Kansas Geological Survey

High Plains Aquifer Index Well Program: 2020 Annual Report

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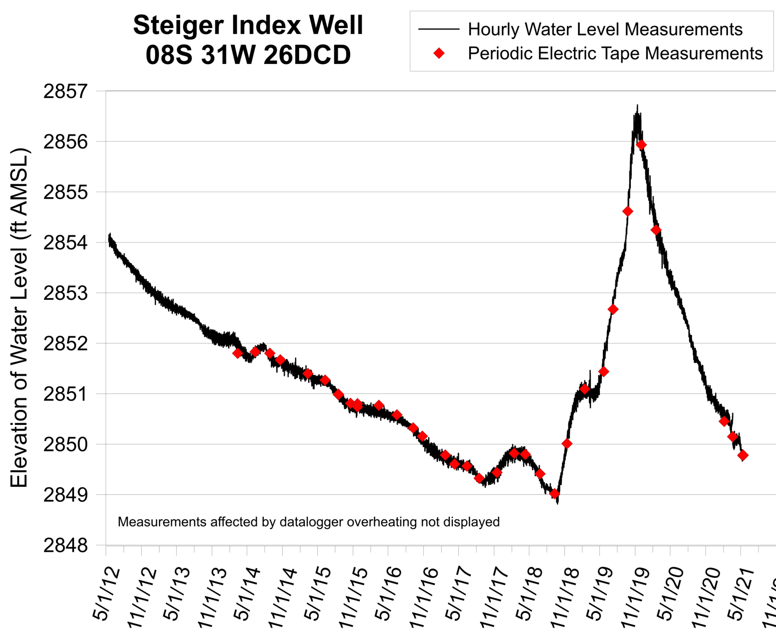

Recharge Pulses At Steiger Index Well

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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 land owners 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 Groundwater Management Districts (GMDs) 1, 2, 3, 4, and 5 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 2020 and the spring of 2021 by the installation of real-time monitoring equipment at an existing well in GMD2 and by adding telemetry equipment at an existing index well in GMD4. The network now consists of 21 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); seven expansion wells are currently 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 spring 2021. The majority of the report consists of an update and interpretation of the hydrographs for all of the index wells and the GMD1 expansion wells. In addition, the report presents a discussion of the relationships among precipitation (as characterized by radar data), annual water-level changes, and nearby water use at the three original index wells and three additional wells, and the implications of those relationships for efforts to moderate water-level declines by pumping reductions.

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

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

3. The annual water-level measurement network data, in conjunction with reliable water-use data, can be used to evaluate the effect of management decisions on the township and larger scale using an approach developed from water-level responses collected as part of this program.
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). In late spring 2021, a scientific journal article on recent program work was accepted for publication (Butler, Knobbe et al., 2021). That article is provided as an appendix to this report.

The focus of activities in 2021 and early 2022 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 GMD2 and two existing wells in GMD5; the drilling of a well nest in GMD3 to monitor the relationship between the Dakota and High Plains aquifers in that area; redevelopment and slug testing of the original three index wells and the Belpre index well; and further assessment of the relationships among radar-determined precipitation, annual water-level change, and water use.

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1 Introduction and Background

Groundwater withdrawals in the Ogallala–High Plains aquifer (hereinafter, High Plains aquifer or HPA) in Kansas have resulted in large water-level declines that call into question the viability of the aquifer as a continuing resource for irrigated agriculture (Butler, Stotler et al., 2013; Buchanan et al., 2015). 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 Groundwater Management Districts (GMDs) 1, 2, 3, 4, and 5 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 HPA in Kansas. 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 thirteen full recovery and pumping seasons and one ongoing or completed, depending on location, recovery season have been obtained. With increasing data, the index well program has demonstrated the following:

