water level in 2021 was 1.2 ft lower than that in 2020 and 1.7 ft lower than that in 2019, which was the highest value since 2011; the minimum level in 2022 will likely be 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.

3.5 GMD5 Index Wells

Four index wells, all of which have telemetry equipment that allows real-time viewing of data, are located in GMD5 (fig. 33). 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 are provided in this section. 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.

Site	2022 WL elev. (ft)[a]	2022 saturated thickness (ft)	Bedrock depth (ft below land surface)	Screened interval (ft below land surface)	2020 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Belpre	2,043.47	137.8–163.5[b]	175–200[b]	89–109	684	2,057	14,855[c]
Larned	1,944.01	59.69	71	66–71	382[d]	3,199[e]	16,945[f]
Rozel	2,042.08	82.58	125.5[b]	49–69[b] 109–129	393	2,871	10,419[g]
Trousdale	2,051.24	106.45	140[b]	47–57	727	3,205[h]	19,470[i]

[a] 2022 January 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. Screened interval information appears questionable.
[c] Includes 12 ac-ft of municipal water.
[d] Includes 10 ac-ft of industrial water.
[e] Includes 10 ac-ft of industrial water and 121 ac-ft of non-irrigation stock water.
[f] Includes 10 ac-ft of industrial water, 212 ac-ft of non-irrigation stock water, and 345 ac-ft of municipal water.
[g] Includes 52 ac-ft of municipal water.
[h] Includes 12 ac-ft of non-irrigation stock water.
[i] Includes 12 ac-ft of non-irrigation stock water and 35 ac-ft of recreation use water.

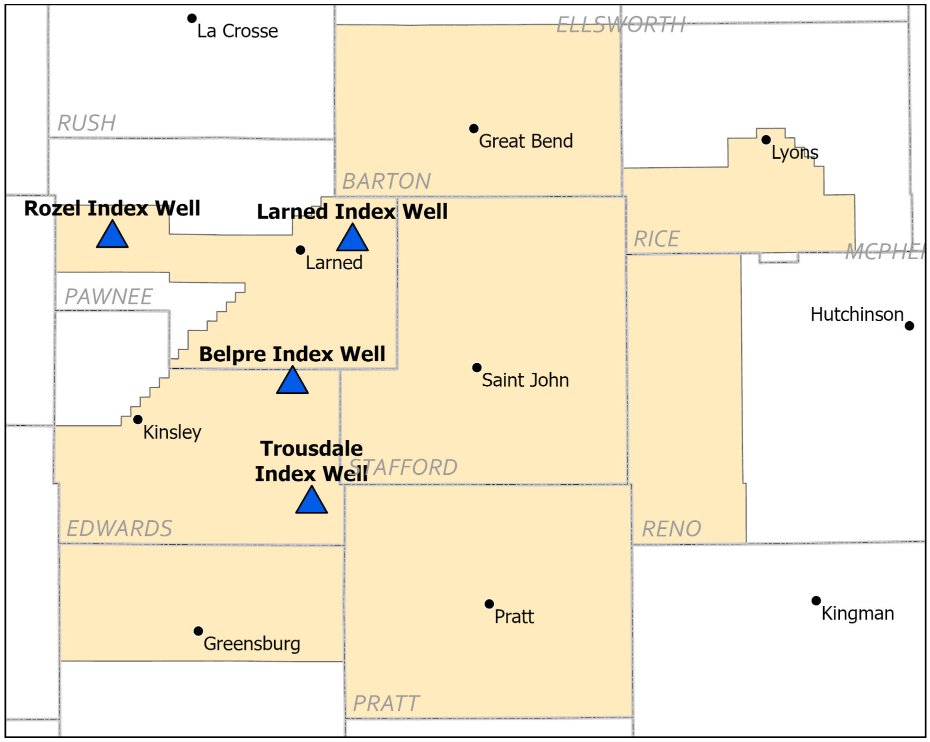


Figure 34—Map of index wells in GMD5 (blue triangles). Data from all four wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

3.5.1 Belpre Index Well

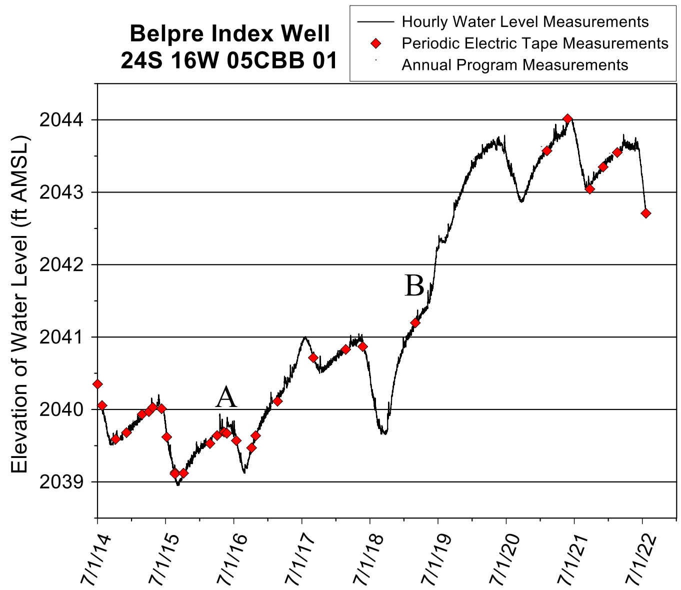


Figure 35—Belpre index well hydrograph—total data run to 7/20/22. A water-level elevation of 2,040 ft corresponds to a depth to water of 40 ft below lsf. The top of the 20 ft screen is 89 ft below lsf (elevation of 1,991 ft), and the bottom of the screen is 109 ft below lsf (elevation of 1,971 ft). The 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. Telemetry equipment ceased operating on 7/28/22 and will be replaced shortly.

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 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 2021 were the highest for the monitoring period. The apparent maximum water level for 2022 appears to be equal to the second highest on record; the minimum water level of 2022 will be lower than the minima for the previous two years.
- The water level has declined 7.05 ft since January 1988 (decline rate of 0.21 ft/yr).
- Transducer readings are generally in good agreement with manual measurements.

3.5.2 Larned Index Well

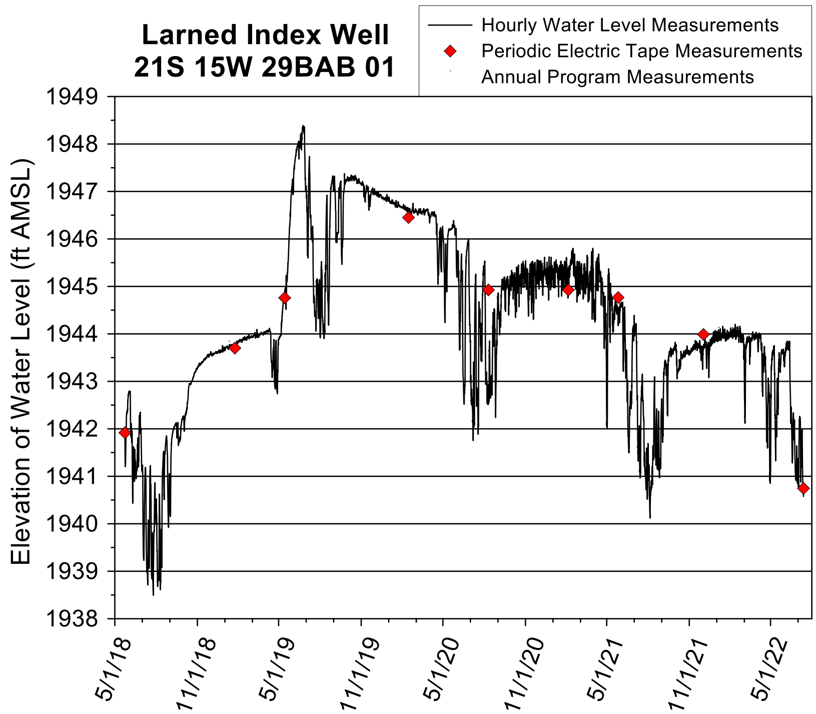


Figure 36—Larned index well hydrograph—total data run to 7/13/22. A water-level elevation of 1,944 ft corresponds to a depth to water of 11.3 ft below lsf. The top of the 5 ft screen is 66 ft below lsf (elevation of 1,889.3 ft), and the bottom of the screen, which is at the base of the aquifer, is 71 ft below lsf (elevation of 1,884.3 ft).

Major Points

- Hydrograph form and small amplitude fluctuations superimposed on water levels (until the fall of 2020) indicate confined conditions. Much larger amplitude fluctuations from 8/10/21 to 5/26/21 are due to atmospheric pressure readings inadvertently being added to the water-level data. Data will be corrected shortly.
- The effect of individual wells turning on and off is clearly visible on the hydrograph, indicating pumping wells in good hydraulic connection with the index well.
- The rapid increase in water level in May and June 2019 was produced by large flow events in the nearby Arkansas River (maximum discharge reached 5,720 ft^3/s with a stage change greater than 9.9 ft at the end of May).
- After the end of the 2018 irrigation season, water levels continued to recover until the start of the next season. After the end of the 2019 irrigation season, water levels continued to decline until near the start of the 2020 irrigation season. Water levels appeared to stabilize after the 2020 and 2021 irrigation seasons, an indication of limited lateral flow to this portion of the aquifer.
- Transducer readings are in reasonable agreement with manual measurements.

3.5.3 Rozel Index Well

Figure 37— Aerial view of the Rozel index well and nearby points of diversion.

Figure 37 is an aerial view of the Rozel index well site (T. 21 S., R. 20 W., 24 DDA 01) at a scale that shows the site of the index well, the Pawnee River, and nearby wells with active water rights.

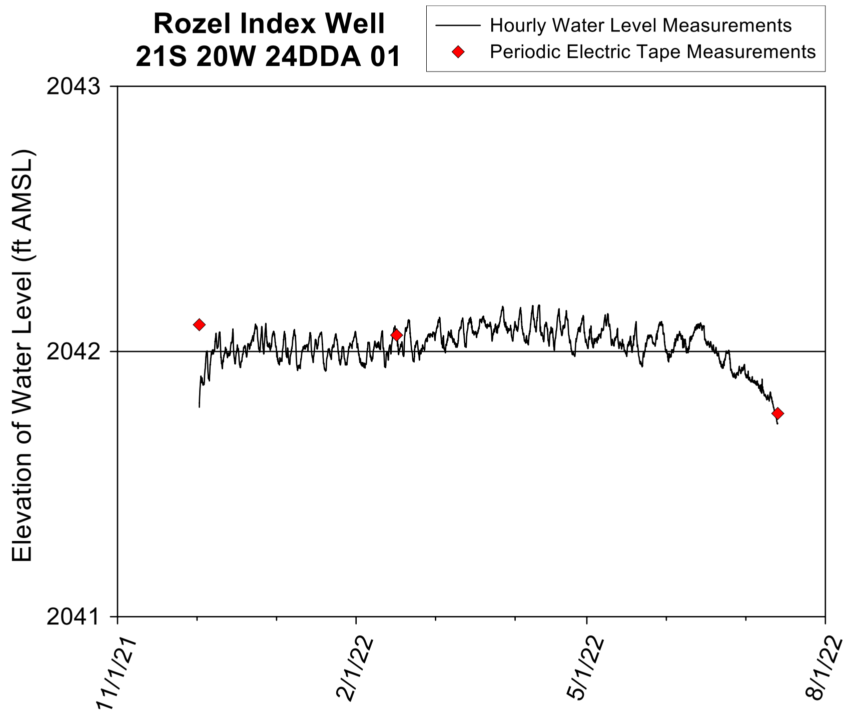


Figure 38—Rozel index well hydrograph—total data run to 7/13/22. A water-level elevation of 2,042 ft corresponds to a depth to water of 43 ft below lsf. Well construction details are not clear. Plans are to run a camera down the well to locate screen intervals and to determine whether the well was completed at a lesser depth than stated in the current WWC5 form associated with this location.

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, an indication of limited lateral flow to this portion of the aquifer.
- Transducer readings are in good agreement with manual measurements.

3.5.4 Trousdale Index Well

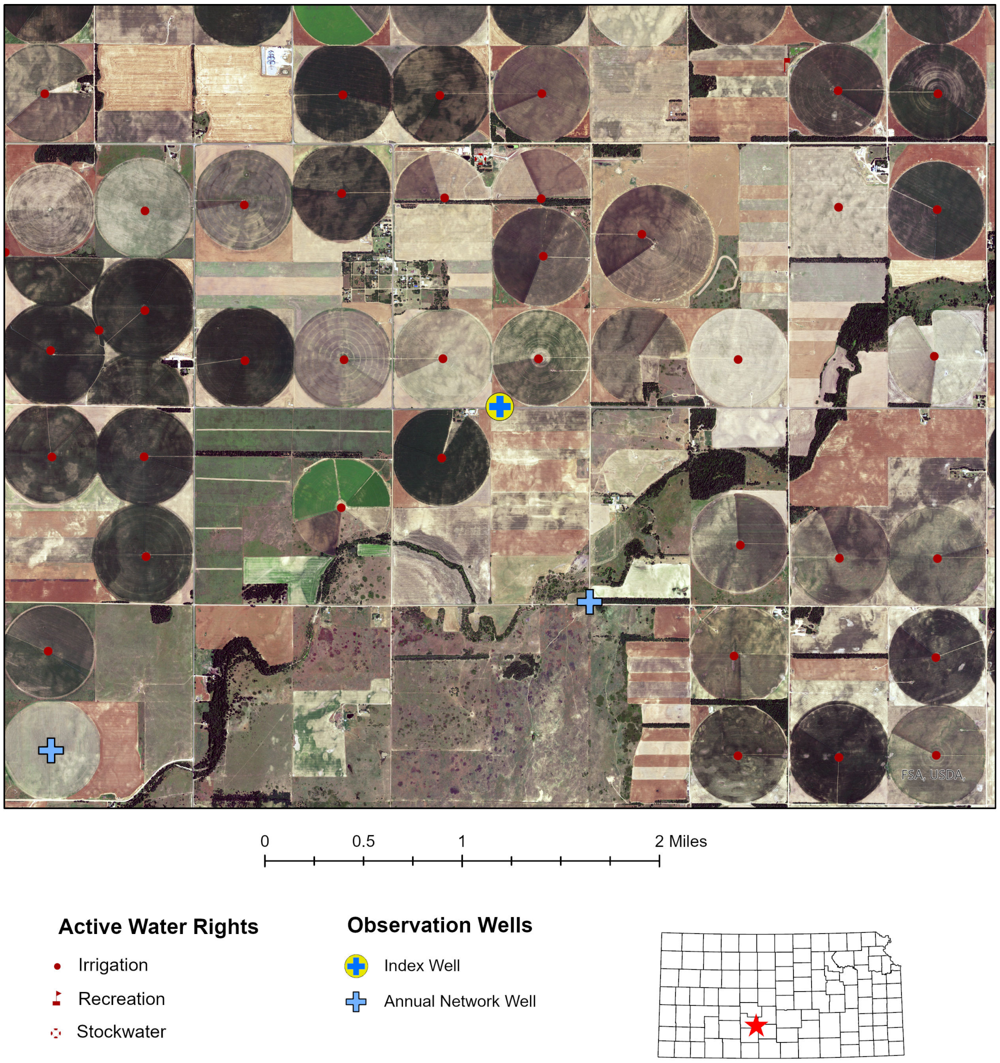


Figure 39— Aerial view of the Trousdale index well and nearby annual wells and points of diversion.

Figure 39 is an aerial view of the Trousdale index well site (T. 26 S., R. 16 W., 4 DCC 01) at a scale that shows the site of the index well, two nearby annual wells, Rattlesnake Creek, and nearby wells with active water rights.

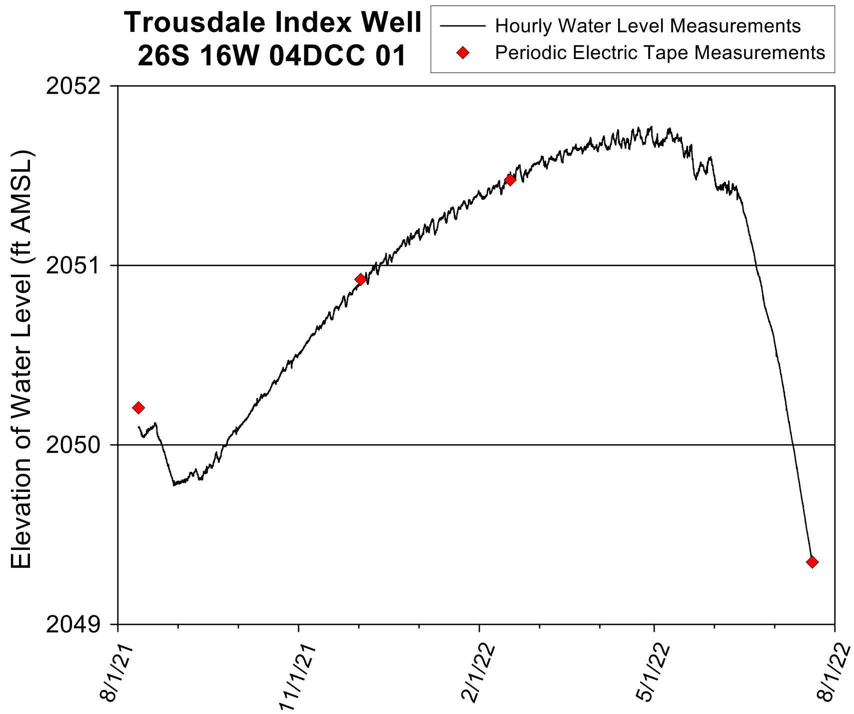


Figure 40—Trousdale index well hydrograph—total data run to 7/20/22. A water-level elevation of 2,051 ft corresponds to a depth to water of 33.8 ft below lsf. The top of the 10 ft screen is 47 ft below lsf (elevation of 2,037.8 ft). The bottom of the well is 57 ft below lsf; the base of the aquifer is at least 80 ft below the bottom of the well.

Major Points

- Further monitoring is needed to assess hydraulic conditions in the screened interval and the impact of nearby wells turning on and off.
- After the 2021 irrigation season, water levels appear to continue to increase until the start of the next irrigation season but further monitoring is needed to confirm that.
- Transducer readings are in good agreement with manual measurements.

3.6 Expansion Wells

3.6.1 GMD1 Expansion Wells

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

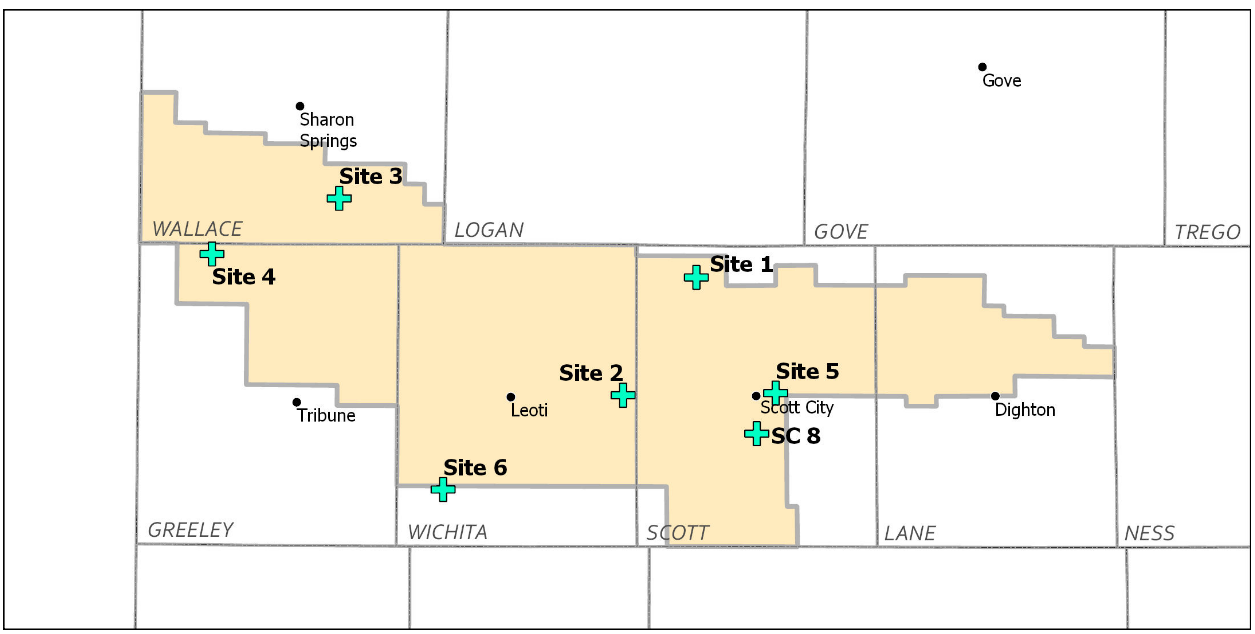


Figure 41—Map of GMD1 expansion wells.

Table 6—Characteristics of the GMD1 expansion well sites.

Site	2022 WL elev. (ft)[a]	2022 saturated thickness (ft)[b]	Bedrock depth (estimated ft below land surface)[b]	Screened interval (ft below land surface)	2020 water use (ac-ft) 1 mi radius circle	2 mi radius circle	5 mi radius circle
SC-8	2,848.2	85.2	174	[c]	586	1,659	10,596[d]
Site 1	2,929.2[e]	26.2	195	[c]	267[f]	983[g]	3,620[h]
Site 2	3,053.2[i]	42.2	160	[c]	0	198	3,550[j]
Site 3	3,424.9	21.9	220	[c]	169	1,697	13,240[k]
Site 4[l]	NA[m]	[n]	[n]	[c]	658	2,919	7,644[o]
Site 5[l]	NA[m]	NA	158	[c]	438[p]	2,797[d]	10,702[q]
Site 6	3,301.6	80.6	184	[c]	0	307[r]	1,778[s]

[a] 2022 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html).

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

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

[d] Includes 531 ac-ft of municipal water, 6 ac-ft of industrial water, 5 ac-ft of domestic water, and 27 ac-ft of non-irrigation stock water.

[e] Annual measurement on 1/3/22 likely in error; 2022 water-level measurements from average of transducer measurements from 8 a.m. to 4 p.m. on that day.

[f] Includes 94 ac-ft of non-irrigation stock water.

[g] Includes 216 ac-ft of non-irrigation stock water.

[h] Includes 423 ac-ft of non-irrigation stock water.

[i] Annual measurement on 1/5/22 likely in error but reported here; transducer average not available due to sensor failure.

[j] Includes 116 ac-ft of non-irrigation stock water.

[k] Includes 20 ac-ft of municipal water and 60 ac-ft of non-irrigation stock water.

[l] Not an annually measured index well.

[m] Transducer average not available due to sensor failure.

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

[o] Includes 602 ac-ft of non-irrigation stock water.

[p] Includes 27 ac-ft of non-irrigation stock water.

[q] Includes 6 ac-ft of industrial water, 1,039 ac-ft of municipal water, 5 ac-ft of domestic water, and 227 ac-ft of non-irrigation stock water.

[r] Includes 234 ac-ft of non-irrigation stock water.

[s] Includes 395 ac-ft of non-irrigation stock water.

3.6.1.1 SC-8 Site – Scott County

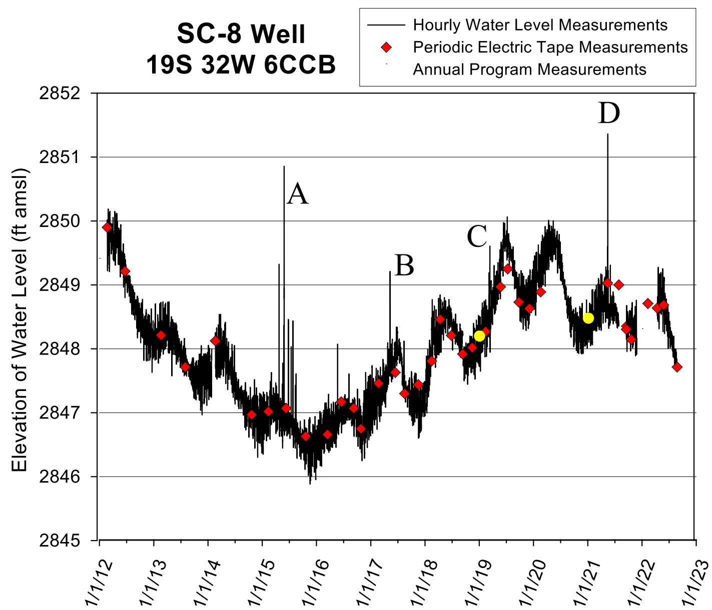


Figure 42—SC-8 well hydrograph—total data run to 8/25/22. A water-level elevation of 2,847 ft corresponds to a depth to water of 89 ft below lsf. Bottom of well is approximately 102 ft below lsf (elevation of 2,834 ft). Transducer measurements have been corrected from earlier reports for an incorrect 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 have 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

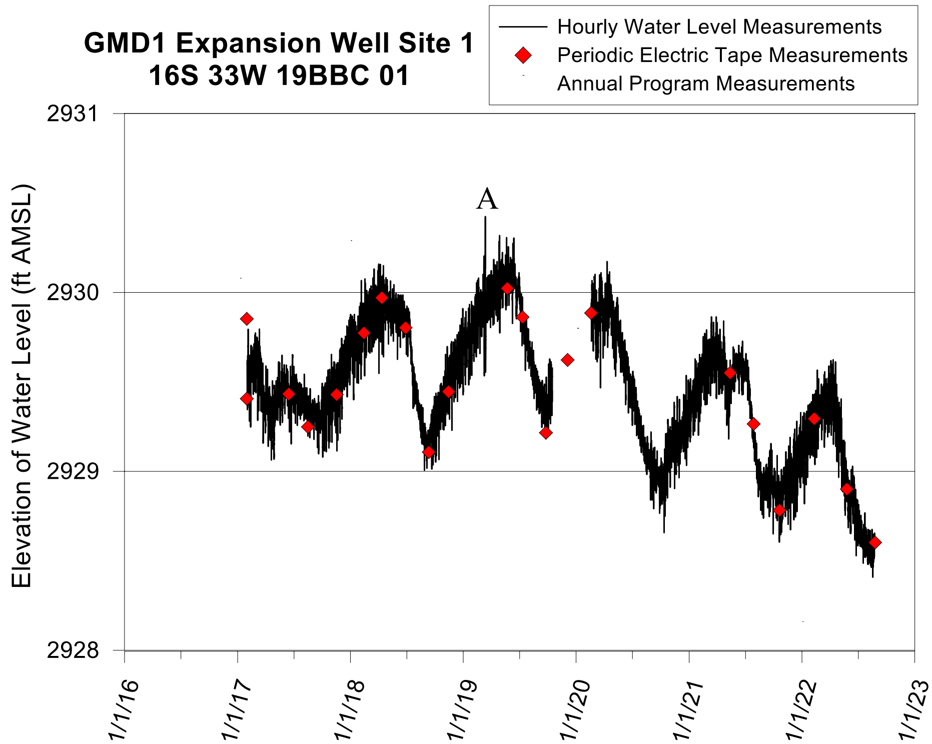


Figure 43—GMD1 Expansion Site 1 well hydrograph—total data run to 8/25/22. A water-level elevation of 2,930 ft corresponds to a depth to water of 168 ft below lsf. Bottom of well is 193.2 ft below lsf (elevation of 2,904.8 ft). A defined in text.