1. Water-level data collected using an integrated pressure transducer-datalogger unit provide a near-continuous record of great practical value that can help in the assessment of the continued viability of the HPA as a source of water for large-scale irrigation.
2. Interpretation of index well hydrographs enables important practical insights to be drawn concerning hydrogeologic conditions, the major mechanisms affecting water levels, and the long-term viability of the aquifer in the vicinity of the index wells. For example, there is little indication of episodic recharge at the index wells in the western Kansas HPA.
3. The annual water-level measurement network data, in conjunction with reliable water-use data, can be used to evaluate the effect of management decisions on the sub-county and larger scale using an approach developed from observed water-level responses as part of this program.
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 2020 by the installation of real-time monitoring equipment in an existing well in GMD2 (Sedgwick County). In addition, telemetry equipment was added to an existing index well in GMD4 (SD-6 Steiger Index Well). Note that the term "index well" is used here to designate a dedicated, non-pumping well at which monitoring is anticipated to continue for many years. There are additional wells, designated here as "expansion wells," at which monitoring is not likely to continue over the long term because of constraints imposed by well depth (i.e., water level is anticipated to drop below the bottom of the well screen), logistics, or management issues. Both types of wells are considered in this report.

This report provides a concise description of conditions as of spring 2021. The majority of the report consists of an update and interpretation of the hydrographs for all of the index wells and the GMD1 expansion wells. In addition, this report discusses the relationships among precipitation (as characterized by radar data), annual water-level changes, and nearby water use at the three original index wells and three additional wells and the implications of those relationships for efforts to moderate water-level declines by pumping reductions. In late spring 2021, a scientific journal article on recent program work was accepted for publication (Butler, Knobbe et al., 2021). 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 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 aquifer responses in the areas of thick saturated 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.

Figure 1 shows the current state of the index well network. There are now 21 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 seven expansion wells in GMD1.