Major Points

- Moderate amplitude fluctuations superimposed on the water levels, which are particularly prominent during the recovery period, are an indication of unconfined conditions.
- The effect of individual wells cutting on and off is difficult to discern.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- The battery of the transducer-datalogger unit died on 10/16/19 and was replaced on 2/18/20.
- Minimum water level at the time of the 8/25/22 download was the lowest during the monitoring period.
- The water level has fallen 8.4 ft since January 1997 (0.3 ft/yr) and 4.2 ft since 2012 (0.4 ft/yr).
- 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.
- The sensor failed on 8/23/22. We will replace the sensor and then restart continuous monitoring at this well.

3.6.1.3 Expansion Site 2 – Wichita County

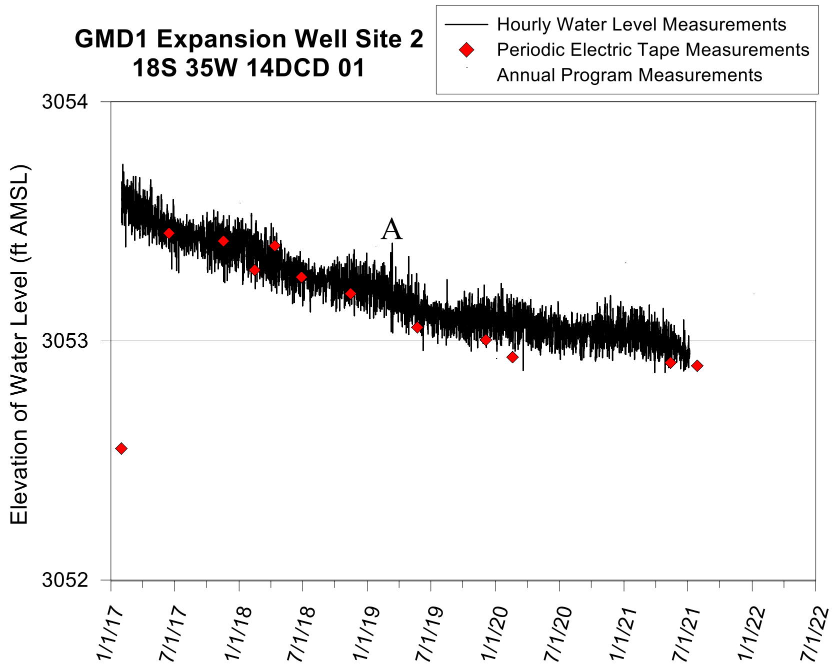


Figure 44—GMD1 Expansion Site 2 well hydrograph—total data run to 1/5/22. A water-level elevation of 3,053 ft corresponds to a depth to water of 118 ft below lsf. Bottom of well is 130.9 ft below lsf (elevation of 3,040.1 ft). First electric-tape measurement may be a transcription error. A defined in text.

Major Points

- Relatively small amplitude fluctuations superimposed on the water levels are an indication of a shallow unconfined aquifer; the seasonal variations in the amplitude are produced by seasonal changes in the range over which barometric pressure can vary with a smaller range during the summer (Butler, Knobbe et al., 2021).
- It is difficult to discern pumping and recovery seasons; cannot discern effect of individual wells cutting on and off.
- The water-level spike on March 13, 2019, (A) was produced by a bomb cyclone (Butler, Knobbe et al., 2021).
- The water level changed 35.6 ft between December 1958 and January 1982 but has only changed about 3.8 ft since January 1982. Water levels declined 1.53 ft between January 2014 and January 2022.
- Transducer readings are generally in reasonable agreement with manual measurements except for the first electric-tape measurement and the last two annual program measurements. Except for the last two annual measurements, the most recent manual measurements are near the lower boundary of the water-level band (likely a sensor calibration issue).
- The transducer failed on 7/6/21. From now on, this well will only be measured as part of the annual measurement program.

3.6.1.4 Expansion Site 3 – Wallace County

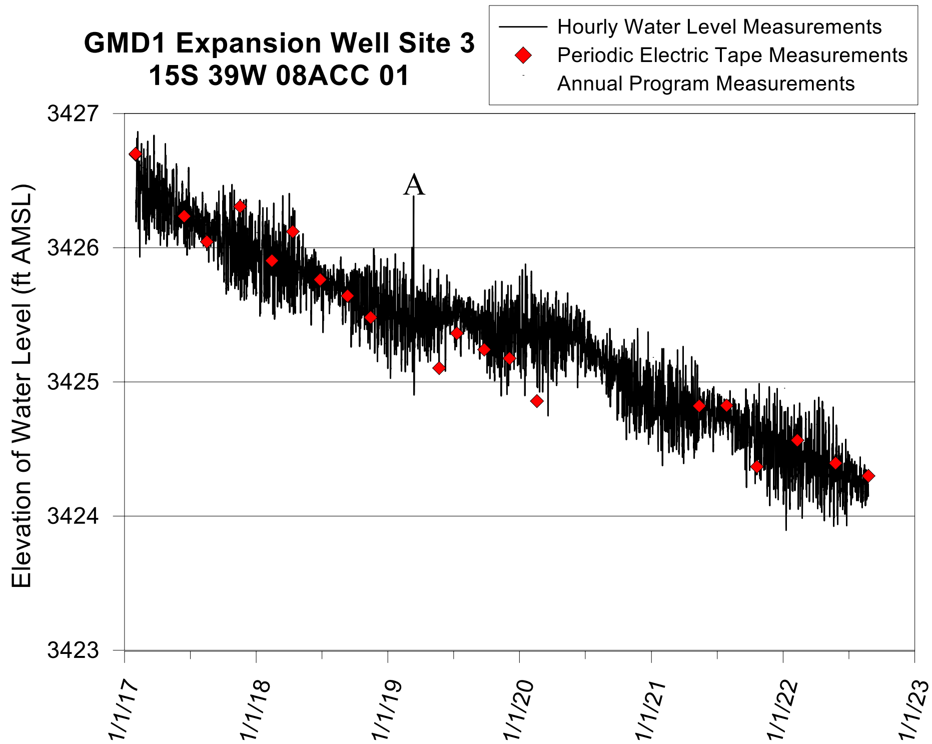


Figure 45—GMD1 Expansion Site 3 well hydrograph—total data run to 8/25/22. A water-level elevation of 3,426 ft corresponds to a depth to water of 197 ft below lsf. Bottom of well is 219.9 ft below lsf (elevation of 3,403.1 ft). A defined in text.

Major Points

- Relatively large amplitude fluctuations superimposed on the water levels are an indication of an unconfined aquifer; the seasonal variations in the amplitude are produced by seasonal changes in the range over which barometric pressure can vary with a smaller range during the summer (Butler, Knobbe et al., 2021).
- It is difficult to discern pumping and recovery seasons; cannot discern the effect of individual wells cutting on and off.
- The water level has declined 78.4 ft since 1964 (1.4 ft/yr) and 7.5 ft since 2012 (0.8 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 this well will be measured quarterly after the transducer fails.

3.6.1.5 Expansion Site 4 – Greeley County

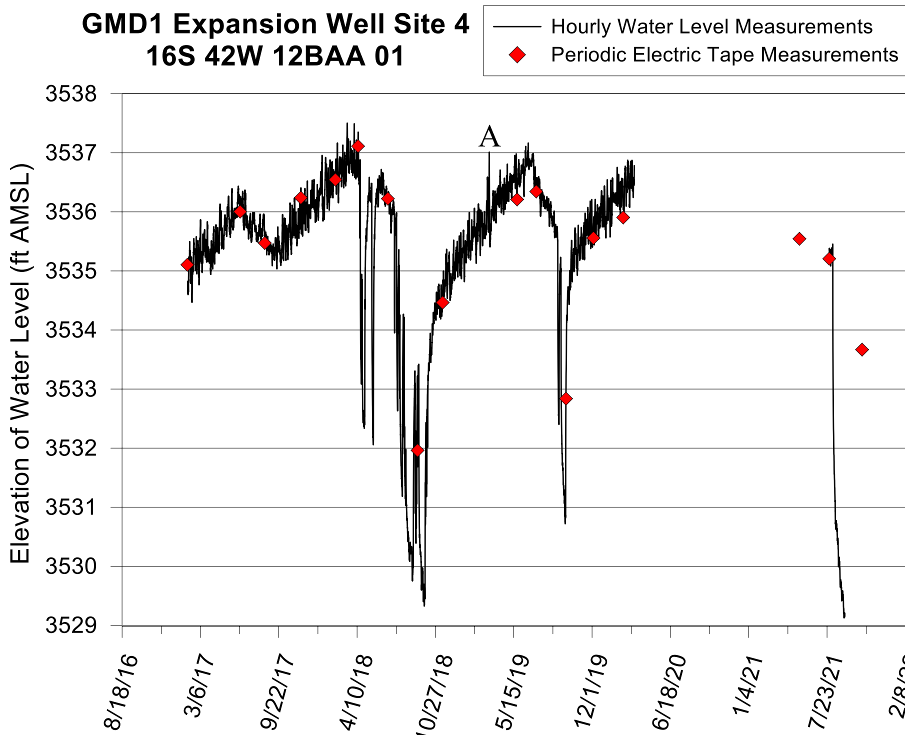


Figure 46—GMD1 Expansion Site 4 well hydrograph—total data run to 10/20/21, hourly measurements to 3/17/20 and from 7/28/21 to 9/5/21. A water-level elevation of 3,537 ft corresponds to a depth to water of 236 ft below lsf. Bottom of well is 264.5 ft below lsf (elevation of 3,508.5 ft). A defined in text.

Major Points

- Hydrograph form and relatively large amplitude fluctuations superimposed on the water levels are an indication of an unconfined aquifer.
- Little nearby pumping occurred in the 2017 irrigation season but much more from 2018 onward. The effect of one or more nearby individual wells cutting on and off is clearly seen in the 2018 and 2019 irrigation seasons.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels do not stabilize).
- The water-level spike on March 13, 2019, (A) was produced by a bomb cyclone (Butler, Knobbe et al., 2021).
- The transducer failed on March 17, 2020, most likely as a result of a water leak. The pandemic limited travel, so the failure was not recognized until May 13, 2021; the sensor was removed from the well and was replaced on July 28, 2021. That sensor then failed on September 9, 2021. A new more robust sensor will be placed in the well in the fall of 2022.
- Prior to the transducer failure, sensor readings are in reasonable agreement with manual measurements.

3.6.1.6 Expansion Site 5 – Scott County

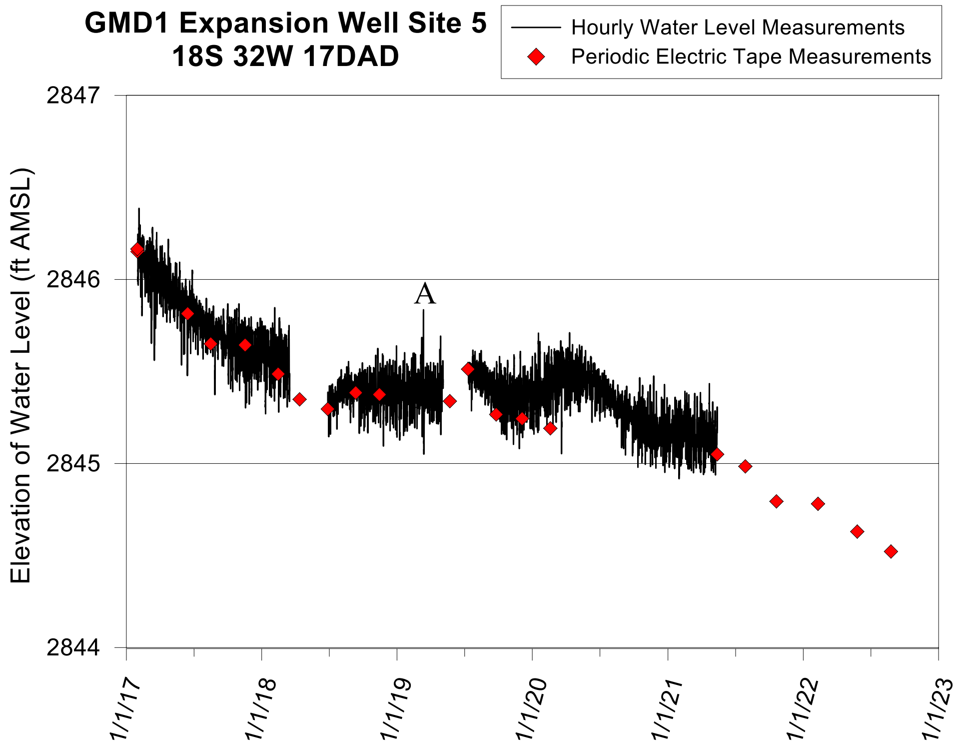


Figure 47—GMD1 Expansion Site 5 well hydrograph—total data run to 8/25/22. A water-level elevation of 2,845 ft corresponds to a depth to water of 131 ft below lsf. Elevation of well bottom is not known. A defined in text.

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 7.2 ft since 2012 (0.7 ft/yr) and 32.01 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 have generally been 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 will now be measured quarterly.

3.6.1.7 Expansion Site 6 – Wichita County

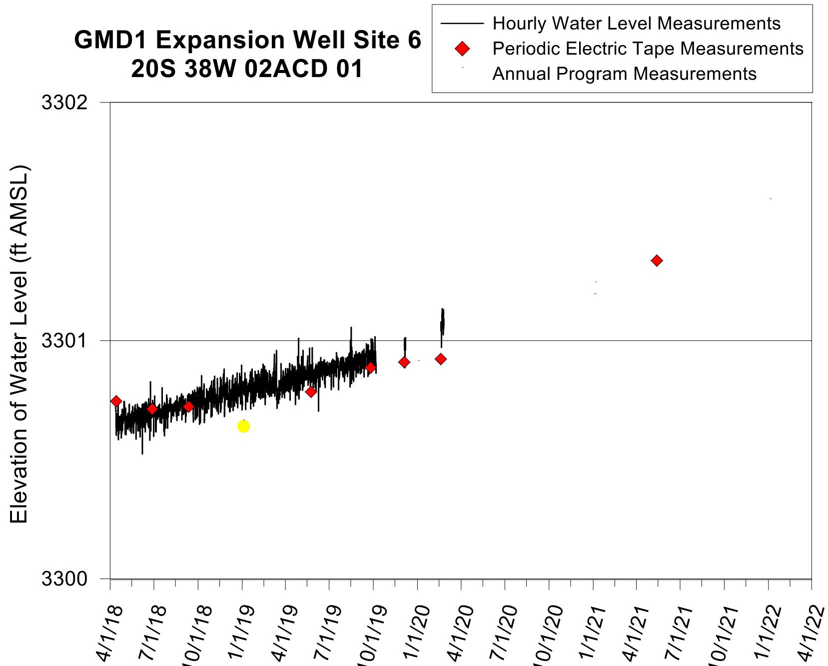


Figure 48—GMD1 Expansion Site 6 well hydrograph—total data run to 1/5/22; continuous hourly measurements ended on 10/6/19. A water-level elevation of 3,301 ft corresponds to a depth to water of 104 ft below lsf. Elevation of well bottom is not known. Bottom of aquifer is at an elevation of 3,221 ft (184 ft below lsf).

Major Points

- Small amplitude fluctuations superimposed on the water levels are an indication of a relatively shallow unconfined aquifer overlain by a vadose zone with high air permeability.
- It is difficult to discern the effect of any nearby or regional pumping.
- The battery of the transducer-datalogger unit died on 10/6/19 and was replaced on 12/4/19. The battery then died again on 12/7/19 and was replaced on 2/18/20. The battery then died again on 2/24/20. The pandemic limited travel, so this last failure was not recognized until May 13, 2021. There appears to be little justification for continuous monitoring at this well, so the sensor has been removed from the well and the well will now be measured annually.
- The water level has been slowly rising over the monitoring period in comparison with the slowly declining water level during 2005 to 2016 measured at a former annual measurement well about 0.25 mi distant (that well was plugged in 2016).
- No reported 2020 water use in 1 mi radius centered on well; smallest 2020 water use for 5 mi radius of any index or expansion well.

3.6.2 Thomas County Expansion Wells

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

3.6.3 Haskell County Expansion Wells

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

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

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

4.1 Introduction

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

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 the 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 2019 ranged from less than a percent to several percent of the current total, depending on the county. For example, the number of active points of groundwater diversion authorized through appropriated and vested groundwater rights in Thomas, Scott, and Haskell counties in 2022 were 856, 898, and 1,074, respectively. The number of these added after 1997 were 35 (4.1% increase), 22 (2.4% increase), and 9 (0.8%) for these three counties, respectively. Thus, for the last 20+ years, the main driver for water-level changes in the HPA in western Kansas has been the amount of pumping from each well.

The main driver of water-level recovery after an irrigation pumping season is the net inflow. The components of net inflow are described in previous index well reports. The main drivers of variations in irrigation water use across the HPA have been the acreage of irrigated fields, crop type, climatic conditions, and the irrigation application rate. Of these, the climatic conditions have generally had the greatest influence over the last few decades because the irrigated acreage, crop type, and application rate have not changed substantially over the HPA in Kansas. The exception is in the Sheridan-6 LEMA, where the crop type and application rate have been altered the last nine 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.

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.

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). The Advanced Hydrologic Prediction Service of the National Weather Service (NWS) provides spatial images and data coverages of radar precipitation for the United States (available at http://water.weather.gov/precip/). The radar precipitation data are adjusted using data from a network of precipitation gages. A brief description of the observation methods that apply to the general Kansas region from the "About NWS Precip Analysis" tab on the above web page was included in a previous project report (Butler, Whittemore et al., 2015). Coverages for radar precipitation are available from the NWS website beginning in 2005.

We now use radar precipitation as the primary metric for characterizing climatic conditions in the Kansas HPA. Figure 49 shows an image of the percent of normal annual precipitation during 2021 from the NWS website. The data have a spatial resolution of approximately 4x4 km; the grid spacing as measured from the data for western Kansas is 2.57 mi north-south and 2.58 mi west-east.

The annual precipitation in 2021 was near average over most of the High Plains aquifer area. The map reveals that substantial spatial variation in precipitation existed within the GMDs; all the districts except GMD1 generally received near average rainfall, while most of GMD1 received somewhat above normal precipitation.

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 2021 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 -0.40, 0.35, 0.11, and -0.01, respectively, in comparison to -1.26, -0.74, -0.64, and -0.05 for 2020. 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 2021 climate for the irrigation season in GMD4 was on the dry side of average, while GMDs 1 and 3 were on the wet side of average, and the combined area of GMDs 2 and 5 was close to average. In all five GMDs, the 2021 climate for the irrigation season was wetter compared to 2020.

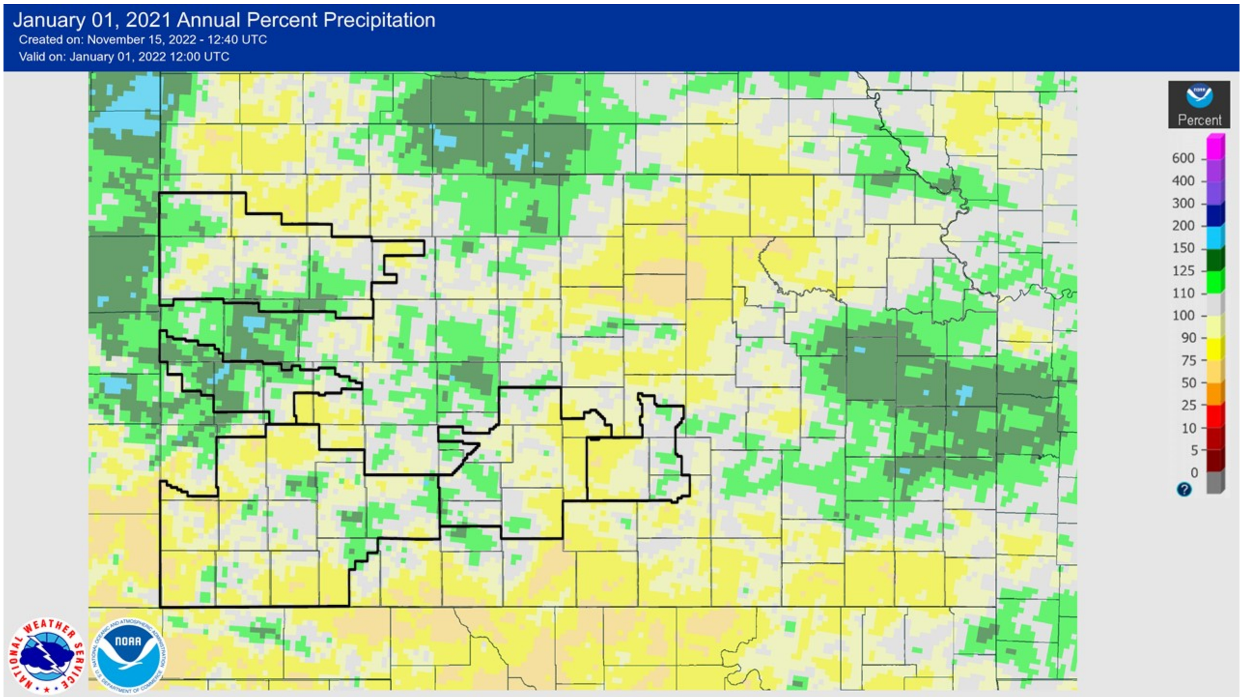


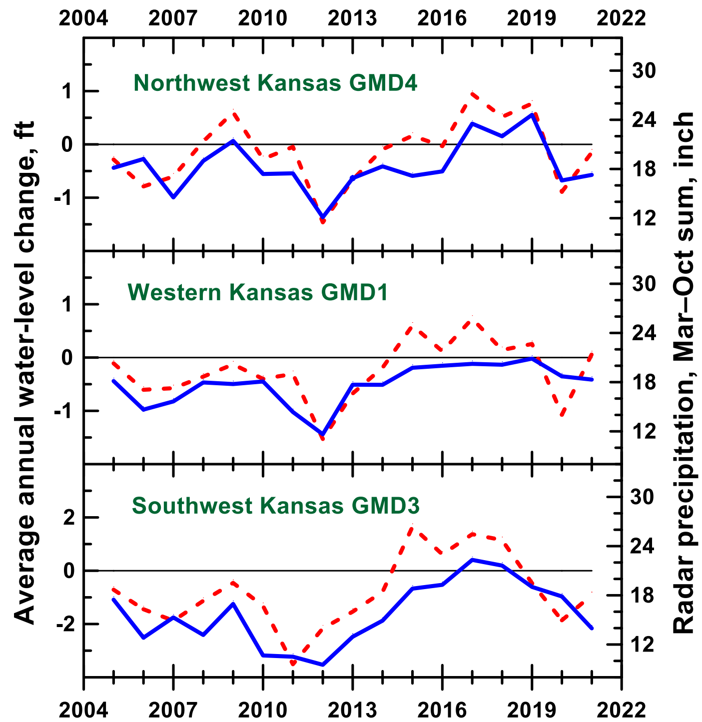
Figure 49—Percent of normal radar precipitation for Kansas in 2021. County lines and the GMD boundaries (bolded) are displayed.

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 2005–2021 for all five GMDs; these values are based on wells for which measurements were made every winter from 2005 to 2022. 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 +0.4 and -1.4 ft. The annual changes in GMD3 during this period were substantially greater (between +0.05 and -3.5 ft), but the largest annual changes were in GMD5 (between +3.1 and -3.0 ft) and GMD2 (between +2.4 and -2.9 ft). Some similarity is evident in the patterns of the water-level changes for the three western GMDs (4, 1, and 3).