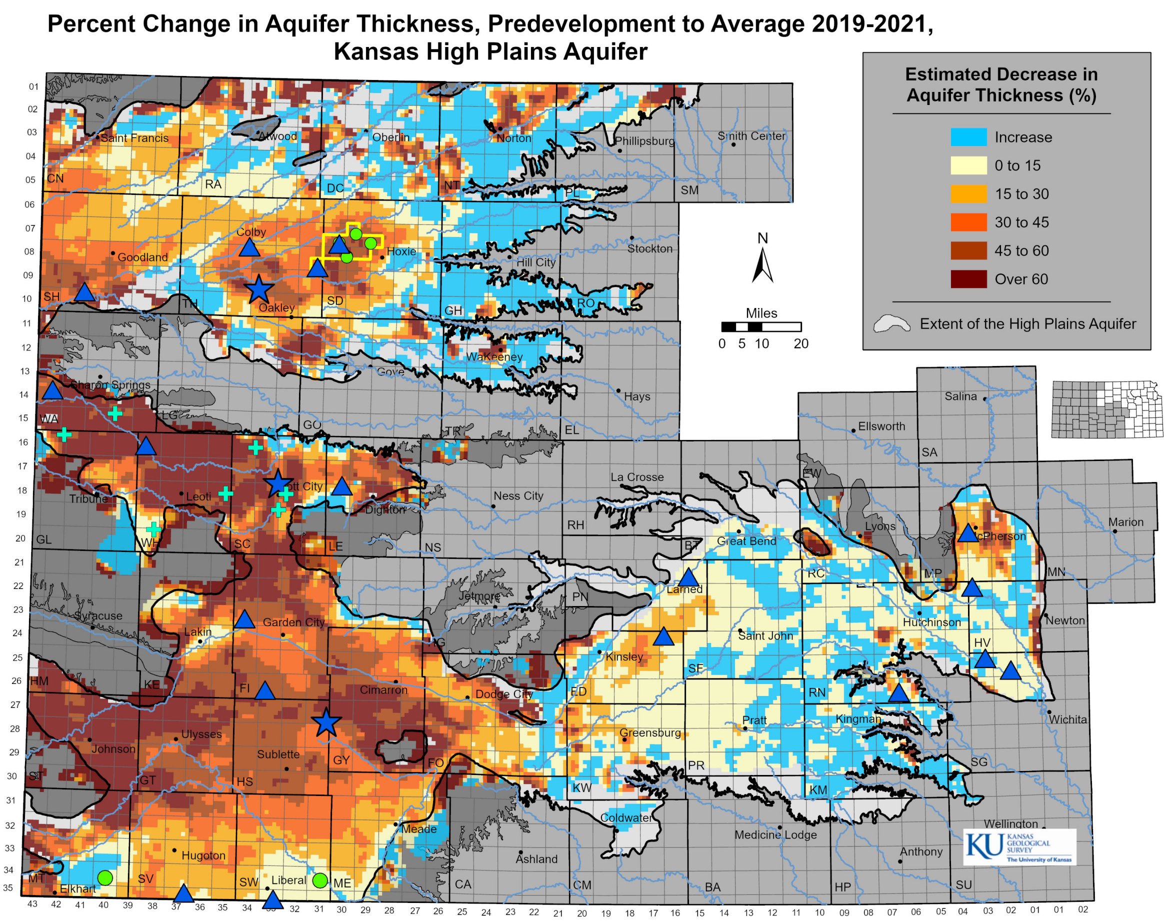


Figure 1—The Kansas portion of the High Plains aquifer, with aquifer and county boundaries shown. Each colored pixel represents one section (1 mi^2), coded for the degree of groundwater depletion from the beginning of large-scale development to the average of conditions in 2019–2021. The blue stars indicate 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 green plus signs are seven expansion wells that are monitored within GMD1.

3 Overview of Index Well Sites and Monitoring Data

This section provides a brief discussion of the hydrographs from the 27 index wells and 7 GMD1 expansion wells currently in operation. The duration of monitoring ranges from more than 13¾ 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 well that was added to the program in 2020, 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

Four 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 wells were drilled in the spring of 2016. Table 1 summarizes the characteristics of these four 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). Section 3.6.1 discusses the GMD1 expansion wells.

Table 1—Characteristics of the GMD1 index well sites.

Site	2021 WL elev. (ft)[a]	2021 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2019 water use (ac-ft)		
					1 mi radius	2 mi radius	5 mi radius
Lane	2,768.7	34.7	118	105–115	381	807	2,475[b]
Scott	2,826.1	81.9	223	215–225	421	2,110[c]	11,626[d]
Wallace	3,555.3	121.3	394	375–385	251[e]	3,041[e]	11,343[f]
Wichita	3,287.8	29.8	190	175–185	209	1,821	5,676[g]

[a] 2021 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html).
[b] Includes 51 ac-ft of municipal water and 10 ac-ft of non-irrigation stock water.
[c] Includes 12 ac-ft of non-irrigation stock water.
[d] Includes 5 ac-ft of domestic, 3 ac-ft of industrial, 906 ac-ft of municipal water, and 315 ac-ft of non-irrigation stock water.
[e] Includes 43 ac-ft of municipal water.
[f] Includes 43 ac-ft of municipal water and 5 ac-ft of non-irrigation stock water.
[g] Includes 42 ac-ft of non-irrigation stock water

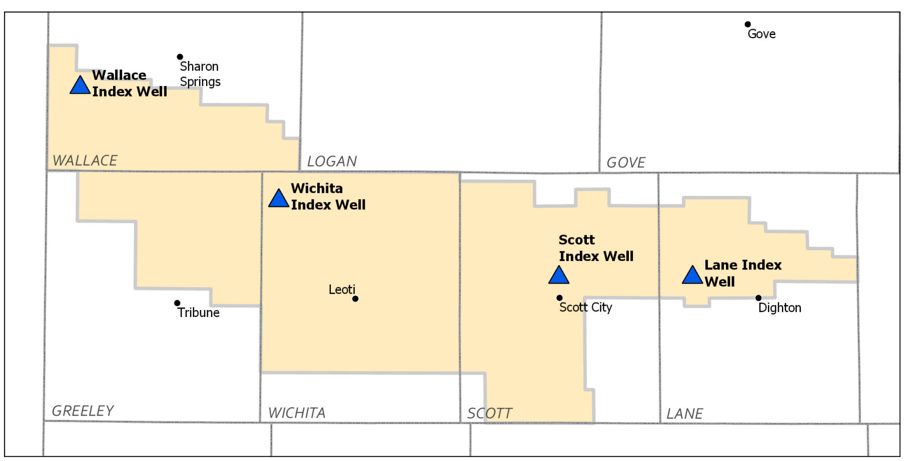


Figure 2—Map of index wells in GMD1. Triangles designate wells with telemetry equipment; data from these wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