The mean annual water-level changes in the five GMDs generally mimic the variations in radar precipitation (March–October sum), which are also displayed on fig. 50. The annual water-level changes in 2021 were negligible in GMD2, moderate in GMDs 4 and 1, somewhat greater (-0.8 ft) in GMD5, and substantially greater in GMD3 (-2.2 ft). Other than GMDs 4 and 2, the 2021 declines were greater than in 2020, which is not consistent with the substantial increase in precipitation from 2020 to 2021.

a)



b)

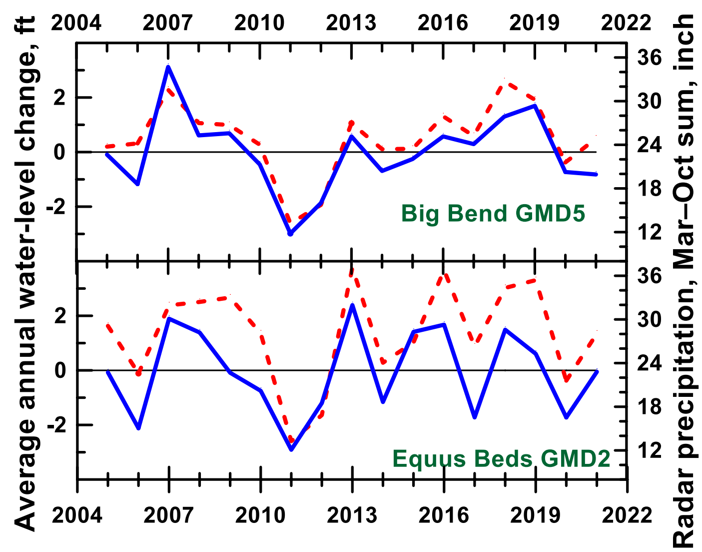


Figure 50—Mean annual water-level change and radar precipitation (sum of March–October precipitation) during 2005–2021 for (a) GMDs 4, 1, and 3 and (b) GMDs 2 and 5. The water-level change for a particular year is the water-level difference between the following year and that year for continuously measured wells for 2005–2022. The blue lines represent the water-level change and the red dashed lines the radar precipitation. 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 2008–2021 (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 network wells with continuous records for this period (same as values in fig. 50). The annual changes in the Scott index well have been within a relatively narrow range (between -0.05 and -1.48 ft for tape measurements; a total absolute range of 1.43 ft), whereas the changes have been appreciably larger at the Thomas index well (between +2.3 and -2.4 ft for tape measurements; a total absolute range of 4.7 ft), and much greater at the Haskell index well (between +4.0 and -10.2 ft for tape measurements; a total absolute range of 14.2 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 2008–2021. In contrast, the ranges in the annual water-level changes for the Thomas and Haskell index wells are substantially greater than the mean water-level changes for GMDs 4 and 3, respectively. Except for the 2015, 2016, 2018, and 2019 change in the Thomas well and the 2016 and 2021 change in the Scott well, the directions of change in the annual water-level changes for the Thomas and Scott index wells are relatively similar to those for the mean annual changes for the GMDs. This indicates that these two wells are usually representative of the patterns in regional water-level variations in the GMDs in which they are located. The main discrepancy in the Thomas well change is for 2018, when a hail storm damaged crops in the vicinity of the well, resulting in cessation of irrigation during the growing season and, thus, greater recovery of water levels than usually expected. If this year is removed from the plot, the changes from 2017 to 2019 for the Thomas well and GMD4 are relatively similar.

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

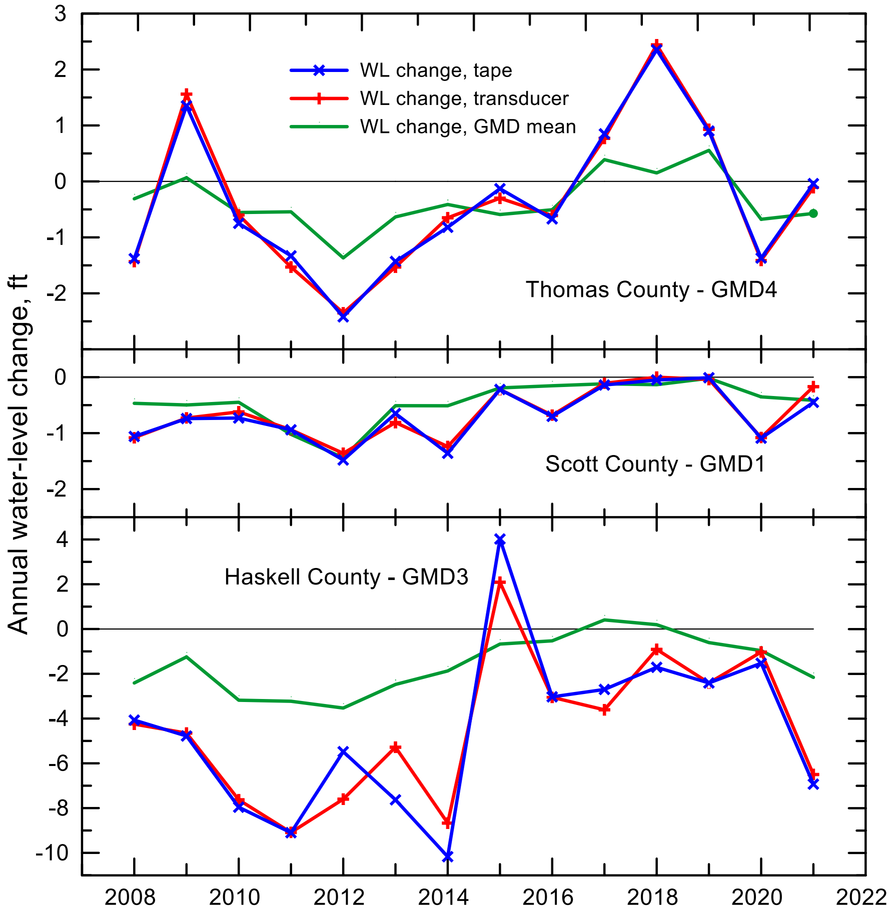


Figure 51—Annual winter (January) water-level changes in the original three index wells and the mean annual changes in the three GMDs in western Kansas in which they are located. Note the different y-axis range for Haskell County versus that for Thomas and Scott counties; suspect 2013 tape measurement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

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

One of the major accomplishments of the index well program has been the discovery of the strong linear relationship between annual water use and annual water-level change in the Kansas HPA and the development of the theoretical support for that relationship. As shown in previous project reports and peer-reviewed publications (e.g., Butler, Whittemore et al., 2015; Butler, Whittemore, Wilson et al., 2016, 2018; Butler et al., 2023), this relationship can be used to assess the aquifer response to pumping reductions over a wide range of spatial scales. For example, the pumping reduction that would achieve stable water levels (i.e., a water-level change of zero) for the near future 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 2008–2020. 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 apparent pumping reduction for stable water levels is 9.3%, which is lower than the 14.4% for 2008-2017 that omits the hail year of 2018 and following years, and considerably smaller than the 16.5% for all of GMD4 for 2005–2020. The average annual water use during 2008–2020 was 3.7 in/yr for the 2 mi radius area centered on the well, which is substantially greater than the 1.5 in/yr for the entire GMD4 area. The water use for stable water levels (net inflow) was 3.4 in/yr for the 2 mi radius area, which again is substantially greater than the 1.2 in/yr for GMD4. The greater density of water use may have produced a locally depressed water table that induces more lateral groundwater inflow, including, potentially, focused recharge along ephemeral stream valleys 1–2 mi to the north and south of the Thomas well. In addition, the greater water-use density would be expected to result in more irrigation return flow and more drainage from the newly formed unsaturated zone.

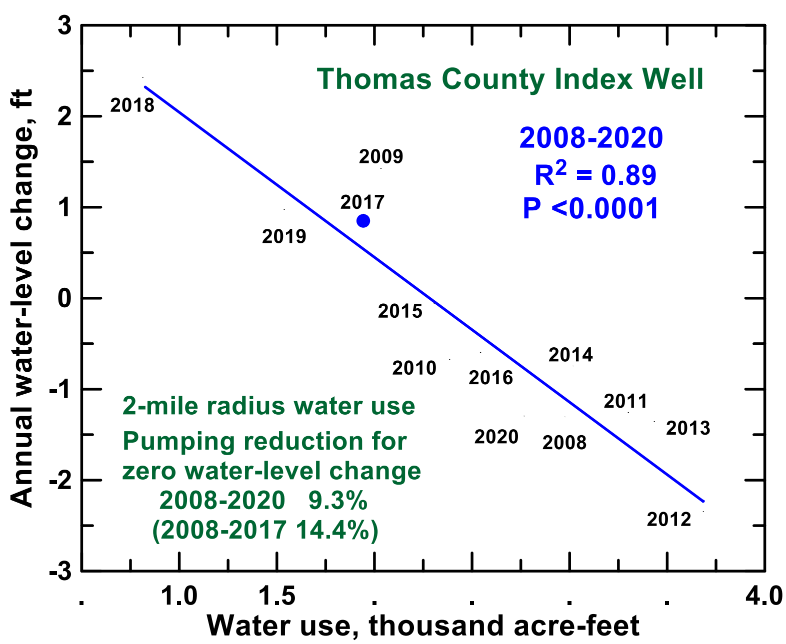


Figure 52—Correlation of annual water-level change based on manual measurements in the Thomas County index well with annual water use within a 2 mi radius centered on the well during 2008–2020.

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 2008–2020. The pumping reduction for stable water levels is 35%, which is about the same as 34% for all of GMD1 for 2005–2020. The average annual water use was 4.5 in/yr for the 2 mi radius area centered on the well, which is substantially greater than the 1.8 in/yr for all of GMD1. The water use for stable water levels (net inflow) was 2.9 in/yr for the 2 mi radius area, which again is substantially greater than the 1.2 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.

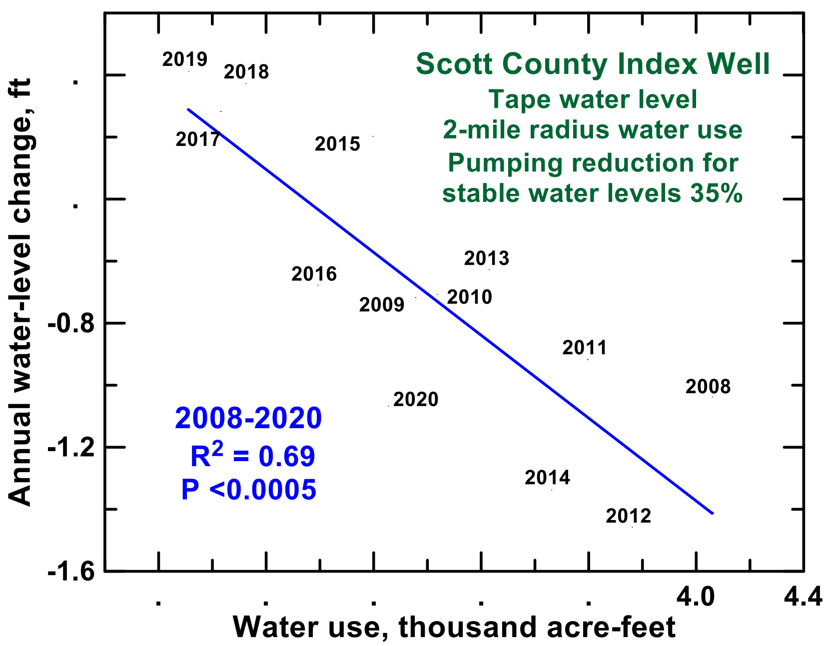


Figure 53—Correlation of annual water-level change based on manual measurements in the Scott County index well with annual water use within a 2 mi radius centered on the well during 2008–2020.

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

2013–2020 (especially during 2015–2019) in comparison to that during 2008–2012 in GMD3 (see fig. 50). The pumping reduction for stable water levels for the average annual water use before the court-ordered pumping shutdowns (2008–2012) is 66% (using the linear regression for 2008–2020 and the average annual water use for 2008–2012), which is much larger than the 22% for all of GMD3 for 2005–2020. The pumping reduction for stable water levels for the average annual water use after the shutdowns (2013–2020) is 46% (again using the linear regression for 2008–2020), which, although much greater than the reduction for all of GMD3, is appreciably less than for the period before the shutdowns. The average annual water-use rates were 14.3 in/yr and 8.8 in/yr for the 2 mi radius area centered on the well during 2008–2012 and 2013–2020, respectively, which are considerably greater than the 4.0 in/yr for the entire GMD3 area. The water use for stable water levels (net inflow) was 5.0 in/yr for the 2 mi radius area based on the 2008–2020 data, which again is substantially greater than the 3.2 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.

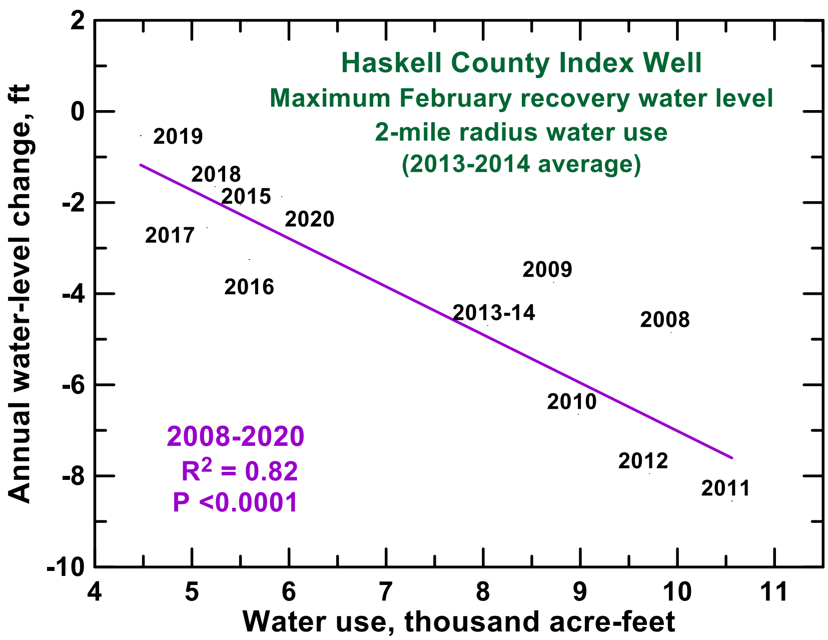


Figure 54—Correlation of change in maximum recovery water level during February based on transducer measurements in the Haskell County index well with annual water use within a 2 mi radius centered on the well during 2008–2020. Red points designate values after the court-ordered shutdowns (see section 3.3.2); 2013 and 2014 values are averaged because of equipment failure at the time of the 2013 maximum recovery.

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. The percent pumping reduction required to attain stable water levels (54%) 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 centered on the well, which is less than that in the vicinity of the Thomas index well (3.7 in/yr for 2 mi radius) but substantially greater than the 1.5 in/yr for all of GMD4. The water use for stable water levels (net inflow) was 1.4 in/yr for the 1 mi radius area, which is somewhat greater than the 1.2 in/yr for all of GMD4 but substantially below that in the vicinity of the Thomas index well (3.4 in/yr for a 2 mi radius).

The correlation for the water-level change versus water use relationship at the SC-8 well is higher for the 1 mi than the 2 mi radius area centered on the well (fig. 55). The percent pumping reduction required to attain stable water levels (21%) is considerably less than that required in the vicinity of the Scott County index well (35% for 2 mi radius) and for all of GMD1 (34%). 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 (4.5 in/yr for 2 mi radius) but substantially greater than the 1.8 in/yr for all of GMD1. The water use for stable water levels (net inflow), however, was 3.2 in/yr for the 1 mi radius area, which is similar to that in the vicinity of the Scott index well (2.9 in/yr for 2 mi radius) but much greater than the 1.2 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 essentially zero, meaning that net inflow was approximately equal to annual pumping for the generally wet period of 2005–2020, and is close to the -0.2% 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 3.3 in/yr for the 2 mi radius area, which is greater than the 2.4 in/yr for the entire GMD5 area. The water use for stable water levels (net inflow) was 3.4 in/yr for the 2 mi radius area, which again is larger than the 2.4 in/yr for all of GMD5.

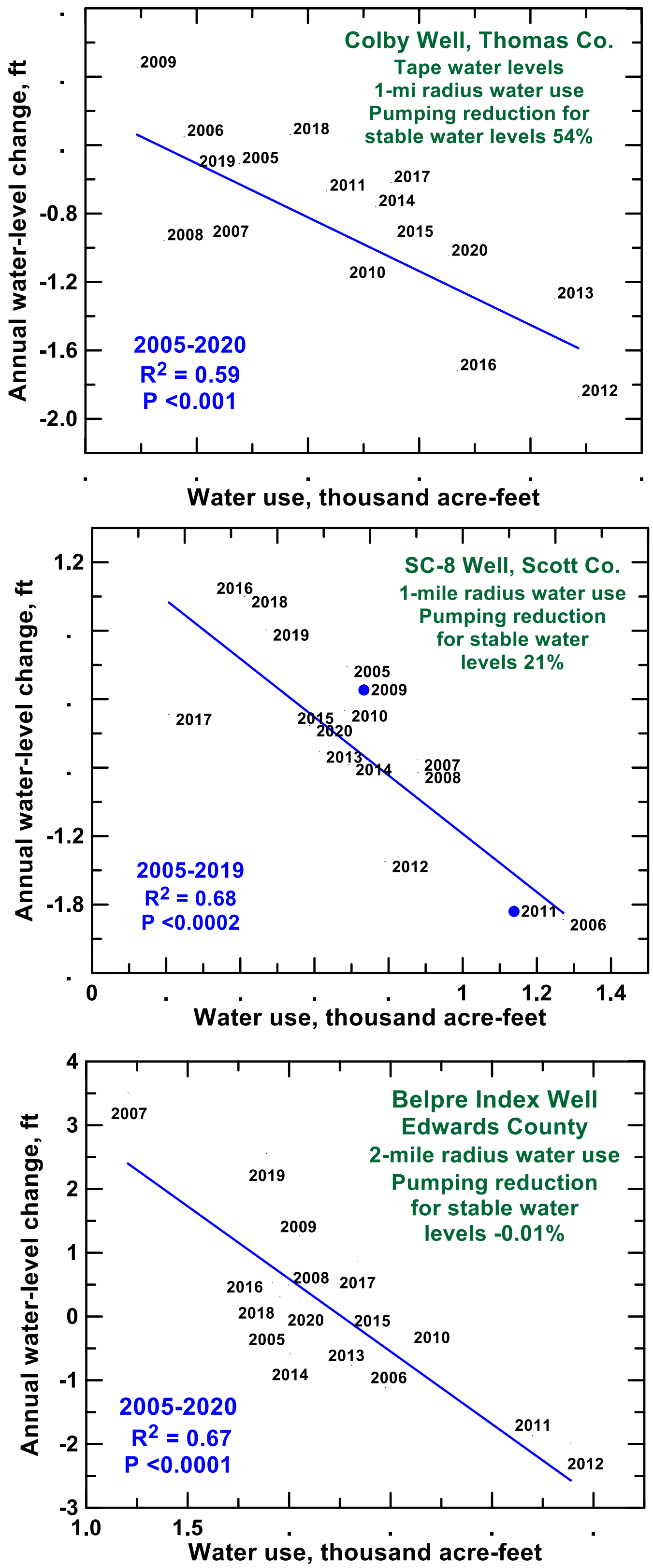


Figure 55—Correlation of annual water-level change in the Colby, SC-8, and Belpre wells with annual water use within a 1 or 2 mi radius centered on the wells during 2005–2020.

4.6 Relationship of Water Use and Climatic Conditions

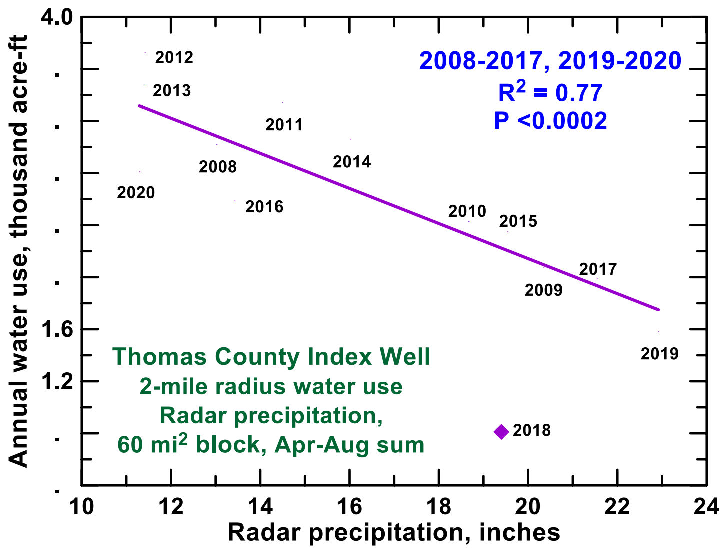
As indicated earlier, climatic conditions have generally had the greatest influence on water-use variations over the last few decades because the irrigated acreage, crop type, and application rate have not changed substantially over the HPA in Kansas. We have found that the sum of the radar precipitation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

4.6.1 Correlation of Annual Water Use with Radar Precipitation

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

The monthly precipitation sums that give optimum correlations for the Thomas County and Scott County index wells are April–August and February–September, respectively (fig. 56), which essentially span the main part of the irrigation season. The 2019 and 2017 precipitation were the greatest during 2008–2020 for the Thomas and Scott wells, respectively. However, the water use surrounding the Thomas County well in 2018 was substantially lower than the water use for any other year, which was caused by the shutdown of irrigation wells in the vicinity due to destruction of crops by a hail storm. Thus, 2018 is plotted as a separate, anomalous point, and data for 2008–2017 and 2019–2020 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). Although 2017 had the least water use of 2008–2019 for the Scott County well, the water use in 2018 was nearly as low. It is unknown at this time whether any storm damage to crops occurred in the area of the Scott County well to cause the water use to be substantially lower than expected for 2018. However, the water use during 2019 and 2020 was also lower than expected given the precipitation, suggesting that likely decreasing aquifer thickness and conservation measures are having an influence. This will be examined more closely in the 2022 report.

Two plots are shown for the water use and radar precipitation relationship for the Haskell index well (fig. 57). The first plot (a) for a 1 mi radius of water use gives the best correlation for the data before the court-ordered shutdown of nearby irrigation wells (see section 3.3.2.); the second plot (b) for a 2 mi radius gives a slightly better correlation for post-shutdown data. The plots show the lower water use for a given precipitation value after compared to before the well shutdowns. A similar break in the relationship is seen for the correlation between annual water use and radar precipitation in the Sheridan-6 LEMA (Butler, Whittemore, Wilson et al., 2018; Whittemore, Butler, and Wilson, 2018), although the two regression lines are closer to being parallel for the LEMA than for the Haskell County index well. The 2013–2014 period was for a limited shutdown and thus may not be appropriate for plotting with the data after the complete shutdown.



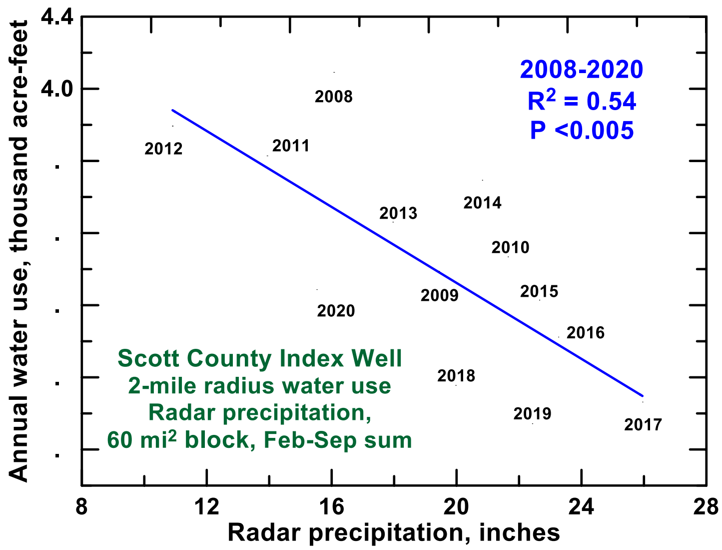


Figure 56—Correlation of annual total groundwater use with radar precipitation at the Thomas and Scott index wells for 2008–2017 and 2019–2020 (Thomas) and 2008–2020 (Scott).