3.1.1 Lane County Index Well

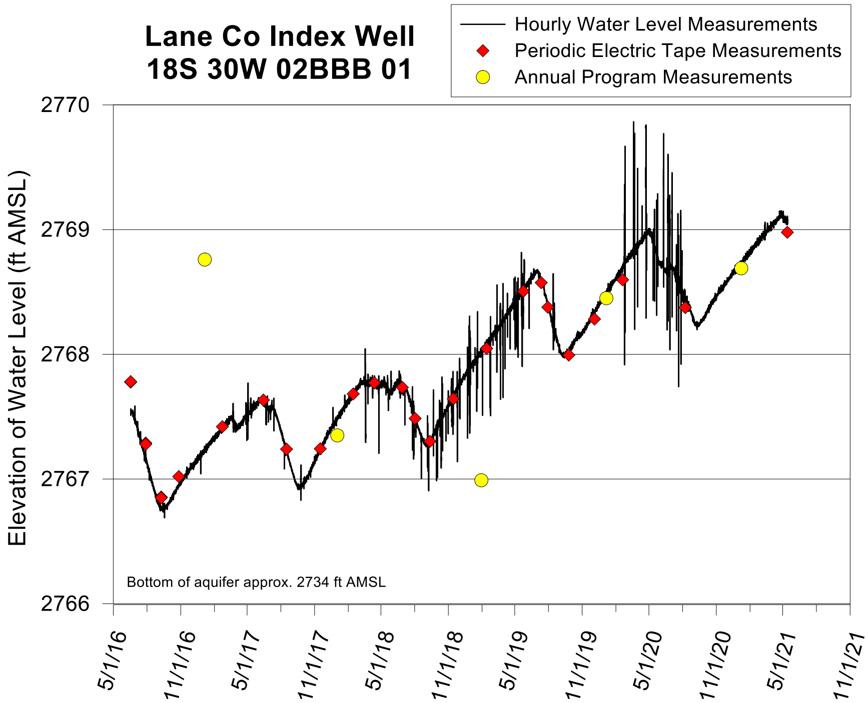


Figure 3—Lane County index well hydrograph—total data run to 5/14/21. A water-level elevation of 2,767 ft corresponds to a depth to water of 85 ft below land surface (lsf). The top of the screen is 105 ft below lsf (elevation of 2,747 ft), and the bottom of the aquifer is 118 ft below lsf (elevation 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. Electric-tape measurements are in good agreement with transducer.

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 2020 was 0.3 ft above that of 2019, whereas the minimum water level for 2020 was also 0.3 ft above that of 2019; 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

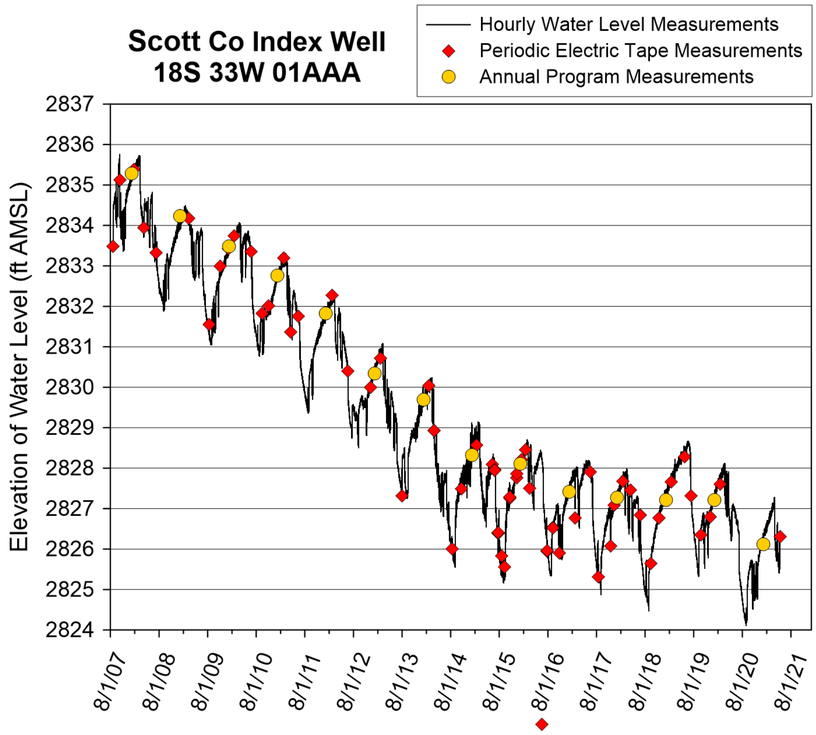


Figure 4—Scott County index well hydrograph—total data run to 5/13/21. A water-level elevation of 2,829 ft corresponds to a depth to water of 138.15 ft below lsf. The top of the screen is 215 ft below lsf (elevation of 2,752.15 ft), and the bottom of the aquifer is 223 ft below lsf (elevation of 2,744.15 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 2020 was the lowest of the monitoring period and 1.2 ft below that for 2019.
- 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

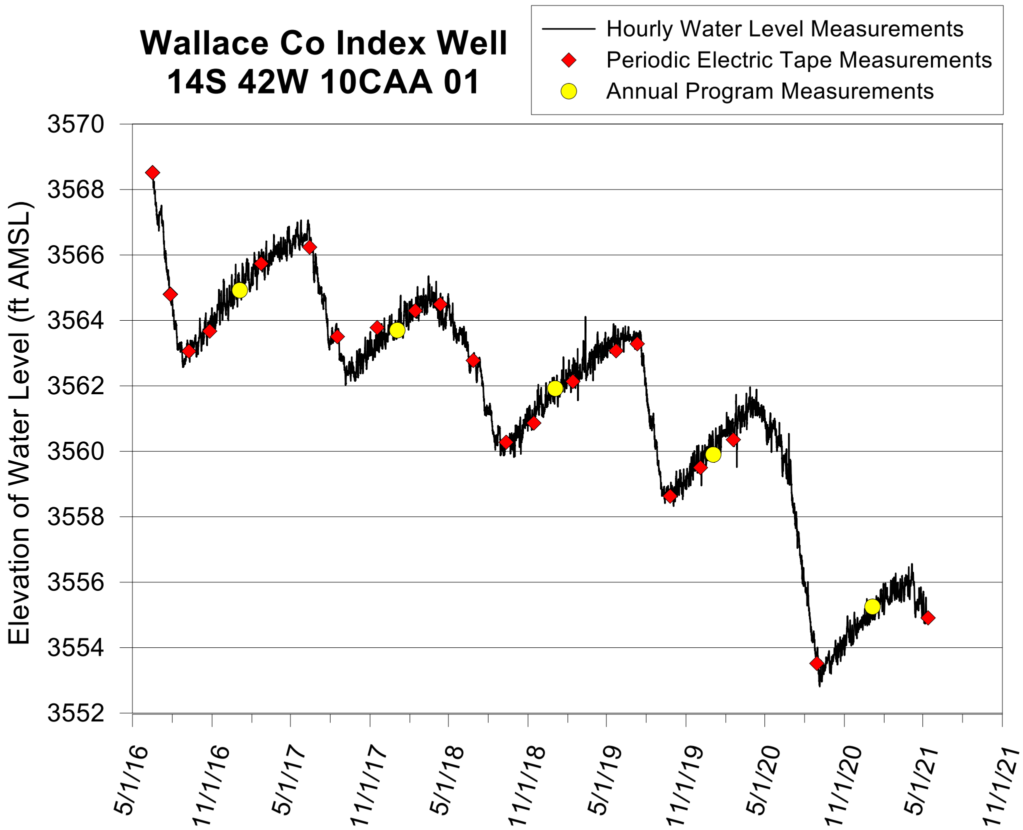


Figure 5—Wallace County index well hydrograph—total data run to 5/13/21. A water-level elevation of 3,565 ft corresponds to a depth to water of 263 ft below lsf. The top of the screen is 375 ft below lsf (elevation of 3,453 ft), and the bottom of the aquifer is 394 ft below lsf (elevation of 3,434 ft). 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 2020 minimum water level was 5.5 ft below that of 2019.
- Transducer readings are in good agreement with manual measurements. Similar to the Lane index well, many short-duration spikes appear on the hydrograph until mid-summer 2020. On August 29, 2020, we replaced the telemetry system with a different vendor’s system and the spikes disappeared.