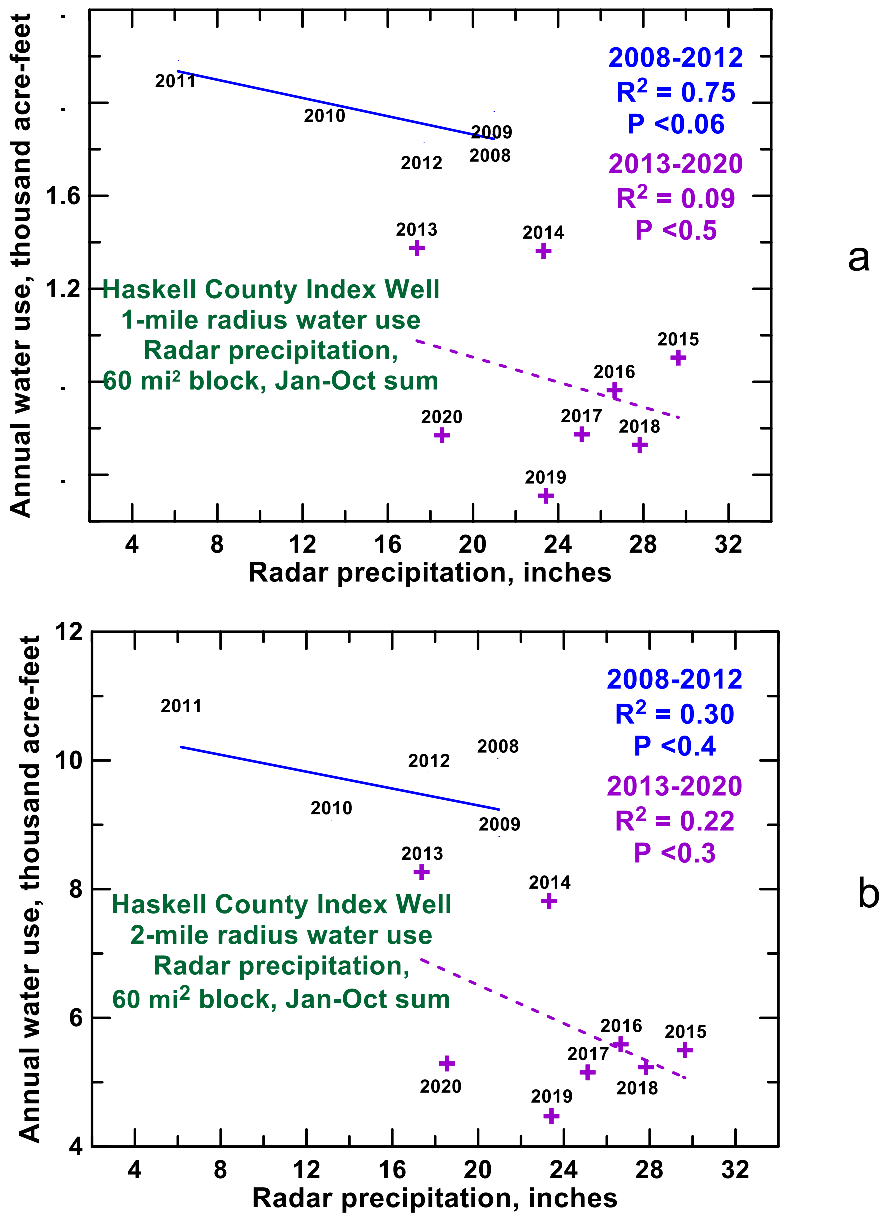


Figure 57—Correlation of annual total groundwater use with radar precipitation at the Haskell index well for 2008–2020 for (a) a 1 mi radius and (b) a 2 mi radius of water use. The 2008–2012 and 2013–2020 periods represent years before and after the onset of a court-ordered shutdown of nearby irrigation well pumping; the 2013–2014 period was for a limited shutdown (see section 3.3.2).

5 Summary of 2021–2022 Accomplishments and Plans for 2022–2023

5.1 Accomplishments, 6/2021–8/2022

- Collected and processed data from all wells currently involved in the index well program. Telemetered data from 25 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.
- Installed equipment (telemetry and sensor) and initiated monitoring at an existing well in GMD1, an existing well in GMD4, and two existing wells in GMD5.
- Continued analysis of hydrographs from all wells.
- Continued comparison of transducer data with the results of the annual water-level network.
- Continued an analysis of the utility of climatic indices and radar precipitation data for use in relationships with annual water-level change and water use in the vicinity of the index wells.
- Continued assessment of relationships among precipitation, annual water-level change, and annual water use at the index wells and the GMDs.
- Continued integration of program data into the digital Kansas High Plains Aquifer Atlas (Fross et al., 2012).
- Gave presentations about the index well program to KWO, DWR, and GMD personnel, among others.
- Wrote a paper on the net inflow approach developed through the index well program; the paper will be published in the journal Groundwater in the first half of 2023 and is included as an appendix to this report.

5.2 Planned Activities, 9/2022–6/2023

- 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 two well nests in GMD3; each nest will have one well in the HPA and one well in the Dakota aquifer.
- Install sensor and telemetry equipment and initiate monitoring at an existing well in GMD5.
- Continue assessment of the information that can be acquired from hydrograph inspection.
- Continue assessment of the relationships among climatic indices, radar precipitation data, annual water-level change, and annual water use for all five GMDs.

6 References

Bohling, G. C., Butler, J. J., Jr., Whittemore, D. O., and Wilson, B. B., 2021, Evaluation of data needs for assessments of aquifers supporting irrigated agriculture: Water Resources Research, v. 57, no. 4, doi: 10.1029/2020WR028320.

Buchanan, R. C., Wilson, B. B., Buddemeier, R. R., and Butler, J. J., Jr., 2015, The High Plains aquifer: Kansas Geological Survey Public Information Circular 18, 6 p. http://www.kgs.ku.edu/Publications/pic18/index.html

Buddemeier, R. W., Stotler, R., Butler, J. J., Jr., Jin, W., Beeler, K., Reboulet, E., Macfarlane, P. A., Kreitzer, S., Whittemore, D. O., Bohling, G., and Wilson, B. B., 2010, High Plains aquifer calibration monitoring well program: Third year progress report: Kansas Geological Survey Open-File Report 2010-3, 117 p. http://www.kgs.ku.edu/Hydro/Publications/2010/OFR10_3/index.html

Butler, J. J., Jr., Bohling, G. C., Perkins, S. P., Whittemore, D. O., Liu, G., and Wilson, B. B., 2023, Net inflow: An important target on the path to aquifer sustainability: Groundwater (in press).

Butler, J. J., Jr., Bohling, G. C., Whittemore, D. O., and Wilson, B. B., 2020a, A roadblock on the path to aquifer sustainability: Underestimating the impact of pumping reductions: Environmental Research Letters, v. 15, 014003, doi:10.1088/1748-9326/ab6002.

Butler, J. J., Jr., Bohling, G. C., Whittemore, D. O., and Wilson, B. B., 2020b, Charting pathways towards sustainability for aquifers supporting irrigated agriculture: Water Resources Research, v. 56, no. 10, doi: 10.1029/2020WR027961.

Butler, J. J., Jr., Knobbe, S., Reboulet, E. C., Whittemore, D. O., Wilson, B. B., and Bohling, G. C., 2021, Water well hydrographs: An underutilized resource for characterizing subsurface conditions: Groundwater, v. 59, no. 6, doi: 10.1111/gwat.13119.

Butler, J. J., Jr., Stotler, R. L., Whittemore, D. O., and Reboulet, E. C., 2013, Interpretation of water-level changes in the High Plains aquifer in western Kansas: Groundwater, v. 51, p. 180–190.

Butler, J. J., Jr., Whittemore, D. O., Reboulet, E., Knobbe, S., Wilson, B. B., and Bohling, G. C., 2017, High Plains aquifer index well program: 2016 annual report: Kansas Geological Survey Open-File Report 2017-10, 144 p. http://www.kgs.ku.edu/Hydro/Publications/2017/OFR17_10/index.html

Butler, J. J., Jr., Whittemore, D. O., Reboulet, E., Knobbe, S., Wilson, B. B., and Bohling, G. C., 2019, High Plains aquifer index well program: 2018 annual report: Kansas Geological Survey Open-File Report 2019-19, 62 p. http://www.kgs.ku.edu/Publications/OFR/2019/OFR2019_19.pdf

Butler, J. J., Jr., Whittemore, D. O., Reboulet, E., Knobbe, S., Wilson, B. B., and Bohling, G. C., 2020, High Plains aquifer index well program: 2019 annual report: Kansas Geological Survey Open-File Report 2020-2, 71 p. http://www.kgs.ku.edu/Publications/OFR/2020/OFR2020-2.pdf

Butler, J.J., Jr., Whittemore, D. O., Reboulet, E., Knobbe, S., Wilson, B. B., and Bohling, G. C., 2021, High Plains aquifer index well program: 2020 annual report: Kansas Geological Survey Open-File Report 2021-8, 108 p. http://www.kgs.ku.edu/Publications/OFR/2021/OFR2021-8.pdf

Butler, J. J., Jr., Whittemore, D. O., Reboulet, E., Knobbe, S., Wilson, B. B., Stotler, R. L., and Bohling, G. C., 2015, High Plains aquifer index well program: 2014 annual report: Kansas Geological Survey Open-File Report 2015-3, 135 p. http://www.kgs.ku.edu/Hydro/Publications/2015/OFR15_3/index.html

Butler, J. J., Jr., Whittemore, D. O., Reboulet, E., Knobbe, S., Wilson, B. B., Stotler, R. L., and Bohling, G. C., 2016, High Plains aquifer index well program: 2015 annual report: Kansas Geological Survey Open-File Report 2016-4, 179 p. http://www.kgs.ku.edu/Hydro/Publications/2016/OFR16_4/index.html

Butler, J. J., Jr., Whittemore, D. O., Wilson, B. B., and Bohling, G. C., 2016, A new approach for assessing the future of aquifers supporting irrigated agriculture: Geophysical Research Letters, v. 43, no. 5, p. 2,004–2,010.

Butler, J. J., Jr., Whittemore, D. O., Wilson, B. B., and Bohling, G. C., 2018, Sustainability of aquifers supporting irrigated agriculture: A case study of the High Plains aquifer in Kansas: Water International, v. 43, no. 6, p. 815–828.

Cain, S., III, Davis, G. A., Loheide, S. P., II, and Butler, J. J., Jr., 2004, Noise in pressure transducer readings produced by variations in solar radiation: Ground Water, v. 42, no. 6, p. 939–944.

Fross, D., Sophocleous, M. A., Wilson, B. B., and Butler, J. J., Jr., 2012, Kansas High Plains Aquifer Atlas: Kansas Geological Survey. http://www.kgs.ku.edu/HighPlains/HPA_Atlas/index.html

McMahon, P. B., 2001, Vertical gradients in water chemistry in the Central High Plains aquifer, Southwestern Kansas and Oklahoma Panhandle, 1999: U.S. Geological Survey Water-Resources Investigations Report 01-4028, 47 p.

Stotler, R., Butler, J. J., Jr., Buddemeier, R. W., Bohling, G. C., Comba, S., Jin, W., Reboulet, E., Whittemore, D. O., and Wilson, B. B., 2011, High Plains aquifer calibration monitoring well program: Fourth year progress report: Kansas Geological Survey Open-File Report 2011-4, 185 p. http://www.kgs.ku.edu/Hydro/Publications/2011/OFR11_4/index.html

Whittemore, D. O., Butler, J. J., Jr., and Wilson, B. B., 2015, Prediction of water-level changes and water use in the High Plains aquifer from radar precipitation: Abstract H14B-04, American Geophysical Union Meeting, San Francisco, California.

Whittemore, D. O., Butler, J. J., Jr., and Wilson, B. B., 2016, Assessing the major drivers of water-level declines: New insights into the future of heavily stressed aquifers: Hydrological Sciences Journal, v. 61, no. 1, p. 134–145.

Whittemore, D. O., Butler, J. J., Jr., and Wilson, B. B., 2018, Status of the High Plains aquifer in Kansas: Kansas Geological Survey Technical Series 22, 24 p. http://www.kgs.ku.edu/Publications/Bulletins/TS22/index.html

Whittemore, D. O., Butler, J. J., Jr., Wilson, B. B., and Woods, J., 2015, Using radar precipitation to estimate water-level changes and water use in the High Plains aquifer: Governor's Conference on Future of Water in Kansas, Manhattan, Kansas, abstract.

Young, D. P., Buddemeier, R. W., Butler, J. J., Jr., Jin, W., Whittemore, D. O., Reboulet, E., and Wilson, B. B., 2008, High Plains aquifer calibration monitoring well program: Year 2 progress report: Kansas Geological Survey Open-File Report 2008-29, 54 p. http://www.kgs.ku.edu/Hydro/Publications/2008/OFR08_29/index.html

Young, D. P., Buddemeier, R. W., Whittemore, D. O., and Reboulet, E., 2007, High Plains aquifer calibration monitoring well program: Year 1 progress report on well installation and aquifer response: Kansas Geological Survey Open-File Report 2007-30, 44 p. http://www.kgs.ku.edu/Hydro/Publications/2007/OFR07_30/index.html

7 Appendix

Net inflow: An important target on the path

to aquifer sustainability

J.J. Butler, Jr.[1,3], G.C. Bohling[1], S.P. Perkins[2], D.O. Whittemore[1],

G. Liu[1], and B.B. Wilson[1]

Manuscript prepared for submission to *Groundwater*

Original Submission: January 14, 2022
Revised Submission: May 30, 2022
Accepted for Publication: July 24, 2022

[1]Kansas Geological Survey, University of Kansas, Lawrence, KS 66047, USA

[2]Division of Water Resources, Kansas Department of Agriculture, Manhattan, KS 66502, USA

[3]Corresponding author – email: jbutler@ku.edu

Keywords: net inflow, capture, aquifer sustainability, irrigated agriculture, pumping reductions, groundwater management, High Plains aquifer, Ogallala aquifer

Article Impact Statement: We examine the net inflow concept and demonstrate its power for charting more sustainable paths in heavily stressed aquifers.

Abstract

Aquifers supporting irrigated agriculture are a resource of global importance. Many of these systems, however, are experiencing significant pumping-induced stress that threatens their continued viability as a water source for irrigation. Reductions in pumping are often the only option to extend the lifespans of these aquifers and the agricultural production they support. The impact of reductions depends on a quantity known as "net inflow" or "capture". We use data from a network of wells in the western Kansas portions of the High Plains aquifer in the central United States to demonstrate the importance of net inflow, how it can be estimated in the field, how it might vary in response to pumping reductions, and why use of "net inflow" may be preferred over "capture" in certain contexts. Net inflow has remained approximately constant over much of western Kansas for at least the last 15-25 years, thereby allowing it to serve as a target for sustainability efforts. The percent pumping reduction required to reach net inflow (i.e. stabilize water levels for the near term [years to a few decades]) can vary greatly over this region, which has important implications for groundwater management. However, the reduction does appear practically achievable (<30%) in many areas. The field-determined net inflow can play an important role in calibration of regional groundwater models; failure to reproduce its magnitude and temporal variations should prompt further calibration. Although net inflow is a universally applicable concept, the reliability of field estimates is greatest in seasonally pumped aquifers.

Introduction

Irrigated agriculture is the largest user of groundwater globally (Siebert et al., 2010). That intensive use has come at a price, as many aquifers supporting irrigated agriculture are under stress and face a highly uncertain future (Alley and Alley, 2017). Extending the lifespan of these aquifers and the food production and regional economies that they support have thus become issues of worldwide importance.

Groundwater-based irrigation is common in many semi-arid areas. There is often little surface water to substitute for groundwater, so reductions in pumping, which are typically accompanied by modifications of agricultural practices, are often the only option to diminish decline rates and extend aquifer lifespans (Hu et al., 2010; Deines et al., 2019; Butler et al., 2020a,b). The critical questions then become 1) how much should pumping be reduced to have a significant impact on water-level decline rates, and 2) is there a possibility of stabilizing water levels for at least the short to medium term?

Data from the High Plains aquifer (HPA) in western Kansas can provide insights into how these questions can be addressed. This portion of the HPA has been heavily stressed for decades, producing large water-level declines that have called into question the continued viability of groundwater-supported irrigated agriculture and the rural communities that depend on it (Figure 1; Buchanan et al., 2015). In response to this condition, Kansas developed the Local Enhanced Management Area (LEMA) program in 2012. This is a grassroots-based initiative for pumping reductions that is supported by regulatory oversight (Kansas Statutes Annotated 82a-1041, 2012). The first LEMA was established in 2013 in a 255 km^2 area in northwest Kansas, the Sheridan-6 Local Enhanced Management Area (SD-6 LEMA; yellow polygon on Figure 1), and has the goal of reducing average annual groundwater use by 20%

(Northwest Kansas Groundwater Management District No. 4, 2016). Figure 2a is a plot of annual water-level change (ΔWL) versus annual pumping (Q) for the SD-6 area. The linearity of this plot of pre-LEMA (prior to the pumping reductions initiated in 2013) and LEMA (2013 and later) data is striking, but is common in ΔWL versus Q plots across the Kansas HPA (Whittemore et al., 2018). Butler et al. (2016, 2018) have shown that the intercept over the slope of the best-fit line to these plots yields a quantity that they term "net inflow". Figure 2b is a plot of annual pumping and cumulative water-level change versus time for the SD-6 area; the horizontal dashed line is the net inflow calculated from Figure 2a. The decline rate moderates and then reverses as the annual pumping approaches and drops below, respectively, the net inflow. This indicates that net inflow is likely one of the primary determinants of how decline rates will be impacted by pumping reductions for at least the near term (several years to few decades). Thus, it appears that a key quantity needed to assess the near-term response to pumping reductions can be directly estimated from field data.

The purpose of this paper is to explore the net inflow concept and its practical utility. We begin by relating it to the well-known "capture" theory (Lohman et al., 1972; Bredehoeft, 2002; Konikow and Leake, 2014) and explain why use of "net inflow" may be preferred over "capture" in some contexts. We then demonstrate the utility of the field-calculated net inflow at a range of spatial scales through a series of applications in the High Plains aquifer in western Kansas. Net inflow can change over time, so we also discuss the importance of monitoring those changes and their ramifications for the impact of pumping reductions on decline rates. We conclude with a brief discussion of the importance of the timing and quality of the water-level and pumping measurements used to estimate net inflow.

Net Inflow

Definition and Determination

The aquifer water balance can be written in its simplest form as:

$$Water\ Volume\ Change\ in\ Aquifer = Inflows - Outflows \tag{1}$$

Although the quantification of the individual fluxes contributing to aquifer inflows and outflows has been a long-term objective of groundwater hydrology, it is still rarely achievable in practice beyond heavily instrumented research sites. As a result, Butler et al. (2016) proposed lumping all aquifer inflows and all outflows save pumping into a term they designated as “net inflow”. Equation (1) can then be rewritten as:

$$Water\ Volume\ Change\ in\ Aquifer = Net\ Inflow - Pumping \tag{2}$$

Butler et al. (2016, 2018) show how equation (2) can be rewritten for an area of an unconfined aquifer like the HPA in Kansas as:

$$\Delta WL = \frac{I}{Area \times S_Y} - \frac{Q}{Area \times S_Y} \approx b - aQ \tag{3}$$

where ΔWL is the average water-level change for the area [L], S_Y is the specific yield [-], I is net inflow [L^3], Q is pumping [L^3], and a and b are constants, with all quantities typically defined on an annual time frame. Equation (3) is consistent with the cumulative water-level plot in Figure 2b, as setting Q equal to or below I will result in stable or increasing water levels, respectively.

Linearity of a plot of ΔWL versus Q indicates that I and S_Y are approximately constant, so that I can be estimated by dividing the intercept (b) by the slope (a), and S_Y can be estimated from the slope parameter. Butler et al. (2016) explain that a near-constant S_Y would be expected for the analysis of aquifer areas of a few hundred square kilometers or greater as heterogeneities would tend to be averaged out within the same aquifer unit. Net inflow could vary more, depending on the primary mechanisms contributing to it and the depth to water. However, as long as S_Y is nearly constant, the average I and its variations in time can be readily calculated. In all cases, a plot of ΔWL versus Q will reveal if the assumptions underlying the approximation on the right-hand side of equation (3) are appropriate.

The term "net inflow" was first proposed by Hill (1946) in a six-page discussion following a paper by Conkling (1946). Hill appears to have developed an approach similar to that described above by taking a method used in surface reservoir studies and applying it to aquifers. The term fell into disuse in the two decades following the Hill discussion and was independently proposed by Butler et al. (2016). Hill (1946) noted that net inflow would vary much less than typical hydrologic phenomena, consistent with our findings in the Kansas HPA (Butler et al., 2020a).

Relation to Capture

Theis (1940), in one of the fundamental papers underlying our discipline, pointed out that water pumped from a well must be "balanced by a loss of water somewhere." A portion of the discharged water from a well comes from a loss of aquifer storage (i.e. groundwater mining or aquifer depletion), while the rest comes from increased recharge and/or decreased discharge. This second portion was later labeled capture (Lohman et al., 1972) in the sense that the well has captured flow that otherwise would have gone elsewhere. The captured volume at any particular time can be calculated as the difference between the pumping volume and the change in aquifer storage (i.e. same as net inflow [equation (2)]). This calculation is typically done with water-level data, the best available estimate of pumping, and an estimate of specific yield (Konikow, 2013). Recent work, however, has shown that the common values used for specific yield in many modeling studies may not be representative of conditions in often highly heterogeneous aquifers (Butler et al., 2020a; Liu et al., 2022). Under certain conditions, stream depletion, a major component of capture in interconnected stream-aquifer systems, can be estimated directly (Barlow and Leake, 2012).

The definition of capture stresses the role of head-dependent boundary conditions, and the primary examples used to illustrate the concept, hypothetical aquifers in arid basins or on circular islands, aptly illustrate that role and the appropriateness of the term “capture” (Bredehoeft, 2002). However, the term may be less intuitive when applied to the budget of an area within a much larger aquifer, such as the SD-6 LEMA (Figure 1). Furthermore, Barlow et al. (2018) point out the confusion that can arise between the “capture” and “capture zone” terminology and state that the “capture zone” concept appears to be better understood by the groundwater community.

Net Inflow or Capture?

Net inflow and capture describe the same phenomenon, but use of net inflow may have advantages over capture in certain contexts. First, the term encapsulates the budget-based definition. Second, as shown in the Introduction, it can be directly estimated from field data and is a clear target quantity for groundwater conservation efforts, particularly in areas such as the Kansas HPA where data have shown that net inflow has been near stable for the last quarter of a century (Butler et al., 2018). Third, it is more accessible to stakeholders who can readily grasp the budget-based definition. Finally, the confusion between “capture” and “capture zones” discussed by Barlow et al. (2018) can be avoided.

Western Kansas Demonstrations

Water use in Kansas is regulated by the Division of Water Resources of the Kansas Department of Agriculture. In the Kansas HPA, the Division works in conjunction with five groundwater management districts (GMDs), which were established to allow local input into the management of the water resources in their areas (Buchanan et al., 2015). In the following paragraphs, we examine how net inflow changes between and within two western Kansas GMDs.

Northwest Kansas Groundwater Management District No. 4 (GMD4) is a 12,623 km^2 area in northwestern Kansas (Figure 1). Figure 3 is a plot of annual pumping and cumulative water level change versus time for the GMD4 area from 1996-2020; the horizontal dashed line is the net inflow calculated from a plot of water-level change versus annual pumping (supporting information [SI], Figure S1). In the four wettest years during this period (2009, 2017-2019), annual pumping was below net inflow and water levels increased. In all other years, water levels decreased with the largest declines occurring in the four driest years (2000, 2002-2003, and 2012). Although water levels rose in the wettest years, that rise was not produced by same-year recharge, as the thick (January 2021 average of 42.7 m) and heterogeneous vadose zone in GMD4 prevents rapid downward movement of surficial recharge (Butler et al., 2021a). Instead, the rise in water levels was produced by an annual pumping that was below the relatively constant net inflow because of the large amount of precipitation during the irrigation season in those years. The pumping reduction that would be required to reach net inflow each year, on average, across the region is 19% when calculated using the 1996-2020 data; this estimate is consistent with the 23% reduction calculated by Butler et al. (2018) using the 1996-2016 data. The percent pumping reduction, in this case 19%, is also the percent of the average annual pumping that is supplied by aquifer depletion. In other words, 81% of the average annual pumping is supplied by net inflow. Although the success of the SD-6 LEMA (2% of the GMD4 area) led to the establishment of a LEMA across the entire district in 2018, the initial reduction goals for the district-wide LEMA are modest and have yet to have a discernible impact on decline rates.

A fundamental assumption of this approach to estimate net inflow is that the measured average annual water-level change is representative of the actual average annual change over the area. Although that cannot be checked rigorously in the field, it can be checked with a recently completed groundwater model of GMD4 (Wilson et al., 2021). The average water-level change calculated from the 19,211 model cells in the active area in GMD4 can be compared to the average change calculated from the 174 cells at the locations of wells measured every year from 1996-2021 (cells ≈ 804 m by 804 m [0.5 miles on a side]). The comparison shows that the average from the 174 wells is in good agreement with the average from all the active cells in GMD4 (Figure S2); the net inflow estimates are within 0.65% of each other. Thus, the assumption appears reasonable for assessments at the scales considered here.

Southwest Kansas Groundwater Management District No. 3 (GMD3) is a 21,605 km^2 area in southwestern Kansas (Figure 1). Pumping data prior to 2005 appear suspect (Butler et al., 2018), so net inflow calculations are based on the 2005-2020 data. Figure 4a is a plot of annual water-level change versus annual pumping for GMD3 (see later discussion of data noise). Figure 4b is a plot of annual pumping and cumulative water-level change versus time for the GMD3 area; the horizontal dashed line is the net inflow calculated from Figure 4a. The pumping reduction that would be required to reach net inflow each year, on average, across the district is 18% (82% of the average annual pumping is supplied by net inflow). This is consistent with the 23% reduction from a reanalysis of the Butler et al. (2018) calculations using the 2005-2016 data (see SI, Text S1). Despite the large declines experienced in the district, no LEMAs have been established in GMD3. The observed stabilization of water levels from 2017 to 2019 (Figure 4b) was produced by a series of wetter-than-average years (labeled on Figure 4a) that reduced the need for pumping rather than by the establishment of a LEMA or similar conservation program.

The above estimates of required pumping reductions are averages across each district. However, there can be a great deal of variability within districts. Finney County (2,691 km^2 in GMD3; cross-hatched area in Figure 1) on the northern boundary of GMD3 illustrates similar behavior to the district-level evaluation (Figures S3a-b). In this case, the pumping reduction that would be required to reach net inflow is 18%, consistent with the district-wide results. In contrast, Figure 5a is a plot of annual pumping and cumulative water-level change versus time for Stevens County (1,884 km^2; stippled area in Figure 1) on the southern boundary of GMD3. The two pairs of dashed lines are the results of two interpretations of a noisy plot of water-level change versus annual pumping (Figure 5b, see later discussion). These interpretations lead to two estimates of the percent reduction required to reach stable water levels (37% and 40%), both of which are over twice that required in Finney County. Similar differences to those between Finney and Stevens counties have been observed at the county and sub-county level in all three GMDs in western Kansas. These differences reveal the importance of the areal scale of the analysis for determining the needed pumping reductions. Zwickle et al. (2021) in an interdisciplinary evaluation of the SD-6 LEMA stress the need to focus on establishing LEMAs and similar management structures in relatively small areas in which aquifer conditions and producer practices do not vary greatly. They state that efforts to establish LEMAs over larger areas could encounter greater problems with adoption because of the lack of homogeneity in terms of aquifer conditions and producer practices and attitudes.

Temporal Variations in Net Inflow

The above analyses have resulted in an average value for net inflow. However, net inflow would be expected to vary somewhat with time. One approach to assess temporal trends would be to perform the analysis over segments of the ΔWL versus Q plot. Figure 6a presents a plot of water-level change versus annual pumping for the first and last halves of the GMD4 data series. This plot reveals the problems associated with such an approach; the four wettest years in the 1996-2020 period were after 2008 so, despite the good fit to the first half of the data series, the lack of data during wet years limits confidence in the results. Thus, trend detection using such plots requires that the individual segments sample the full range of climatic conditions expected in the area.

An alternative approach is to calculate the net inflow each year and assess trends in that time series. This is done by assuming the S_Y estimated from the ΔWL versus Q plot remains constant over the entire period and substituting it, along with the annual ΔWL and Q values, into equation (3) to calculate I for each year. This is admittedly a worst-case analysis, as we are assuming that all of the regression residual is attributable to annual variations in I, but it is useful for a first-order assessment of temporal trends. Figure 6b is an example of this approach for the GMD4 data series. Net inflow varies from year to year but the variations are relatively small (Coef. of Variation = 0.10), consistent with the findings of Butler et al. (2020a). Visually, there appears to be a slight decreasing trend over the 25-year period (0.27%/yr) but it is not statistically significant (R^2=0.04, p=0.30); moreover, removal of one year on either end of the time series results in an even more negligible trend (0.11%/yr; R^2=0.01, p=0.70). Thus, the assumption of a near-constant I appears reasonable for this period.

The variations in Figure 6b are related to a variety of factors including errors in water-level measurements and reported pumping data, pumping shortly before the annual measurements, small fluctuations in S_Y, and climatic forcings. Given that the majority of the annual water-level measurements are completed within a few days in each area and that wells in the unconfined western Kansas HPA display atmospheric-pressure-driven water-level fluctuations that can be up to 0.3 m in magnitude (Butler et al., 2021b), year-to-year variations in atmospheric pressure can be an important climatic contributor to the apparent temporal variations in net inflow.

The data plots presented here indicate that net inflow has remained approximately constant across GMDs 3 and 4 for the last 15-25 years. However, trends in net inflow should eventually arise from both natural (e.g., climate-induced changes in recharge) and anthropogenic (e.g., changes in pumping) forcings. Although we have not observed net inflow trends in the SD-6 LEMA (Figure 2a), we expect that the pumping reductions will eventually lead to a decrease in I as a result of reductions in irrigation return flow, changes in lateral hydraulic gradients, etc. (Butler et al., 2020b; Glose et al., 2022). The reductions in I would be revealed on ΔWL versus Q plots by a downward shift in the data points (i.e. the same pumping would produce a greater water-level decline). The slope of the plot should not change because S_Y will vary little at this spatial scale if water levels remain in the same hydrogeologic unit. Similarly, increases in I would be revealed by an upward shift in the data points.

Many of the literature examples of capture illustrate a quantity that increases for many decades to centuries prior to stabilizing (Bredehoeft, 2002; Konikow and Leake, 2014). Widespread pumping for irrigated agriculture began in GMD4 in the early 1960s; the number of water rights increased sharply before gradually leveling out in the mid-1970s to early 1980s (Wilson et al., 2021). By 1996, if not earlier, net inflow appears to have stabilized over the district. This relatively short time to stabilization, which is likely a result of the distribution of the large number of pumping wells, aquifer heterogeneity, and the rapid drying up of the vast majority of streams in the district (there is essentially no baseflow into stream channels in western Kansas), may be a characteristic of many heavily stressed aquifers in semi-arid areas. In aquifers where net inflow is still increasing, the pumping reductions based on the estimated net inflow will be overly conservative as not all the mechanisms contributing to the net inflow would have fully come into play.

Data Quality

The field calculation of net inflow discussed in the earlier sections is dependent on reliable measurements of water levels and pumping.

Water Levels

For decades in Kansas, annual water-level measurements have been taken in a network of wells (about 1,400) distributed approximately uniformly (every ≈ 40 km^2) over the HPA (Miller et al., 1998; Bohling and Wilson, 2012). The guiding principles for the program have been to minimize measurement error, take measurements at a time when pumping activity is at a minimum, and be consistent with the timing of measurements from year to year. In the Kansas HPA, the preferred time for measurements is January, typically three to four months after cessation of irrigation pumping. As a result, year-to-year variations in the timing of the end of the irrigation season have relatively little influence on the measurements and thus the ΔWL values. However, in some years, particularly in southwestern Kansas, pumping late in the year can have a sizable impact on the ΔWL values. The small difference in ΔWL but the large difference in Q for 2010 and 2011 in Figure 4a is an example of the impact of December pumping activity on the annual measurements (see Text S2 for further discussion). The noise introduced into the ΔWL data by the late-year pumping made little difference in this case as the

I values differed by less than 3% between estimates made using the original values or the average of the two as in Figure 4a. In other cases, pumping activity prior to the measurements can introduce so much noise that the calculation is of little value. Thus, estimation of net inflow from a ΔWL versus Q plot is most effective in a seasonally pumped aquifer using water-level measurements taken three to four months after the end of the pumping season.

Measurement errors may have little influence on net inflow calculations over a large area, such as GMDs 3 and 4 where the ΔWL values are averages of 251 and 174 values, respectively, but their impact can be larger when the number of wells is relatively small. Although the impact on the net inflow calculation may still be small, the confidence in the results can be lessened. Figure 5b shows the influence of suspected measurement errors on the ΔWL values in Stevens County. The ΔWL values are the annual averages of measurements taken at 21 wells. In 13 of the 16 years, one or two of the 21 wells (six wells total) had water-level changes that were significantly different from the other 19 to 20 (see Text S3). When those wells are removed from the averages, the ΔWL values change from the circles to the triangles in Figure 5b. Although the R^2 increased by 15% and the p value decreased by 77%, *I* changed by less than 4%. However, as the number of wells gets smaller (i.e., in the single digits), such apparent measurement errors could have a much larger impact.

Annual Pumping

Every non-domestic pumping well is required to have a totalizing flowmeter in the Kansas HPA; the recorded pumping volumes must be reported annually and are subject to regulatory verification (Butler et al., 2016). Direct measurements of pumping allow important insights to be gleaned about aquifer behavior, but may not be available in many aquifers (Foster et al., 2020). Bohling et al. (2021) have shown that a random subset of metered wells as small as 10-

20% can be used to obtain excellent estimates of the pumping in an area if the total number of pumping wells is known. Even when the number of wells may be uncertain, working with bounding values can provide a likely range for the pumping and thus a range for net inflow. Reliable estimates of net inflow become more problematic in the absence of direct measurements of pumping.

Discussion and Conclusions

Groundwater depletion in aquifers supporting irrigated agriculture has become an issue of global concern (Alley and Alley, 2017). The major purpose of this paper is to draw more attention to the net inflow concept and its practical utility. Through a series of demonstrations at scales of relevance for many practical applications, we have shown how estimates of net inflow from field data can be used to help redirect these heavily stressed systems onto more sustainable paths. We also have explored the impact of the quality, quantity, and timing of the water-level and pumping data on the resulting estimates of net inflow, and found that the estimation process should be most effective in seasonally pumped aquifers.

The net inflow concept is nothing new. It was originally proposed over 75 years ago, a few years after Theis' seminal 1940 paper that introduced the concept later named capture. Net inflow and capture are equivalent but each may have a context where its use is preferred. For example, in discussions with stakeholders in the Kansas portion of the High Plains aquifer (HPA), the concept of net inflow has been readily grasped and accepted. The pairing of the ΔWL versus Q plot with the Q and cumulative ΔWL versus time plot has proven to be a convincing demonstration of the concept and its relationship to field data.

The reductions in pumping required to diminish decline rates in these heavily stressed systems will likely lead to decreases in net inflow and thus further pumping reductions in the future (Butler et al., 2020b). The decreases in net inflow will be a function of the major fluxes that are contributing to it, so the quantification of those fluxes is critical. This will require more attention to long-term monitoring of the aquifers of interest. This monitoring must move beyond annual water-level measurements and limited-term, campaign-style projects. In particular, more attention must be paid to the major stress on these aquifers, pumping. Direct measurement of pumping at a subset of wells in an area should become the rule, and not the exception, if we are to develop the insights into an aquifer's functioning that are needed to reliably assess its future prospects. Pumping estimates based on utility records, evapotranspiration estimates, various remote sensing platforms, and machine-learning approaches will be most effective if integrated with direct measurements.

Net inflow appears to have been near constant over much of the western Kansas HPA for the last quarter of a century. The thick vadose zone is likely primarily responsible for this condition, as the temporal variability in infiltration at the land surface is greatly damped with depth (Dickinson et al., 2014; Dickinson and Ferré, 2018). Reductions in pumping for irrigated agriculture may therefore take years to decades to result in decreases in net inflow. Although the impact may be delayed for an extended period of time, it will eventually occur. As we have discussed elsewhere (Butler et al., 2020b), this delay may give rise to a period of apparent sustainability (water levels, on average, changing little or even increasing with time) when pumping is reduced to or below net inflow. The agencies that are responsible for groundwater management will need to educate water users in their areas so that this apparent sustainability does not result in increased pumping, which would lead to further water-level declines that would be accelerated once the reductions in net inflow begin. When they do occur, the decreases in net inflow will be evident on ΔWL versus Q plots, so that groundwater management practices can be modified.

The estimates of net inflow and percent pumping reductions given here can vary with the period of analysis because of the strong correlation between precipitation and pumping in the Kansas HPA (Whittemore et al., 2016; Butler et al., 2021b). The variation in these estimates, however, will be small once the full range of climatic conditions in an area has been experienced.

Groundwater models of seasonally pumped aquifers should be able to exploit certain aspects of the approach described here. The net inflow estimate obtained from a ΔWL versus Q plot could serve as an important constraint for regional groundwater models. If a model cannot reproduce the magnitude and temporal behavior of the field-calculated net inflow, then further calibration should be considered. As we have shown elsewhere, the specific yield estimate obtained from this plot can also serve as an important model constraint (Butler et al., 2020a; Liu et al., 2022).

The findings presented here should be representative of conditions in seasonally pumped aquifers in semi-arid areas with relatively thick vadose zones. However, the approach described in this paper is not limited to that setting. Butler et al. (2016, 2017) examined its applicability in Equus Beds Groundwater Management District No. 2 (GMD2), the easternmost Kansas GMD, which is located in a subhumid area with perennial streams and relatively shallow water tables. As shown in Figure 4 in Butler et al. (2016), similar linear relationships are observed in that setting, although the data spread about the best-fit line is often larger as a result of greater interannual variability driven by stream-aquifer interactions and rapid recharge. Given our experience in GMD2, we expect that reliable estimates of net inflow will be attainable in many seasonally pumped aquifers with relatively shallow depths to water and perennial streams. Further assessments are required to determine the response of net inflow to changes in natural and anthropogenic forcings in other settings. We anticipate that linear relationships will be difficult to obtain from once-a-year measurements in aquifers that are dominated by year-round industrial and municipal pumping. Use of annual average water levels, however, may enable linear relationships to be obtained under those conditions.

Our discipline faces many challenges as we strive to meet societal expectations and provide reliable estimates of what the future holds for aquifers supporting critically needed agricultural production. Hopefully, the concepts discussed here can play a role in helping us meet those expectations and better prepare the world for what lies ahead.

Acknowledgments

This work was supported, in part, by the Kansas Water Plan under the Ogallala-High Plains Aquifer Assessment Program (OHPAAP), the Kansas Water Office (KWO), and the United States Department of Agriculture (USDA) and the United States National Science Foundation (NSF) under USDA-NIFA/NSF INFEWS subaward RC108063UK. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the OHPAAP, KWO, USDA, or NSF. We thank Sam Zipper and three anonymous reviewers for their helpful comments.

Supporting Information

Additional Supporting Information may be found in an online document that contains texts S1 through S3, figures S1 through S5, and tables S1 through S6 as referenced in the main text. Supporting Information is generally *not* peer reviewed.

References

Alley, W. M., and R. Alley. 2017. *High and Dry: Meeting the Challenges of the World's Growing Dependence on Groundwater*. New Haven, CT: Yale University Press.

Barlow, P. M., and Leake, S. A. 2012. Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow. *U.S. Geological Survey Circular 1376*. https://pubs.usgs.gov/circ/1376/.

Barlow, P. M., Leake, S. A., and Fienen, M. N. 2018. Capture versus capture zones: Clarifying terminology related to sources of water to wells. *Groundwater* 56, no. 5, 694-704.

Bohling, G. C., J. J. Butler Jr., D. O. Whittemore, and B. B. Wilson. 2021. Evaluation of data needs for assessments of aquifers supporting irrigated agriculture. *Water Resour. Res.* 57, no. 4, doi: 10.1029/2020WR028320.

Bohling, G. C., and B. B. Wilson. 2012. Statistical and geostatistical analysis of the Kansas High Plains water-table elevations, 2012 measurement campaign. *Kansas Geological Survey Open-File Report 2012-16*. http://www.kgs.ku.edu/Hydro/Publications/2012/OFR12_16/index.html.

Bredehoeft, J. D. 2002. The water budget myth revisited: Why hydrogeologists model. *Groundwater* 40, no. 4, 340-345.

Buchanan, R. C., B. B. Wilson, R. R. Buddemeier, and J. J. Butler, Jr. 2015. The High Plains aquifer. *Kansas Geological Survey Public Information Circular 18*. http://www.kgs.ku.edu/Publications/pic18/index.html.

Butler, J. J., Jr., G. C. Bohling, D. O. Whittemore, and B. B. Wilson. 2020a. A roadblock on the path to aquifer sustainability: Underestimating the impact of pumping reductions. *Environmental Research Letters* 15, 014003, doi: 10.1088/1748-9326/ab6002.

Butler, J. J., Jr., G. C. Bohling, D. O. Whittemore, and B. B. Wilson. 2020b. Charting pathways towards sustainability for aquifers supporting irrigated agriculture. *Water Resour. Res.* 56, no. 10: doi: 10.1029/2020WR027961.

Butler, J. J., Jr., S. Knobbe, E. C. Reboulet, D. O. Whittemore, B. B. Wilson, and G. C. Bohling. 2021a. Water well hydrographs: An underutilized resource for characterizing subsurface conditions. *Groundwater* 59, no. 6: 808-818, doi: 10.1111/gwat.13119.

Butler, J. J., Jr., D. O. Whittemore, E. Reboulet, S. Knobbe, B. B. Wilson, and G. C. Bohling. 2021b. High Plains aquifer index well program: 2020 annual report. *Kansas Geological Survey Open-File Rept. 2021-8*. http://www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml.

Butler, J. J., Jr., D. O. Whittemore, and B. B. Wilson. 2017. Equus Beds Groundwater Management District No. 2 sustainability assessment. *Kansas Geological Survey Open-File Rept. 2017-3*, https://www.kgs.ku.edu/Hydro/Publications/2017/OFR17_3/index.html.

Butler, J. J., Jr., D. O. Whittemore, B. B. Wilson, and G. C. Bohling. 2018. Sustainability of aquifers supporting irrigated agriculture: a case study of the High Plains aquifer in Kansas. *Water International* 43, no. 6: 815-828, doi: 10.1080/02508060.2018.1515566.

Butler, J. J., Jr., D. O. Whittemore, B. B. Wilson, and G. C. Bohling. 2016. A new approach for assessing the future of aquifers supporting irrigated agriculture. *Geophysical Research Letters* 43, no. 5: 2004-2010, doi:10.1002/2016GL067879.

Conkling, H. 1946. Utilization of ground-water storage in stream system development. *American Society of Civil Engineers Transactions* 111, 275-305.

Deines, J. M., A. D. Kendall, J. J. Butler, Jr., and D. W. Hyndman. 2019. Quantifying irrigation adaptation strategies in response to stakeholder-driven groundwater management in the US

High Plains Aquifer. *Environmental Research Letters*, 14, no. 4, 044014, doi: 10.1088/1748-9326/aafe39.

Dickinson, J. E., and T. P. A. Ferré. 2018. Filtering of periodic infiltration in a layered vadose zone: 2. Applications and a freeware screening tool. *Vadose Zone Journal* 17, 80048, doi:10.2136/vzj2018. 03.0048.

Dickinson, J. E., T. P. A. Ferré, M. Bakker, and B. Crompton. 2014. A screening tool for delineating subregions of steady recharge within groundwater models, *Vadose Zone Journal* 13, no. 6, 15 pp.

Foster, T., T. Mieno, and N. Brozovic. 2020. Satellite-based monitoring of irrigation water use: Assessing measurement errors and their implications for agricultural water management policy. *Water Resour. Res.* 56, no. 11, e2020WR028378, doi: 10.1029/2020WR028378.

Glose, T. J., S. Zipper, D. W. Hyndman, A. D. Kendall, J. M. Deines, and J. J. Butler, Jr. 2022. Quantifying the impact of lagged hydrological responses on the effectiveness of groundwater conservation. *Water Resour. Res.* 58, e2022WR032295, doi: 10.1029/2022WR032295.

Hill, R. A. 1946. Discussion of "Utilization of ground-water storage in stream system development" by H. Conkling. *American Society of Civil Engineers Transactions* 111, 306-311.

Hu, Y., J. P. Moiwo, Y. Yang, S. Han, and Y. Yang. 2010. Agricultural water-saving and sustainable groundwater management in Shijiazhuang Irrigation District, North China Plain. *Journal of Hydrology* 393, 219-232.

Kansas Statutes Annotated 82a-1041. 2012. Local enhanced management areas; establishment procedures; duties of chief engineer; hearing; notice; orders; review. (available at www.ksrevisor.org/statutes/chapters/ch82a/082a_010_0041.html).

Konikow, L. F. 2013. Groundwater depletion in the United States (1900−2008). *U.S. Geological Survey Scientific Investigations Report 2013−5079*. http://pubs.usgs.gov/sir/2013/5079.

Konikow, L. F., and S. A. Leake. 2014. Depletion and capture: Revisiting "The source of water derived from wells". *Groundwater* 52, no. S1, 100-111.

Liu, G., B. B. Wilson, G. C. Bohling, D. O. Whittemore, and J. J. Butler, Jr. 2022. Estimation of specific yield for regional groundwater models: Pitfalls, ramifications, and a promising path forward. *Water Resour. Res.* 58, no. 1: doi: 10.1029/2021WR030761.

Lohman, S.W., et al. 1972. Definitions of selected groundwater terms—revisions and conceptual refinements. *U.S. Geological Survey Water-Supply Paper 1988*. Reston, VA: U.S. Geological Survey.

Miller, R. D., R. C. Buchanan, and L. Brosius. 1998. Measuring water levels in Kansas. *Kansas Geological Survey Public Information Circular 12*. http://www.kgs.ku.edu/Publications/pic12/ pic12_1.htm.

Northwest Kansas Groundwater Management District No. 4. 2016. Revised management program. http://gmd4.org/Management/GMD4-MgtPro.pdf.

Siebert, S., J. Burke, J. M. Faures, K. Frenken, J. Hoogeveen, P. Döll, and F. T. Portmann. 2010. Groundwater use for irrigation – a global inventory. *Hydrol. Earth Syst. Sci.* 14, 1863–1880.

Theis, C. V. 1940. The source of water derived from wells: Essential factors controlling the response of an aquifer to development. *Civil Engineering* 10, no. 5, 277-280.

Whittemore, D. O., J. J. Butler, Jr., and B. B. Wilson. 2016. Assessing the major drivers of water-level declines: New insights into the future of heavily stressed aquifers. *Hydrological Sciences Jour.* 61, no. 1, 134-145.

Whittemore, D. O., J. J. Butler, Jr., and B. B. Wilson. 2018. Status of the High Plains aquifer in Kansas. *Kansas Geological Survey Technical Series 22*. Lawrence, KS; Kansas Geological Survey. http://www.kgs.ku.edu/Publications/Bulletins /TS22/index.html.

Wilson, B. B., G. Liu, G. C. Bohling, and J. J. Butler, Jr. 2021. GMD4 groundwater flow model: High Plains aquifer modeling maintenance project. *Kansas Geological Survey Open-File Report 2021-6*. Lawrence, KS; Kansas Geological Survey. http://www.kgs.ku.edu/Publications/OFR/2021/OFR2021-6.pdf

Zwickle, A., B. C. Feltman, A. J. Brady, A. D. Kendall, and D. W. Hyndman. 2021. Sustainable irrigation through local collaborative governance: Evidence for a structural fix in Kansas. *Environmental Science and Policy* 124, 517–526.

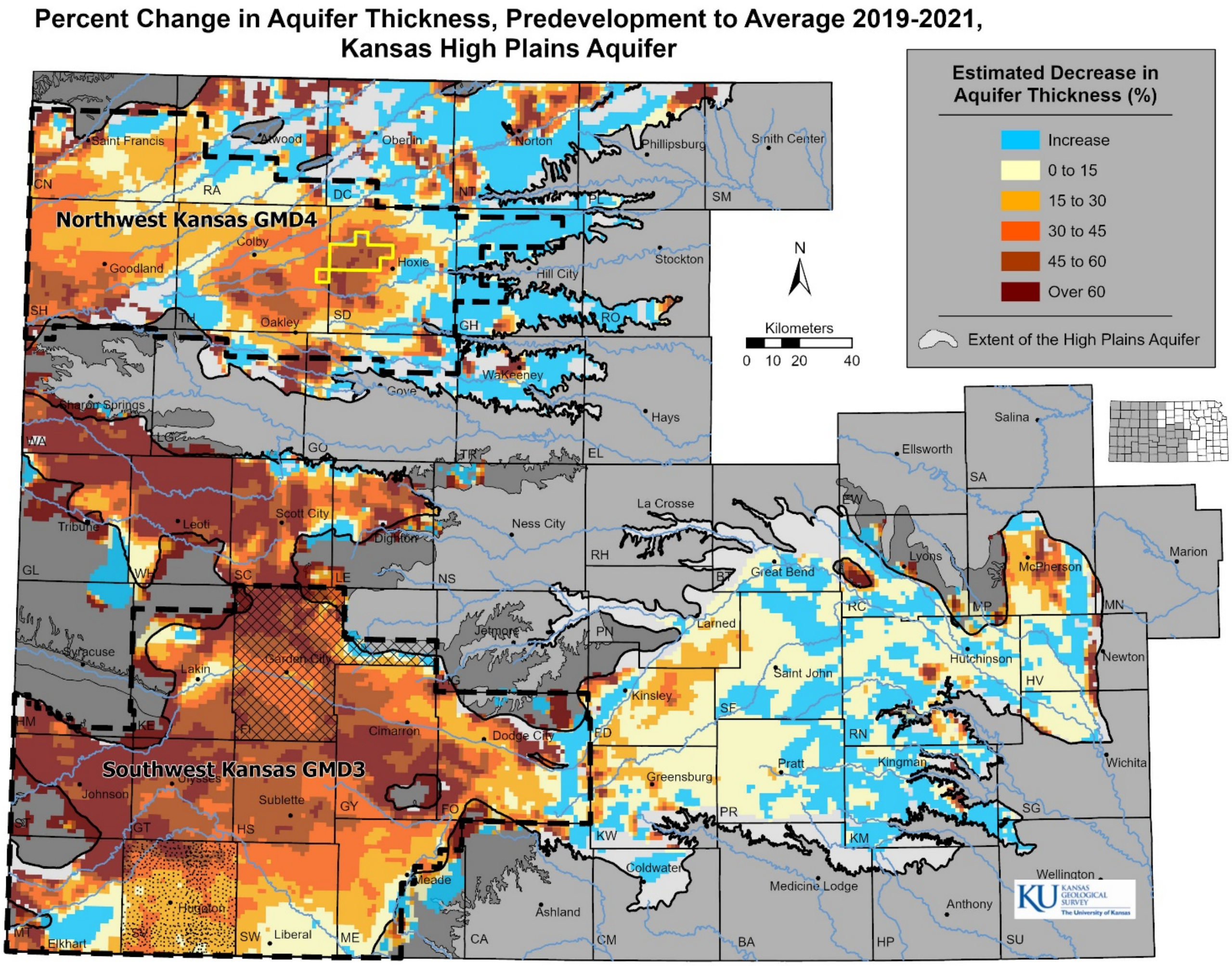


Figure 1 - Map of the percent change in aquifer thickness from predevelopment to present for the High Plains aquifer (HPA) in Kansas (the inset on the right shows the portion of the state pictured here). Predevelopment is defined as period prior to onset of widespread pumping for irrigated agriculture, which occurred between 1940 and the late 1950s in most of the Kansas HPA; present is defined as average of 2019-2021 winter conditions. Groundwater management districts (GMDs) 3 and 4 are delineated by dashed black lines. The yellow polygon in GMD4 is the Sheridan-6 Local Enhanced Management Area (SD-6 LEMA); the crosshatched region in GMD3 marks the portions of Finney County lying within GMD3 and the county marked by the stippled pattern in southern GMD3 is Stevens County. The areas of aquifer increase in the western third of the figure are areas of thin aquifer that are of little practical importance.

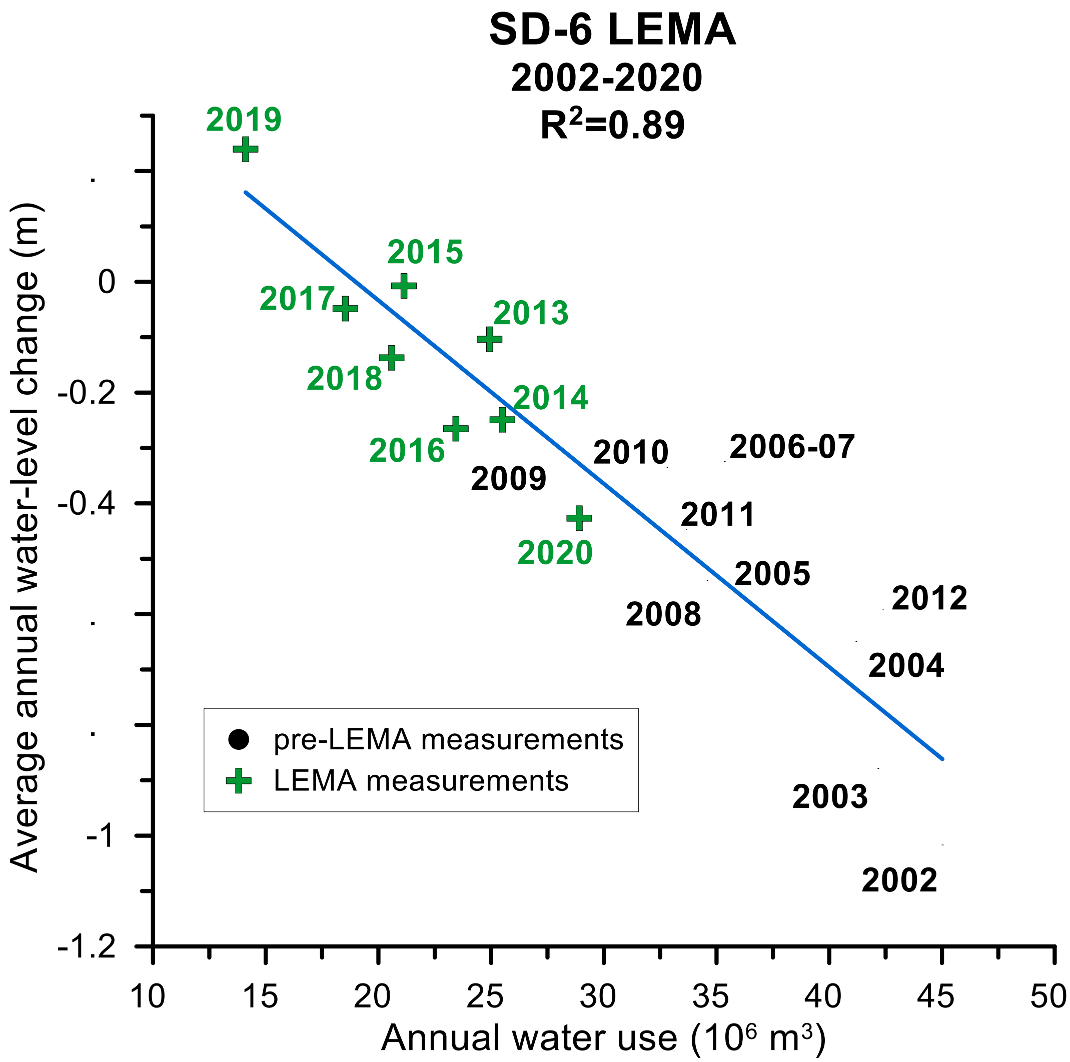


Figure 2a - Average annual water-level change (ΔWL) versus annual water use (Q) plot for the SD-6 LEMA in GMD4. Solid line is the best fit to the 2002–2020 data ($\Delta WL = 0.6286– 0.03310Q$, $p < 0.0001$). ΔWL for the circles is the average water-level change for the seven wells measured every year from 2002 to 2012 (pre-LEMA wells); ΔWL for the pluses is the average for the pre-LEMA wells with two, three, and four additional wells (2013, 2014–15, and 2016-20, respectively) that were drilled later (Butler et al., 2018). Heavy snows delayed 2007 water-level measurements from early January to late February through early April, so the average ΔWL value for 2006 and 2007 is used here. Annual water use is sum of reported use from a maximum of 195 pumping wells (total varies slightly from year to year). The estimated uncertainty (one standard deviation) in ΔWL is ±0.19 m and that in Q is ±0.4% of plotted value (determined using methods described in Butler et al. [2016] and Bohling et al. [2021]). Data are provided in Table S1.

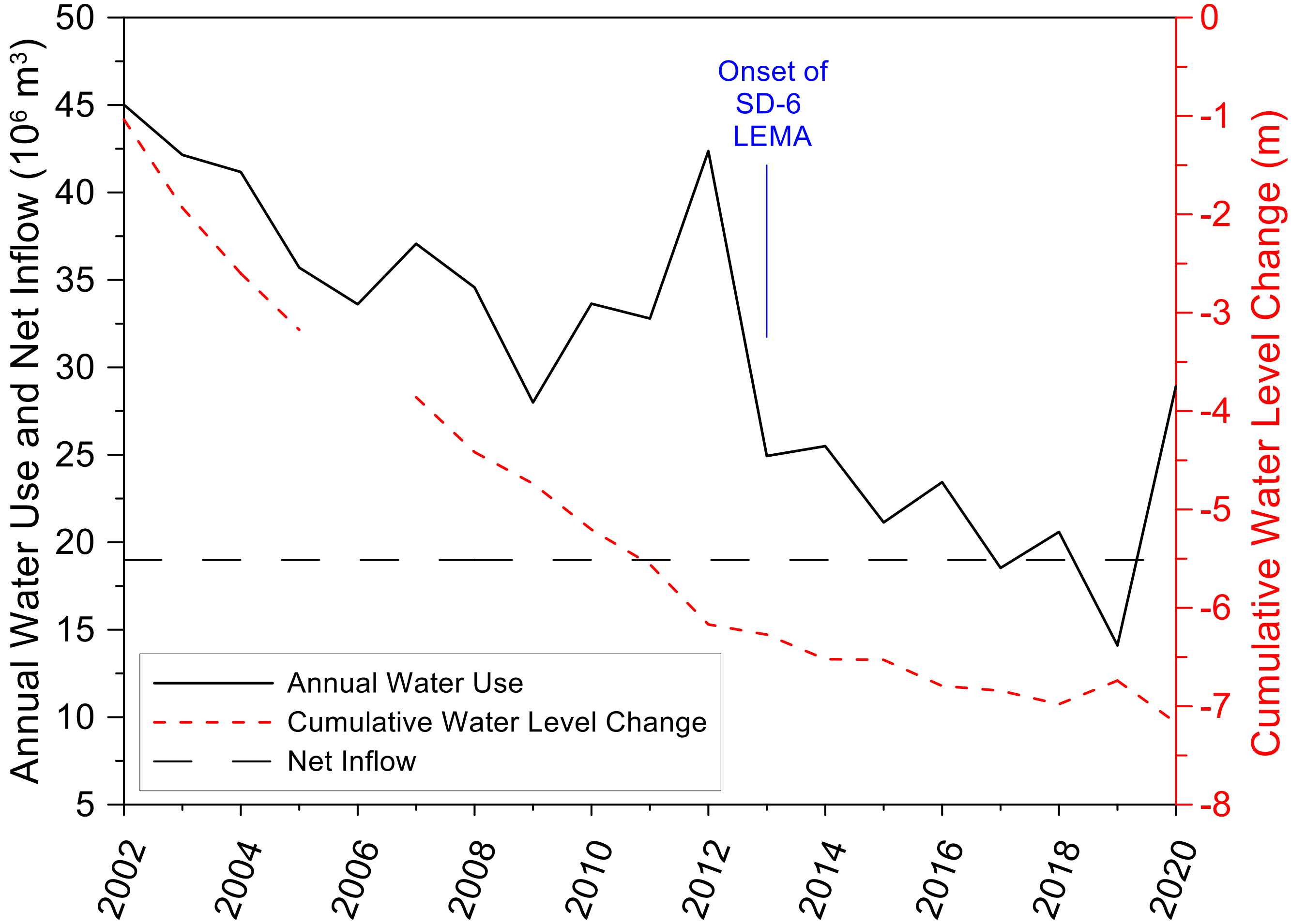


Figure 2b – Annual water use (left y-axis) and cumulative water-level change (right y-axis) versus time for the SD-6 LEMA in GMD4. Large dashed line is the average net inflow (left y-axis) calculated from Figure 2a; onset of LEMA pumping reductions (2013) is marked by vertical line and gap in the cumulative water-level change plot is due to the lack of the 2006 ΔWL value. The estimated uncertainty (one standard deviation) in net inflow is 1.3×10^6 m^3 (determined using methods described in Butler et al. [2016] and Bohling et al. [2021]).

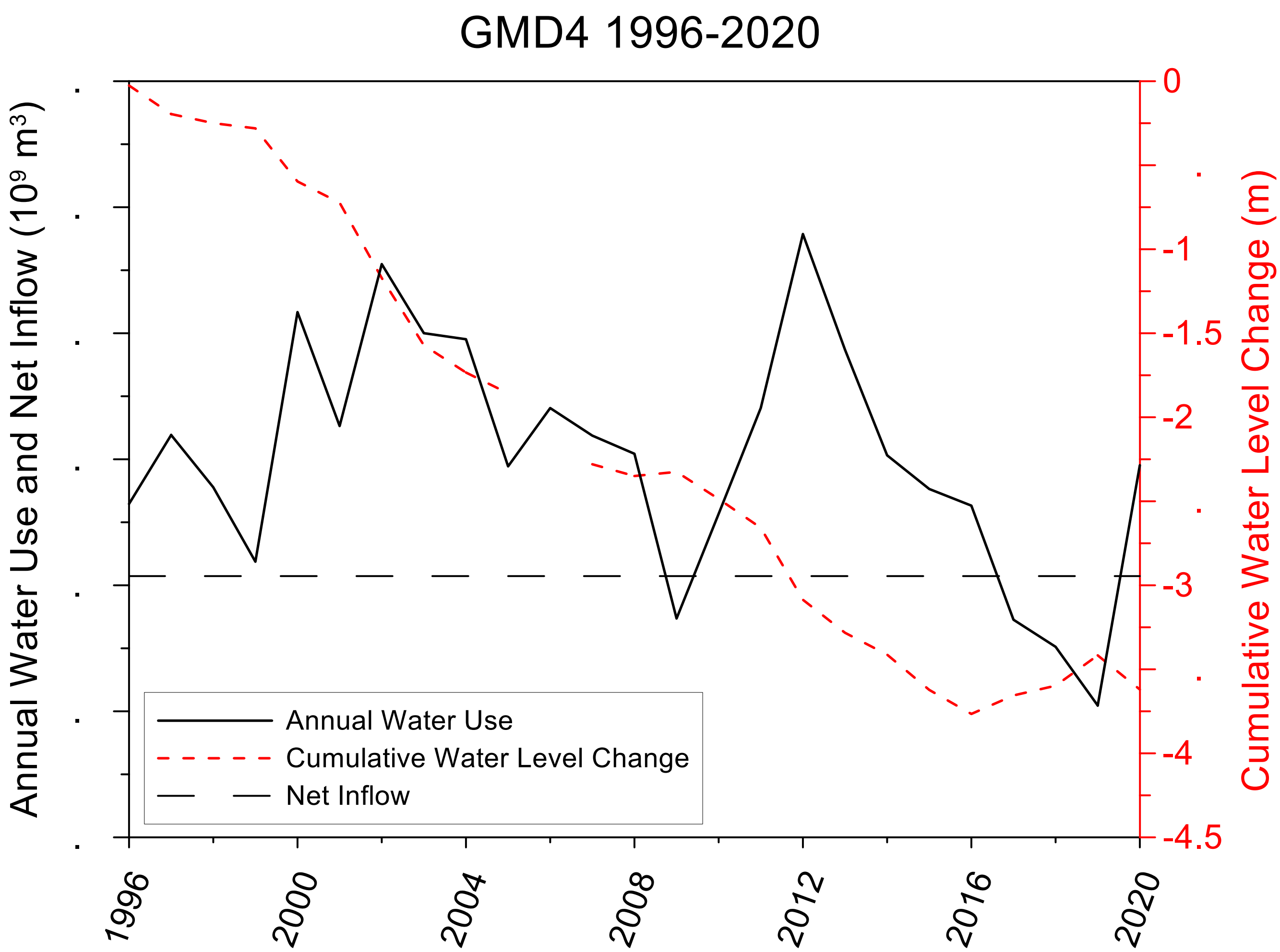


Figure 3 - Annual water use (left y-axis) and cumulative water-level change (right y-axis) versus time for GMD4. Large dashed line is the average net inflow (left y-axis) calculated from Figure S1; gap in the cumulative water-level change plot is due to the lack of the 2006 ΔWL value (see further explanation in Figure S1). The estimated uncertainty (one standard deviation) in net inflow is 0.012×10^9 m^3 (determined using methods described in Butler et al. [2016] and Bohling et al. [2021]). Data are provided in Table S2.

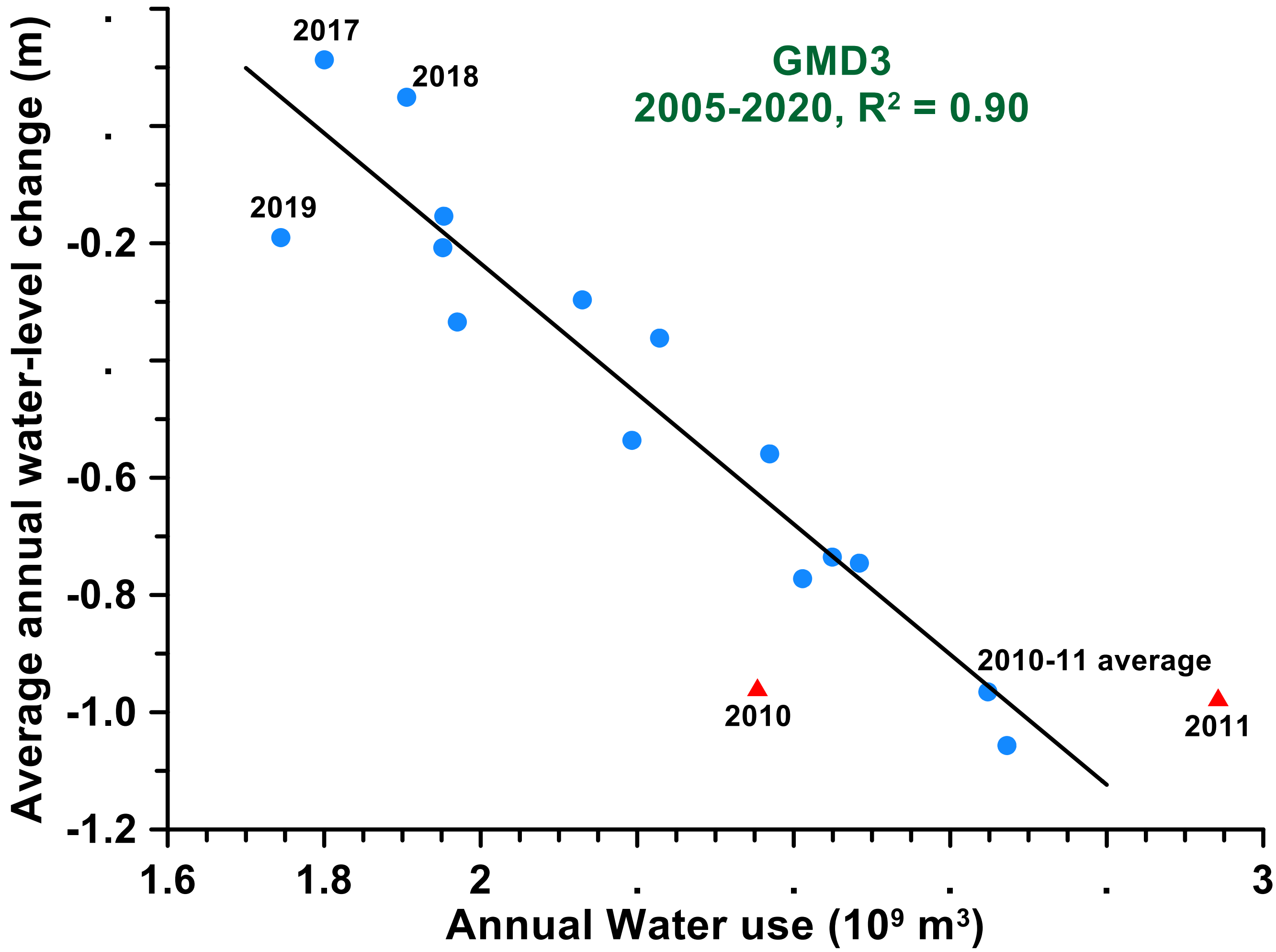


Figure 4a - Average annual water-level change (ΔWL) versus annual water use (Q) plot for GMD3. Solid line is the best fit to the 2005–2020 data ($\Delta WL = 1.9886–1.1116Q$, $p < 0.0001$) using the average ΔWL and Q values for 2010-11 (see Text S2). ΔWL is the average computed using the 251 wells measured every year from 2005 to 2021. Q is the sum of reported use from a maximum of 15,175 pumping wells (total varies slightly from year to year). The estimated uncertainty (one standard deviation) in ΔWL is ±0.070 m and that in Q is ±0.05% of plotted value (determined using methods described in Butler et al. [2016] and Bohling et al. [2021]). Data are provided in Table S3.

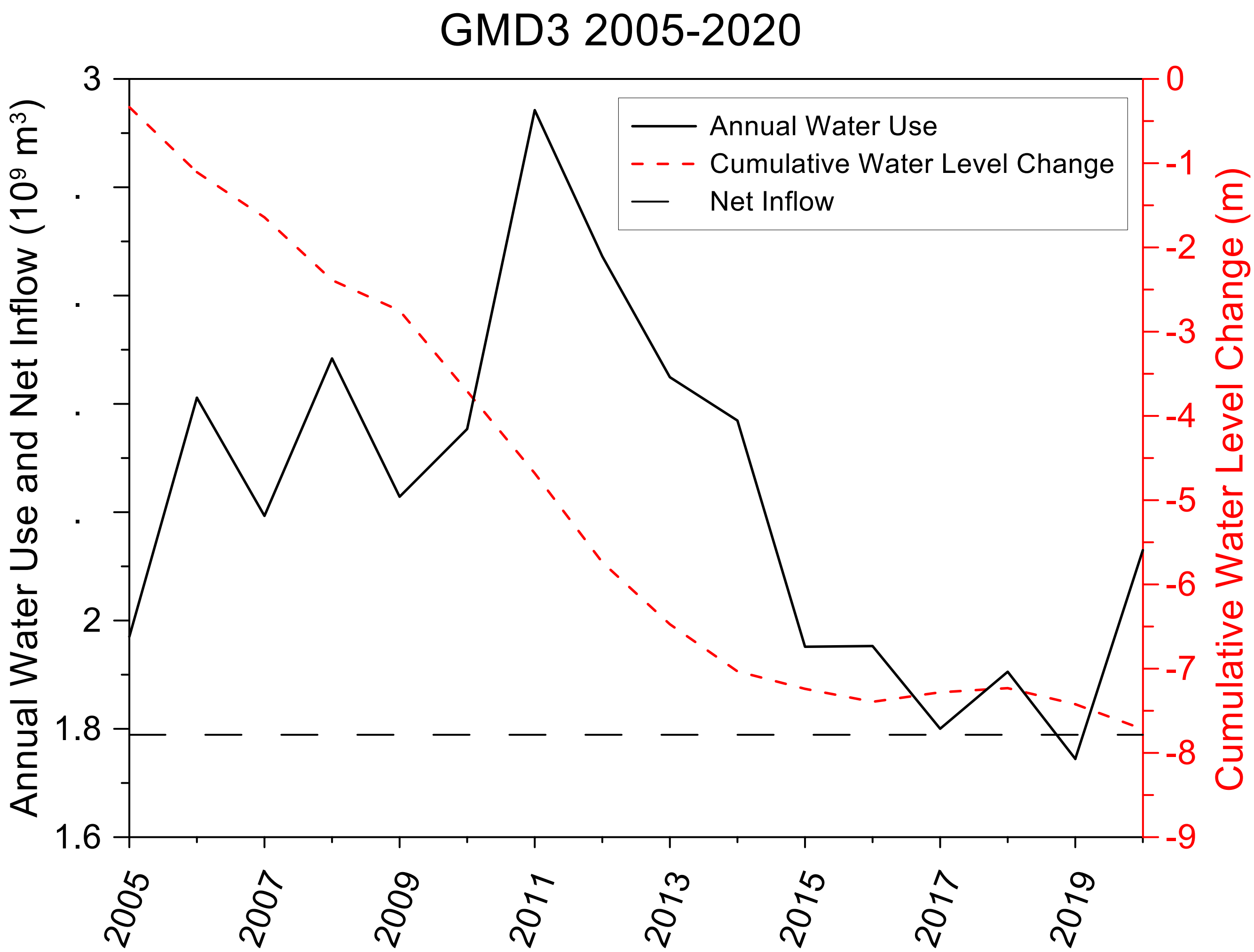


Figure 4b - Annual water use (left y-axis) and cumulative water-level change (right y-axis) versus time for GMD3. Large dashed line is the average net inflow (left y-axis) calculated from Figure 4a. The estimated uncertainty (one standard deviation) in net inflow is 0.076×10^9 m^3 (determined using methods described in Butler et al. [2016] and Bohling et al. [2021]).

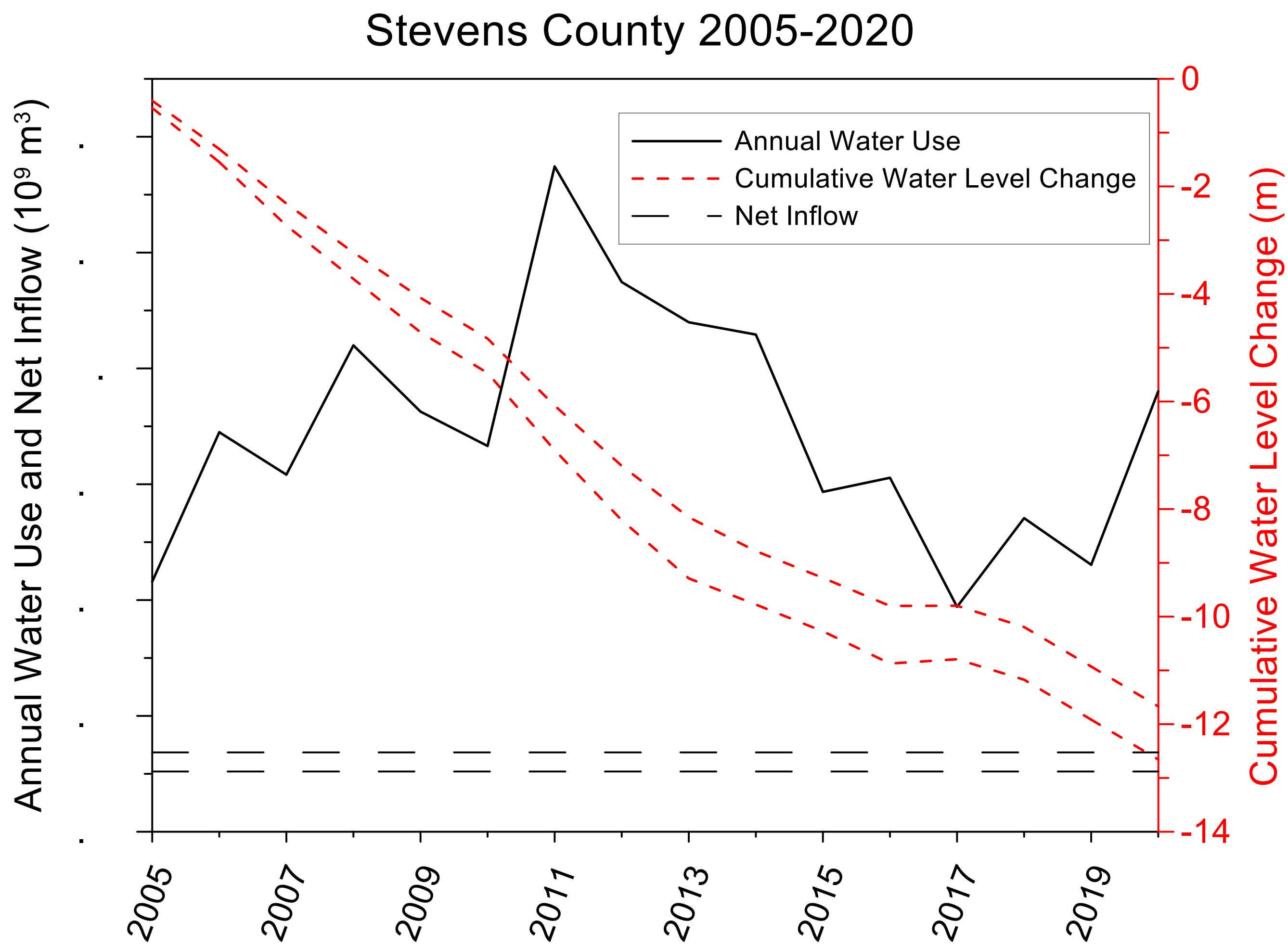


Figure 5a - Annual water use (left y-axis) and cumulative water-level change (right y-axis) versus time for Stevens County in GMD3. Large dashed lines are the average net inflow (left y-axis) calculated from Figure 5b. The lower cumulative ΔWL line and the upper net inflow line are based on the solid circles in Figure 5b, while the upper cumulative ΔWL line and the lower net inflow line are based on the modified ΔWL values (triangles in Figure 5b). The estimated uncertainty (one standard deviation) in net inflow is 0.032 x10^9 m^3 for lower line and 0.12x10^9 m^3 for upper line (determined using methods described in Butler et al. [2016] and Bohling et al. [2021]).

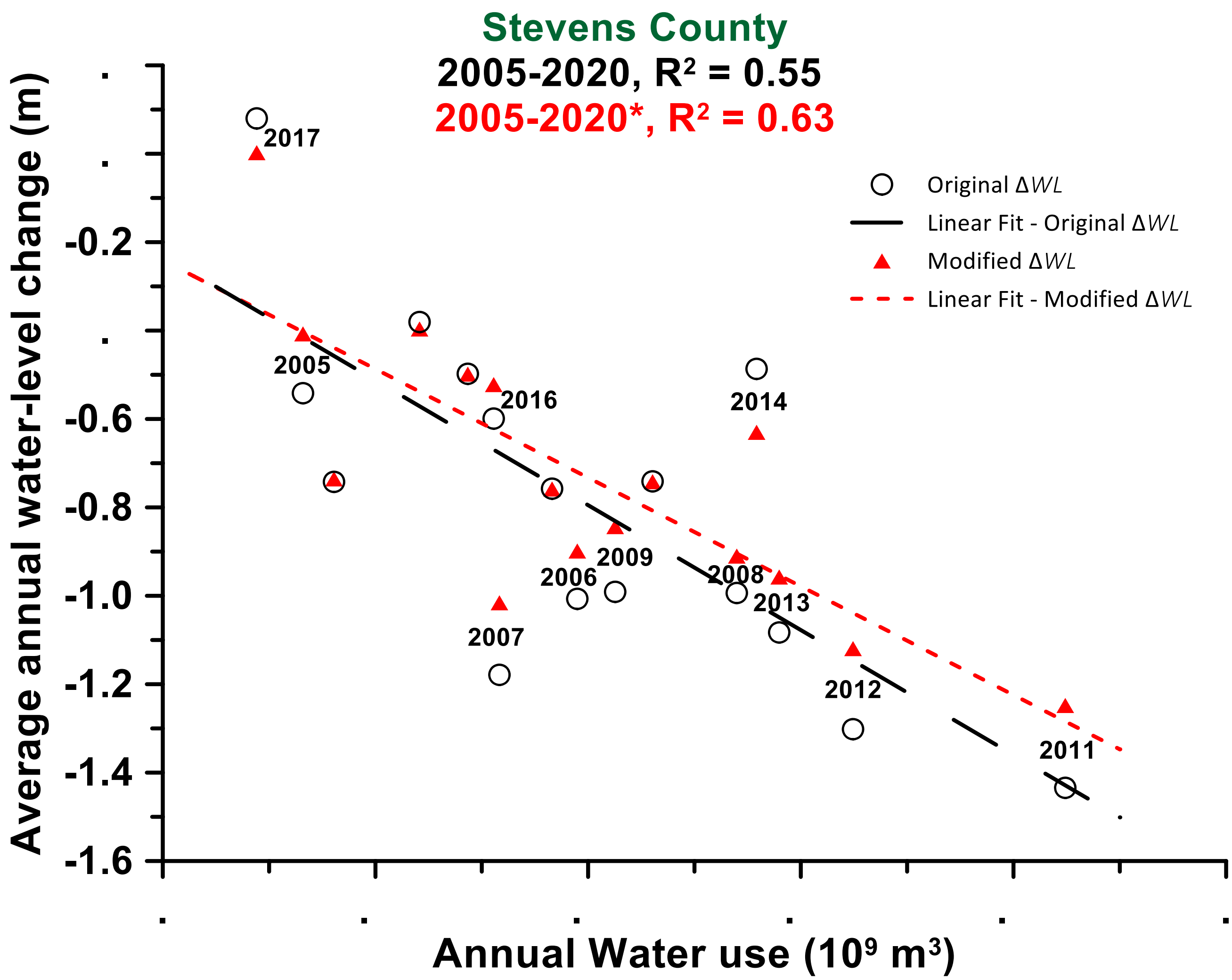


Figure 5b - Average annual water-level change (ΔWL) versus annual water use (Q) plot for Stevens County in GMD3. Large dashed line is the best fit to the 2005–2020 data (ΔWL = 1.1825–7.0623Q, p=0.00094) with ΔWL being the average computed using the 21 wells measured every year from 2005 to 2021. Small dashed line is the best fit to the modified 2005–2020 data (ΔWL = 0.9879–6.1453Q, p = 0.00022) with ΔWL being the modified average described in the text (triangles represent the modified values). In both cases, Q is the sum of reported use from a maximum of 1,214 pumping wells (total varies slightly from year to year). The estimated uncertainty (one standard deviation) in ΔWL is ±0.18 m and ±0.14 m for the original and modified data, respectively, and that in Q is ±0.2% of plotted value (determined using methods described in Butler et al. [2016] and Bohling et al. [2021]). The years with sizable differences between the two quantities are labeled; data are provided in Table S4.

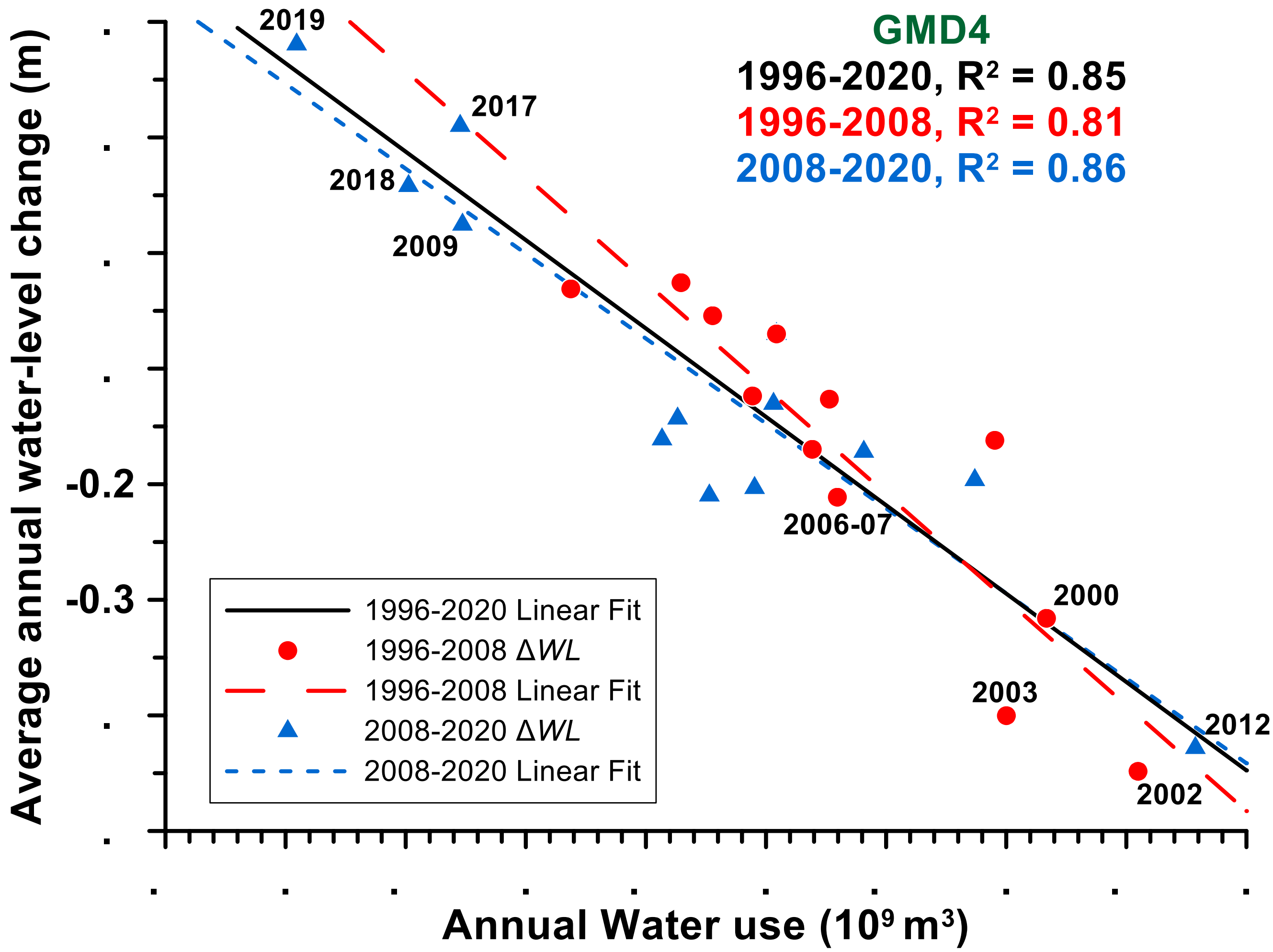


Figure 6a - Average annual water-level change (ΔWL) versus annual water use (Q) plot for GMD4. Solid line is the best fit to the 1996–2020 data, large dashed line is the best fit to the 1996-2008 data, and small dashed line is the best fit to the 2008-2020 data. The average ΔWL and Q values for 2006-07 are used in the 1996-2020 and 1996-2008 plots. Years with the highest and lowest water use during the period and 2006-07 are labeled; data are provided in Table S2. See caption in Figure S1 for further information.

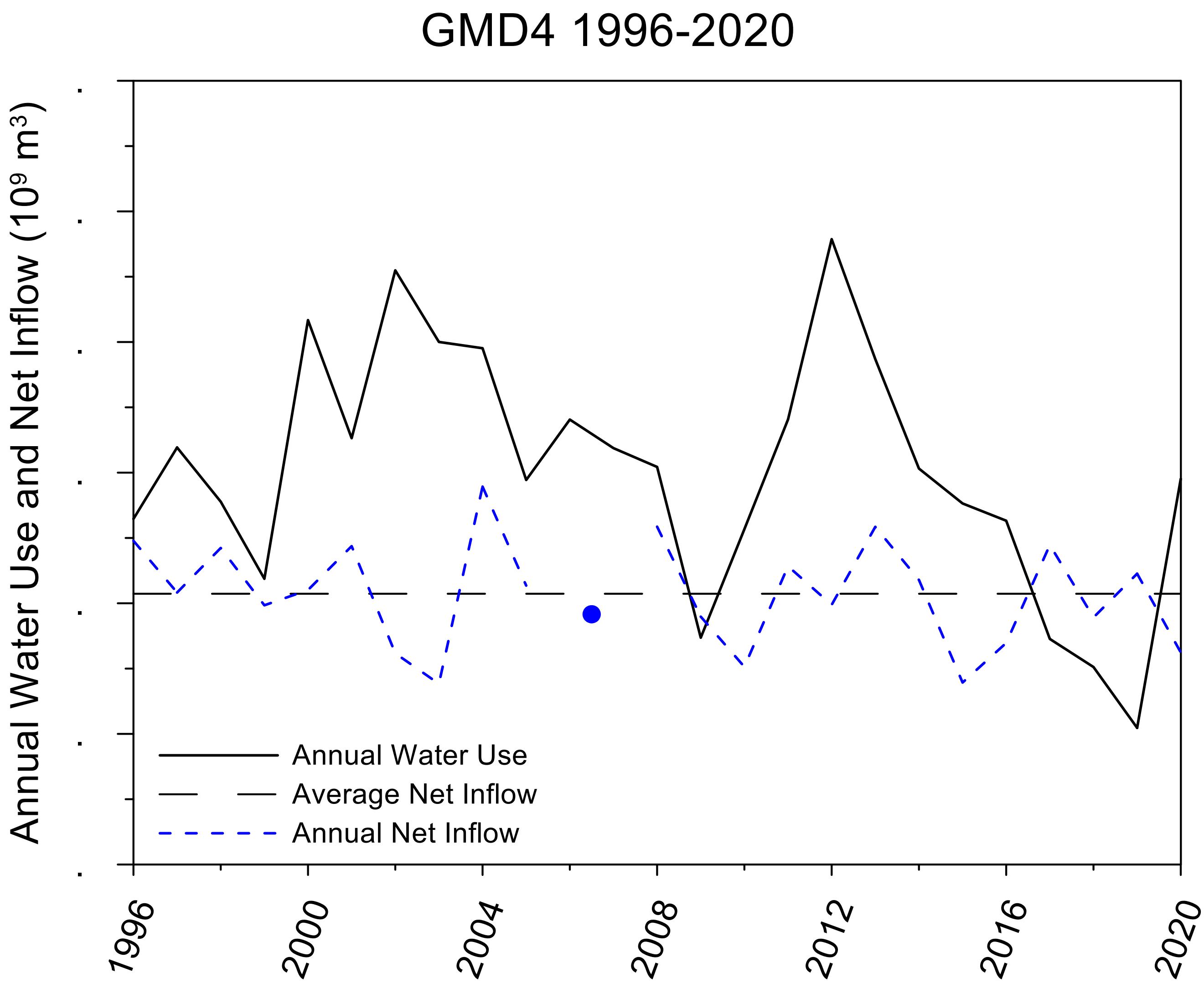


Figure 6b - Annual water use and average and annual net inflow versus time for GMD4. The large dashed line is the average net inflow calculated from the solid line in Figure 6a, while the small dashed line is the annual net inflow calculated as described in text; the circle is the average annual net inflow for 2006 and 2007. Uncertainty estimates (one standard deviation) in annual water use, average net inflow, and annual net inflow are ±0.09% of plotted value, 0.012×10^9 m^3, and 0.041×10^9 m^3, respectively (determined using methods described in Butler et al. [2016] and Bohling et al. [2021]). Data are provided in Table S2.

Supporting Information for

Net inflow: An important target on the path to aquifer sustainability

J. J. Butler, Jr.[1,3], G. C. Bohling[1], S.P. Perkins[2], D. O. Whittemore[1], G. Liu[1], and B. B. Wilson[1]

[1]Kansas Geological Survey, University of Kansas, Lawrence, KS 66047, USA

[2]Division of Water Resources, Kansas Department of Agriculture, Manhattan, KS 66502, USA

[3]Corresponding author - email: jbutler@ku.edu

Text S1 – Reassessment of the Butler et al. (2018) analysis for GMD3

The analysis presented in Butler et al. (2018) used the 205 wells measured every year from 1996 to 2017; the percent reduction needed to stabilize water levels for the short term was determined to be 33%. That analysis repeated using the 251 wells measured every year from 2005 to 2017 resulted in a percent reduction of 27%. Differences in the pumping data between these two analyses were negligible.

Neither of the above analyses averaged the 2010 and 2011 ΔWL values as done in this paper. When the Butler et al. (2018) analysis is repeated using the 205 wells and averaging the 2010 and 2011 ΔWL values, the percent reduction is 27%. When that analysis is repeated using the 251 wells and averaging the 2010 and 2011 ΔWL values, the percent reduction is 23%, as stated in the main text. The analysis in this paper included the three wettest years (2017-2019) in the 2005-2020 period. Thus, the difference between the analysis in this paper and that in Butler et al. (2018) is a result of the larger number of wells used here to estimate ΔWL, the averaging of the 2010 and 2011 ΔWL values, and the inclusion of the three wettest years in this analysis. The averaging of the 2010 and 2011 values is needed to lessen the influence of the late year pumping in 2010 in GMD3 (see Text S2). The inclusion of the three wet years resulted in a lower average annual pumping for this analysis, thus requiring a smaller percent reduction to reach net inflow. This result again emphasizes the importance of performing the analyses using periods that sample the full range of climatic conditions expected in the area.

Text S2 – Discussion of the 2010 and 2011 ΔWL values in Figure 4a

In Figure 4a, the 2010 ΔWL decline is much greater than expected for the reported annual pumping (i.e. value lies well below the best-fit line), while the 2011 ΔWL decline is much less than expected (i.e. value lies well above the best-fit line). The explanation is that there was a relatively large amount of pumping in GMD3 in December 2010 as a result of a dry autumn; the hydrograph from a continuously monitored well with a pressure transducer in Haskell County (Haskell County index well; Haskell County is to the immediate northeast of Stevens County in Figure 1) reveals 15 days of pumping in December 2010 with the last pumping period ending just 10 days before the annual water-level measurement at that well (Figure S4). In contrast, there were just five days of pumping in December 2011 with the last pumping period ending 23 days before the annual measurement. The result was that the January 2011 water-level measurement was lower than expected and, therefore, the ΔWL decline for 2010 larger than expected given the reported pumping. The January 2011 water level measurement then served as the base elevation for the 2011 ΔWL decline, resulting in a ΔWL decline for 2011 that was less than expected. The annual reported pumping for 2011 was 17% greater than that in 2010 at the Haskell site and 25% greater than that in 2010 for GMD3 as a whole.

Text S3 – Modifications of ΔWL values in Stevens County

Figure 5b shows the scatter observed about the best-fit line using the 21 wells measured each year from 2005-2021. The large scatter prompted a review of the measurements at the 21 wells to assess if apparent anomalous measurements (outliers) could be identified. We used the widely applied Chauvenet criterion to identify outliers (Coleman and Steele, 2018). The standard form of this method is based on the assumption of normally distributed measurements. A band around the mean value spans the range of assumed valid measurements. The probability of measurements falling within the band depends on the number of measurements. That probability (P_w) is given as:

$$P_w = 1 - \frac{1}{2n} \tag{S3-1}$$

where n is the number of measurements.

Chauvenet set the width of the band to incorporate n-0.5 measurements. Thus, for this case of 21 measurements, the probability of having 20.5 measurements inside the band is 97.6%. The distance, in terms of unit standard deviations, from the mean to the band boundary on either side is given by the Z score in the normal distribution table for the probability of $1 - \frac{1}{4n}$. For this case of 21 measurements, the distance, which is known as the Chauvenet criterion, is 2.26. If a measurement lies further than a distance of 2.26 from the mean, it is considered an outlier and removed. For example, in 2005, well 9 (Figure S5 and Table S6) has a value of -3.5, which falls far outside of the lower criterion of -2.26. The expected number of measurements falling at that distance from the mean in a sample of 21 measurements is 0.008. The 2005 measurement for well 9 is therefore identified as an outlier.

Figure S5 is a series of normal quantile-quantile plots of standardized ΔWL values for each year from 2005-2021. A single measurement falls outside of the Chauvenet criterion in 11 of the 16 years, two measurements fall beyond the criterion in two of the 16 years, and no values fall beyond the criterion in three years. Six of the 21 wells have one or more measurements that fall outside the criterion during this period. The measurements for those six wells in the years in which they were identified as outliers were removed to create the modified dataset (red triangles in Figure 5b) discussed in the main text.

The advantage of the Chauvenet criterion is that it provides an objective approach for identifying and removing suspected outliers from datasets. Although the standard form of the approach is based on the assumption of normality, other distributions can be used (Lin and Sherman, 2007).

References

Coleman, H. W., and W. G. Steele. 2018. *Experimentation and Uncertainty Analysis for Engineers, 4th Edition*. Hoboken, NJ: Wiley.

Lin, L., and P. D. Sherman. 2007. Cleaning data the Chauvenet way. *The Proceedings of the SouthEast SAS Users Group*, SESUGProceedings, Paper SA11.

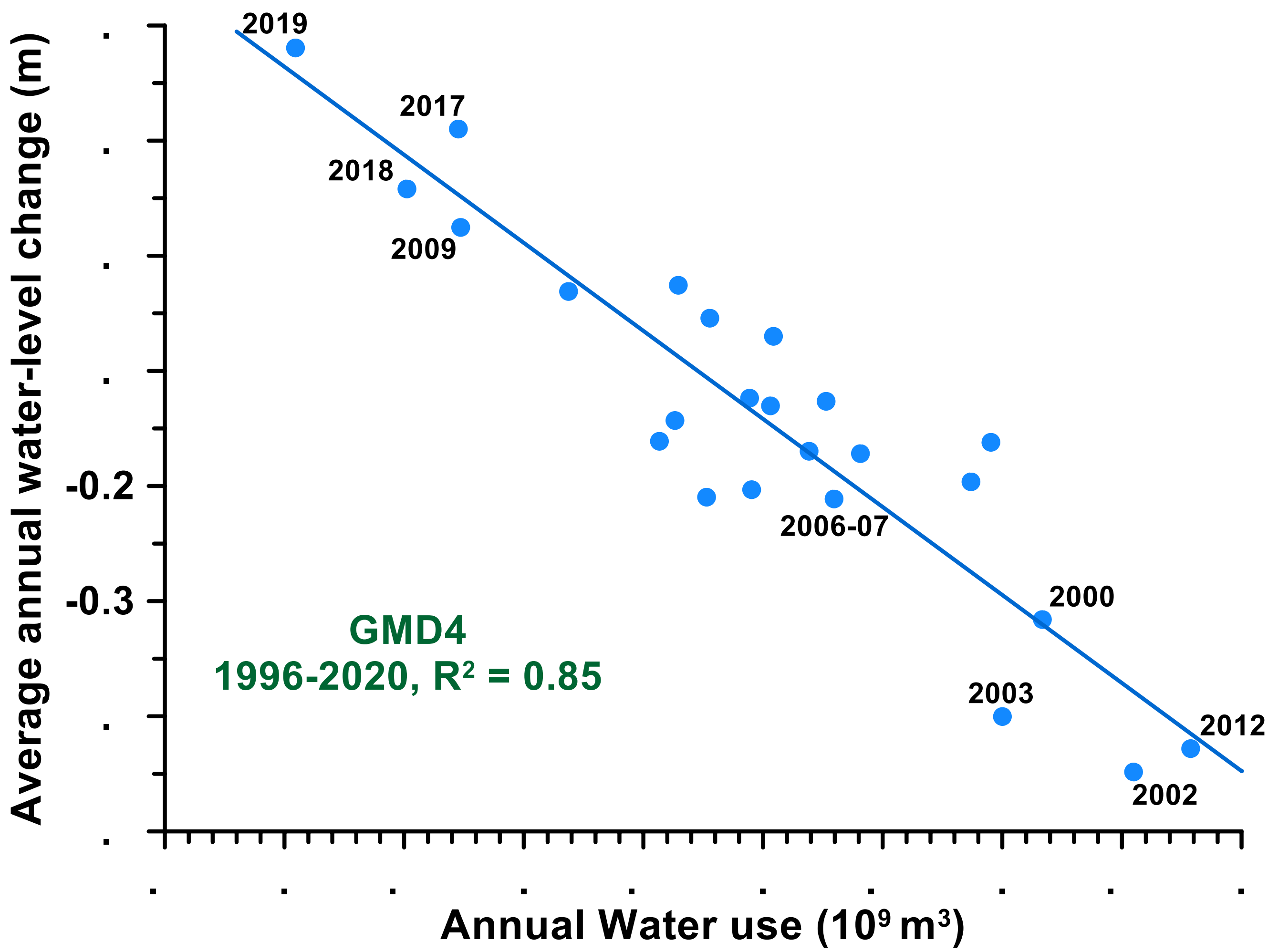


Figure S1 - Average annual water-level change (ΔWL) versus annual water use (Q) plot for GMD4. Solid line is the best fit to the 1996–2020 data ($\Delta WL = 2.0439–0.006189Q$, $p < 0.0001$) using the average ΔWL and Q values for 2006-07 (heavy snows delayed 2007 water-level measurements from early January to late February through early April). ΔWL is the average computed using the 174 wells measured every year from 1996 to 2021. Q is the sum of reported use from a maximum of 4,304 pumping wells (total varies slightly from year to year). The estimated uncertainty (one standard deviation) in ΔWL is ±0.029 m and that in Q is ±0.09% of plotted value (determined using methods described in Butler et al. [2016] and Bohling et al. [2021]). Years with the highest and lowest water use during the period and 2006-07 are labeled; data are provided in Table S2.

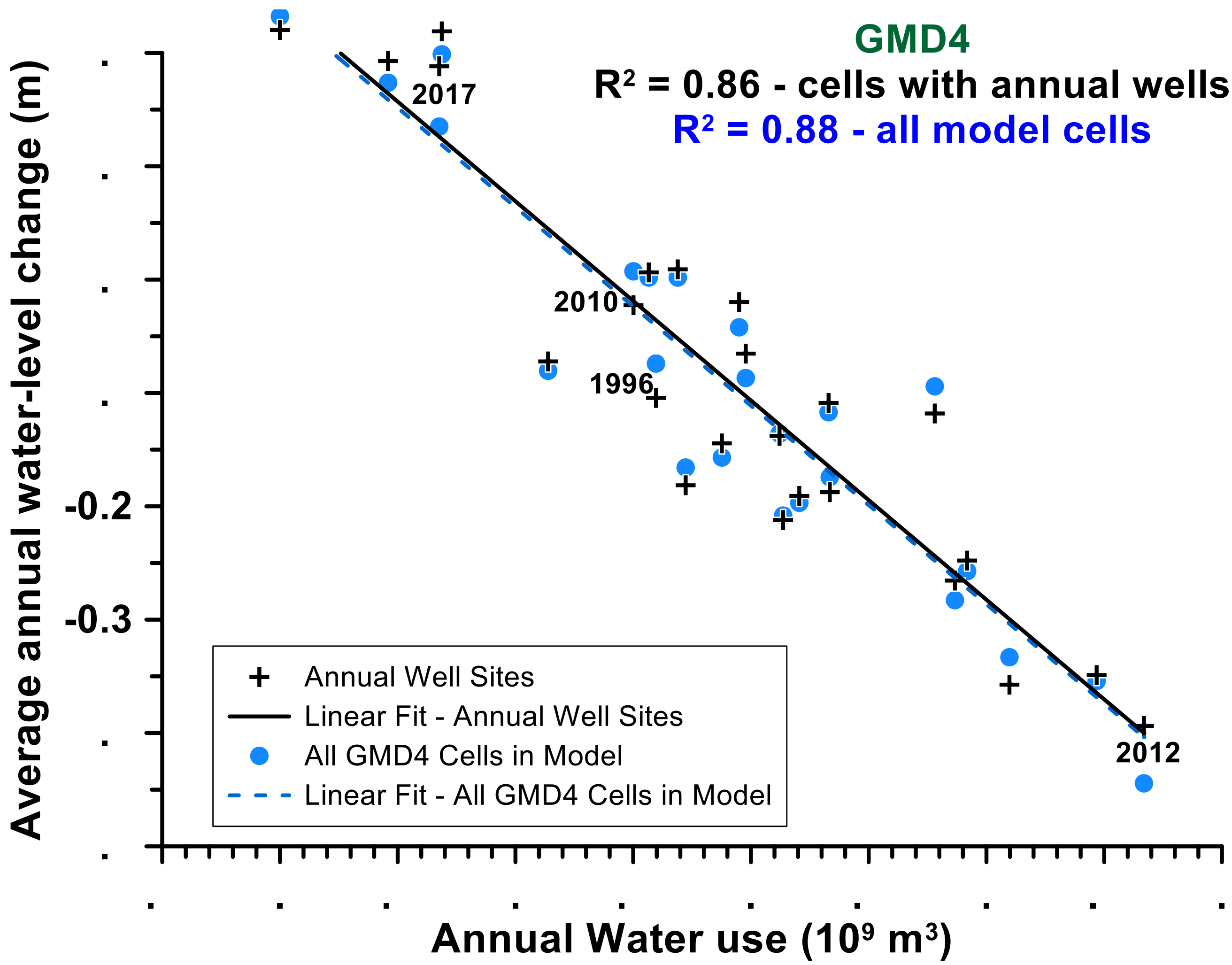


Figure S2 – Simulated 1996-2019 average annual water-level change (ΔWL) versus annual water use (Q) from the recently completed model of the GMD4 region (Wilson et al., 2021). The circles correspond to the ΔWL values based on the simulated values from the 19,211 active model cells within GMD4, while the plus signs correspond to the ΔWL values based on the simulated values from the 174 model cells within GMD4 corresponding to the locations of the wells measured every year from 1996 to 2020. The four years with the largest differences between the values are labeled; values are provided in Table S5. The GMD4 model was calibrated to a data set that includes streamflows, predevelopment water levels (prior to 1946), and water-level changes at 60 of the 174 wells analyzed in this work. Therefore, model calibration does not have a significant impact on the water-level comparison shown here.

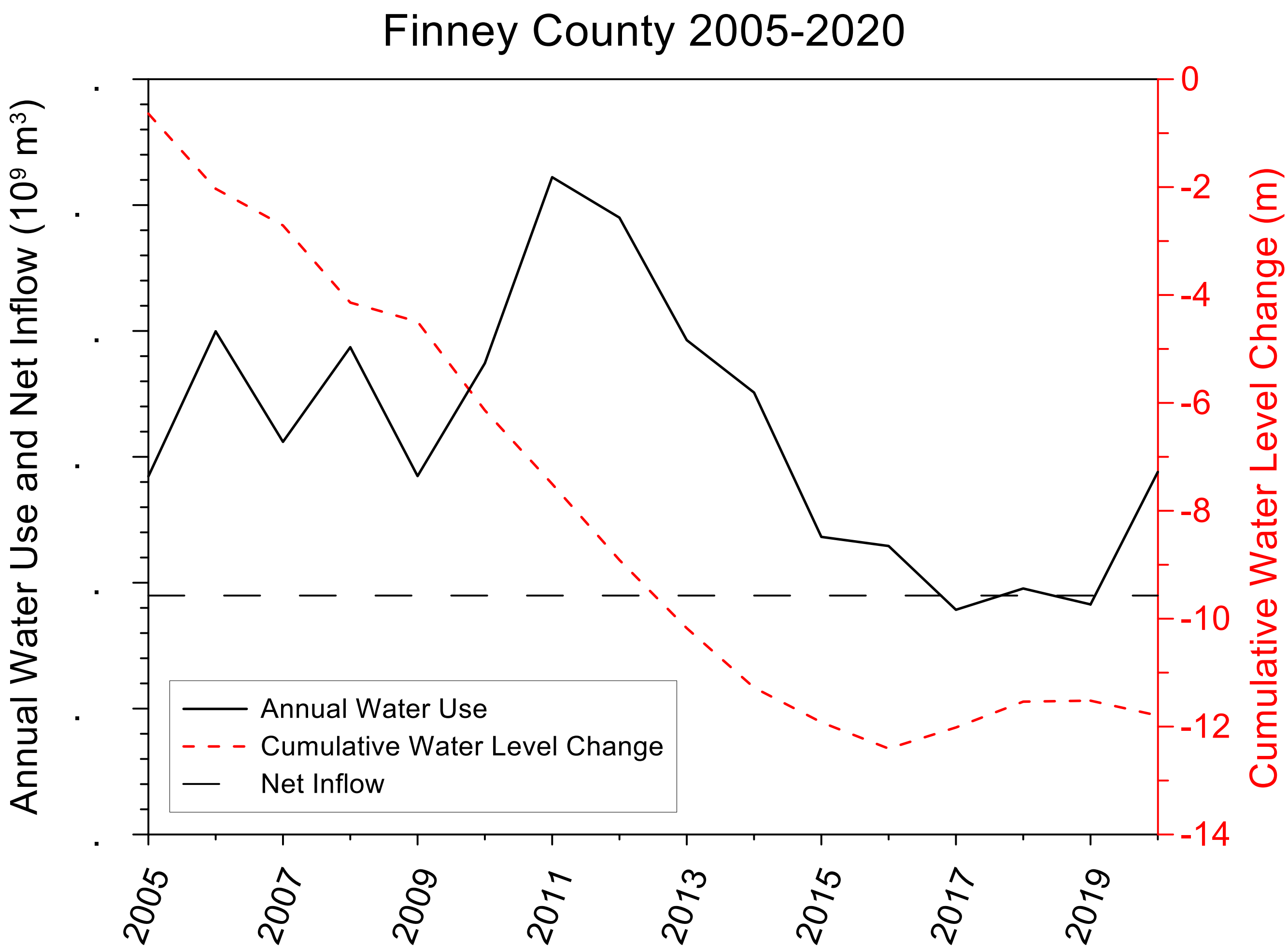


Figure S3a - Annual water use (left y-axis) and cumulative water-level change (right y-axis) versus time for Finney County in GMD3. Large dashed line is the average net inflow (left y-axis) calculated from Figure S3b. The estimated uncertainty (one standard deviation) in net inflow is 0.013×10^9 m^3 (determined using methods described in Butler et al. [2016] and Bohling et al. [2021]). Data are provided in Table S3.

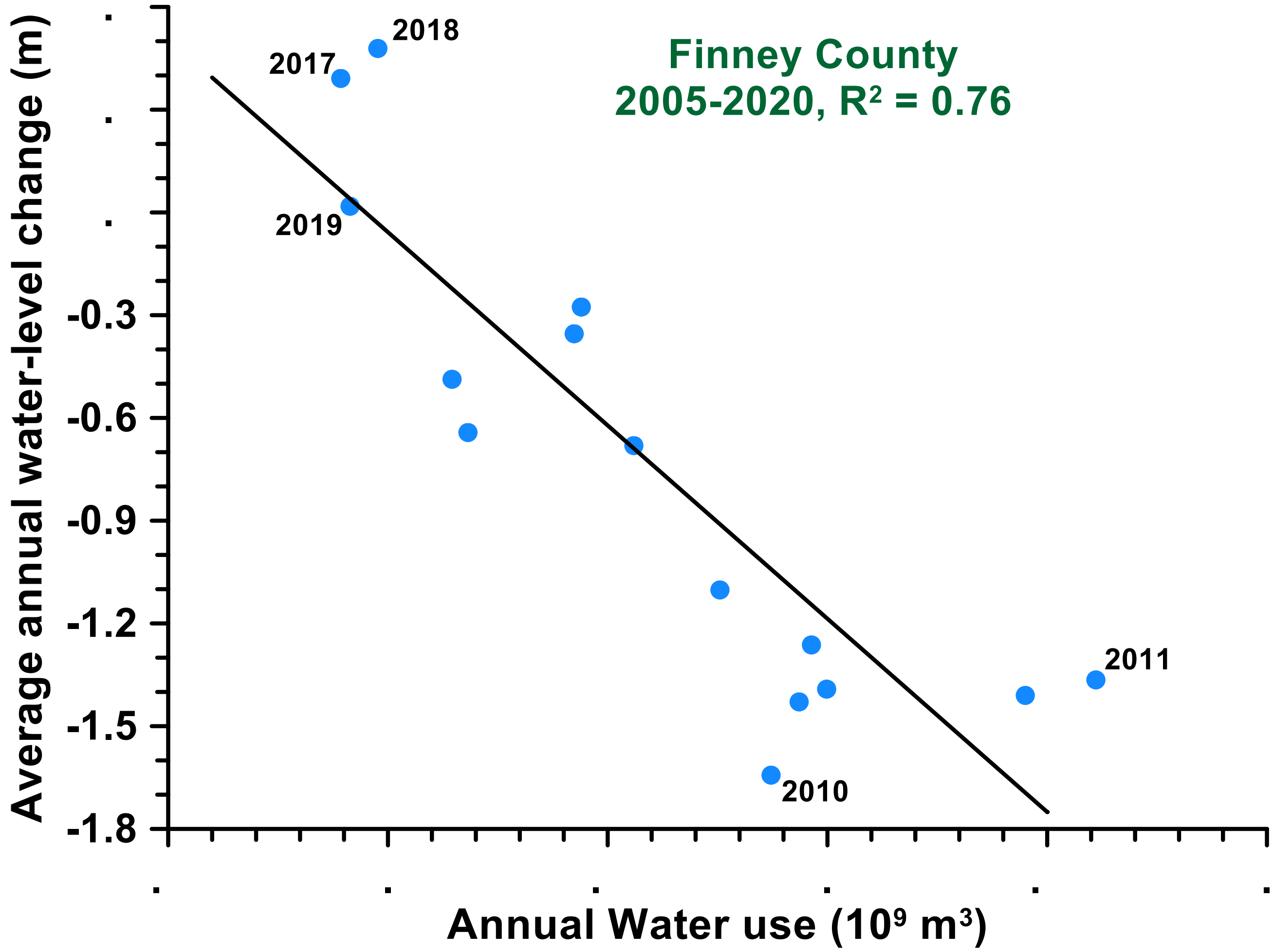


Figure S3b - Average annual water-level change (ΔWL) versus annual water use (Q) plot for Finney County in GMD3. Solid line is the best fit to the 2005–2020 data ($\Delta WL = 3.3282 – 11.2860Q$, $p < 0.0001$). ΔWL is the average computed using the 46 wells measured every year from 2005 to 2021. Q is the sum of reported use from a maximum of 2,724 pumping wells (total varies slightly from year to year). The estimated uncertainty (one standard deviation) in ΔWL is ±0.21 m and that in Q is ±0.1% of plotted value (determined using methods described in Butler et al. [2016] and Bohling et al. [2021]). Data are provided in Table S3.

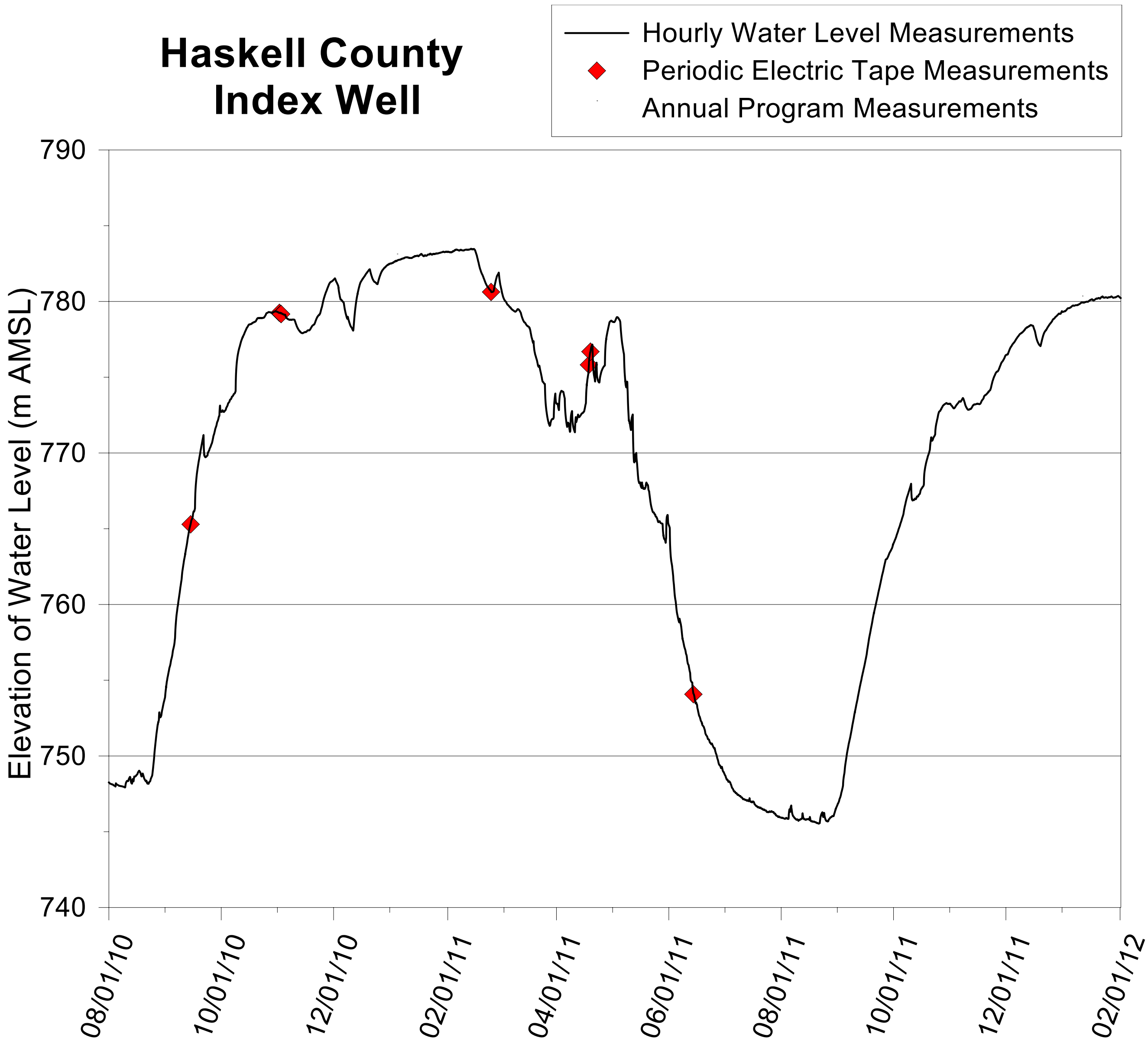


Figure S4 - Elevation of water level versus time for the Haskell County index well in southwest Kansas (Latitude: 37.65701, Longitude: -100.6648; Butler et al., 2021b). The solid line corresponds to measurements taken every hour by a transducer at a fixed position in the water column; the circles designate the annual water-level measurements in January 2011 and 2012, and the diamonds designate periodic manual measurements taken throughout the year. An elevation of 780 m corresponds to a depth to water of 84.99 m below land surface (lsf). The top of the 3.05-m screen is 128.02 m below lsf (elevation of 736.97 m), and the bottom of the aquifer is 131.98 m below lsf (elevation of 733.01 m). The screen terminates 0.9 m above the bottom of the aquifer. Data available at https://www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml.

Figure S5 - Normal quantile-quantile plots of standardized ΔWL values in Stevens County for 2005-2020. The 21 ΔWL values for each year are standardized by shifting to a zero mean and scaling to a unit standard deviation. The red dashed lines represent Chauvenet's criterion (±2.26) for this case (21 data points). The labeled red points are suspected outliers according to Chauvenet's criterion and were removed to create the modified dataset (red triangles) used in Figure 5b. USGS identification numbers for wells with labeled points are provided in Table S6.

Year	SD-6 Groundwater Use (10^6 m^3)	SD-6 Average Annual Water-Level Change (m)	Cumulative Water-Level Change (m)
2002	45.017	-1.035	-1.035
2003	42.149	-0.897	-1.933
2004	41.171	-0.668	-2.601
2005	35.703	-0.572	-3.173
2006	33.609	-0.343**	NA
2007	37.068		-3.859
2008	34.571	-0.558	-4.417
2009	27.994	-0.321	-4.738
2010	33.641	-0.466	-5.204
2011	32.795	-0.354	-5.558
2012	42.370	-0.611	-6.169
2013	24.933	-0.104	-6.272
2014	25.497	-0.249	-6.521
2015	21.135	-0.007	-6.529
2016	23.436	-0.265	-6.794
2017	18.532	-0.048	-6.842
2018	20.589	-0.137	-6.979
2019	14.109	0.240	-6.740
2020	28.909	-0.427	-7.166

Table S1 – SD-6 2002-2020 annual volumes of reported groundwater use (maximum of 195 pumping wells), average annual water-level change (see Figure 2a), and cumulative water-level change data. Heavy snows delayed 2007 water-level measurements from early January to late February through early April, so only the average ΔWL value for 2006 and 2007 is given here (value with ** in table) and the cumulative change cannot be calculated for 2006 (NA stands for "Not Available").

Year	GMD4 Groundwater Use (10^9 m^3)	GMD4 Average Annual Water-Level Change (m)	GMD4 Cumulative Water-Level Change (m)	GMD4 Annual Net Inflow (10^9 m^3)
1996	0.465	-0.026	-0.026	0.448
1997	0.519	-0.170	-0.195	0.408
1998	0.478	-0.054	-0.250	0.442
1999	0.419	-0.031	-0.281	0.398
2000	0.617	-0.316	-0.597	0.410
2001	0.526	-0.126	-0.723	0.444
2002	0.655	-0.448	-1.171	0.362
2003	0.600	-0.400	-1.572	0.338
2004	0.595	-0.162	-1.734	0.489
2005	0.494	-0.124	-1.857	0.414
2006	0.541	-0.211**	NA	0.392**
2007	0.519		-2.280	
2008	0.504	-0.070	-2.350	0.459
2009	0.374	0.025	-2.325	0.390
2010	0.457	-0.161	-2.486	0.351
2011	0.541	-0.172	-2.658	0.428
2012	0.679	-0.428	-3.086	0.399
2013	0.587	-0.196	-3.282	0.459
2014	0.503	-0.130	-3.413	0.418
2015	0.476	-0.210	-3.623	0.339
2016	0.463	-0.143	-3.766	0.370
2017	0.373	0.110	-3.656	0.445
2018	0.351	0.058	-3.598	0.389
2019	0.305	0.181	-3.417	0.423
2020	0.495	-0.203	-3.620	0.362

Table S2 – GMD4 1996-2020 annual volumes of reported groundwater use (maximum of 4,304 pumping wells), average annual water-level change (174 wells measured every year), cumulative water-level change, and annual net inflow. Heavy snows delayed 2007 water-level measurements from early January to late February through early April, so only the average ΔWL and net inflow values for 2006 and 2007 are given here (values with ** in table) and cumulative change cannot be calculated for 2006 (NA stands for "Not Available").

Year	GMD3 Q (10^9 m^3)	GMD3 ΔWL (m)	GMD3 Cumul. ΔWL (m)	FI Cty Q (10^9 m^3)	FI Cty ΔWL (m)	FI Cty Cumul. ΔWL (m)
2005	1.970	-0.334	-0.334	0.342	-0.638	-0.638
2006	2.411	-0.772	-1.106	0.400	-1.392	-2.030
2007	2.193	-0.536	-1.643	0.356	-0.681	-2.711
2008	2.484	-0.746	-2.388	0.394	-1.429	-4.140
2009	2.229	-0.362	-2.750	0.342	-0.354	-4.494
2010	2.354	-0.957	-3.707	0.387	-1.643	-6.138
2011	2.942	-0.974	-4.681	0.461	-1.365	-7.503
2012	2.672	-1.057	-5.737	0.445	-1.410	-8.913
2013	2.449	-0.735	-6.473	0.396	-1.263	-10.176
2014	2.369	-0.559	-7.032	0.376	-1.102	-11.278
2015	1.952	-0.208	-7.240	0.318	-0.643	-11.921
2016	1.953	-0.154	-7.393	0.315	-0.487	-12.408
2017	1.800	0.113	-7.281	0.289	0.391	-12.016
2018	1.905	0.049	-7.231	0.298	0.479	-11.538
2019	1.745	-0.190	-7.422	0.291	0.018	-11.520
2020	2.130	-0.297	-7.718	0.344	-0.276	-11.796

Table S3 – GMD3 and Finney County (FI Cty) 2005-2020 annual volumes of reported groundwater use (maximum of 15,175 and 2,724 pumping wells, respectively), average annual water-level change (251 and 46 wells measured every year, respectively), and cumulative water-level change.

Year	SV Cty Q (10^9 m^3)	SV Cty ΔWL (m)	SV Cty Cumul. ΔWL (m)	SV Cty ΔWL mod. (m)	SV Cty Cumul. ΔWL mod. (m)
2005	0.226	-0.542	-0.542	-0.542	-0.542
2006	0.278	-1.007	-1.549	-0.811	-1.352
2007	0.263	-1.179	-2.727	-0.890	-2.242
2008	0.308	-0.994	-3.721	-0.994	-3.236
2009	0.285	-0.991	-4.712	-0.991	-4.227
2010	0.273	-0.758	-5.470	-0.758	-4.985
2011	0.370	-1.434	-6.904	-1.434	-6.419
2012	0.330	-1.302	-8.206	-1.302	-7.721
2013	0.316	-1.083	-9.289	-1.083	-8.804
2014	0.312	-0.487	-9.775	-0.722	-9.526
2015	0.257	-0.498	-10.273	-0.498	-10.024
2016	0.262	-0.599	-10.872	-0.599	-10.623
2017	0.218	0.080	-10.792	-0.071	-10.694
2018	0.248	-0.381	-11.173	-0.381	-11.075
2019	0.232	-0.742	-11.915	-0.593	-11.668
2020	0.292	-0.741	-12.656	-0.741	-12.409

Table S4 – Stevens County (SV Cty) 2005-2020 annual volumes of reported groundwater use (maximum of 1,214 pumping wells), average annual water-level change (21 wells measured every year), and cumulative water-level change. Modified ΔWL and cumulative ΔWL values also presented; modifications are as described in main text and Text S3.

Year	GMD4 Modeled Groundwater Use (10^9 m^3)	GMD4 Average Annual Water-Level Change All Model Cells (m)	GMD4 Average Annual Water-Level Change Annual Well Cells (m)
1996	0.460	-0.074	-0.104
1997	0.514	-0.208	-0.212
1998	0.472	-0.166	-0.181
1999	0.414	-0.080	-0.072
2000	0.610	-0.333	-0.357
2001	0.521	-0.197	-0.191
2002	0.647	-0.354	-0.349
2003	0.592	-0.257	-0.248
2004	0.587	-0.283	-0.266
2005	0.488	-0.157	-0.144
2006	0.533	-0.174	-0.188
2007	0.512	-0.136	-0.138
2008	0.498	-0.087	-0.065
2009	0.369	0.199	0.219
2010	0.450	0.007	-0.023
2011	0.533	-0.117	-0.109
2012	0.667	-0.444	-0.394
2013	0.578	-0.094	-0.118
2014	0.495	-0.042	-0.020
2015	0.469	0.002	0.009
2016	0.457	0.002	0.006
2017	0.368	0.135	0.188
2018	0.346	0.174	0.193
2019	0.300	0.232	0.220

Table S5 – Simulated water use and average annual water-level change (ΔWL) for GMD4 from the recently completed model of the GMD4 region (Wilson et al., 2021). The third column is the ΔWL values based on the simulated values from the 19,211 active model cells within GMD4, while the fourth column is the ΔWL values based on the simulated values from the 174 model cells within GMD4 corresponding to the locations of the wells measured every year from 1996 to 2020.

Well Label in Figure S5	Well USGS ID#
1	370012101070901
2	370218101103301
3	370304101180901
4	370352101055301
7	370714101244701
9	370958101055501
10	371420101185501
11	371530101320601
13	371621101194001
17	372016101201201
18	372117101280901

Table S6 – Label and USGS Identification Number for each well identified in Figure S5.