3.1.4 Wichita County Index Well

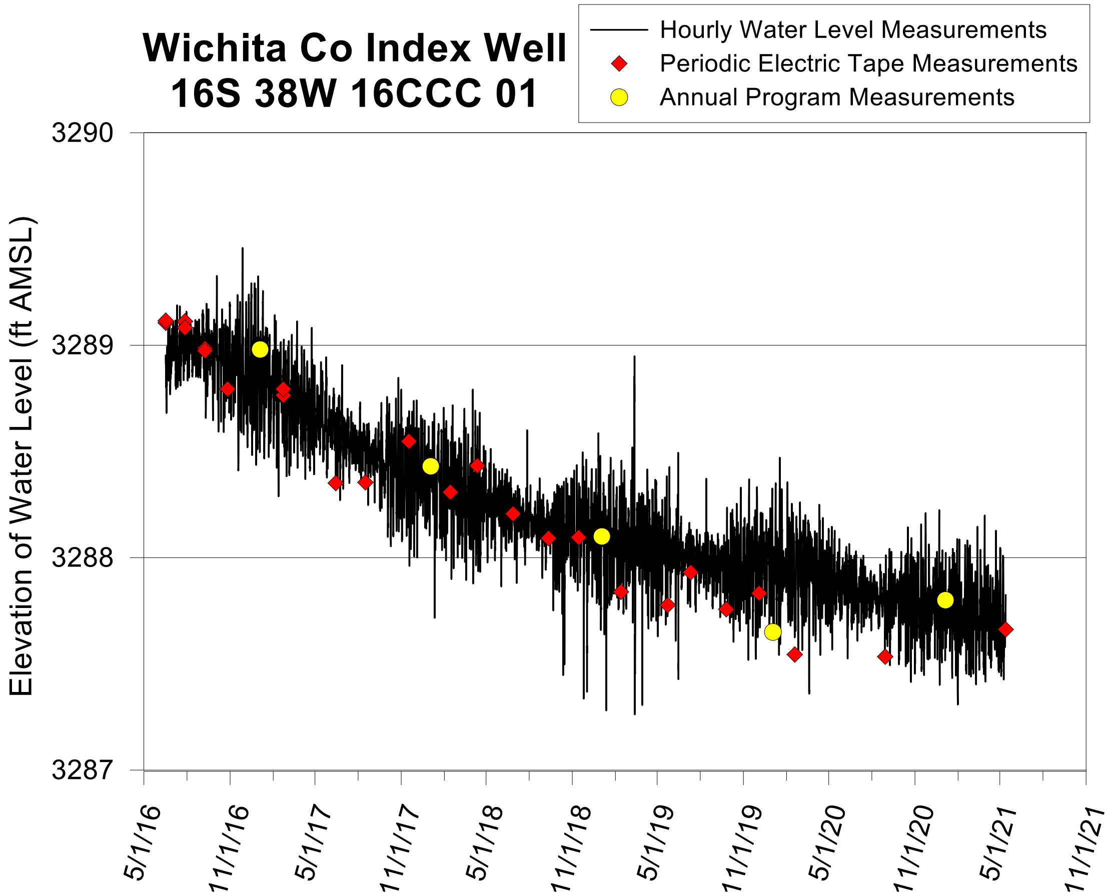


Figure 6—Wichita County index well hydrograph—total data run to 5/13/21. A water-level elevation of 3,289 ft corresponds to a depth to water of 159 ft below lsf. The top of the screen is 175 ft below lsf (elevation of 3,273 ft), and the bottom of the aquifer is 190 ft below lsf (elevation of 3,258 ft). 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 good 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.

3.2 GMD2 Index Wells

There are currently five index wells in GMD2 (fig. 7), 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 this section and the 2019 annual report (Butler, Whittemore et al., 2020), respectively, and the online appendices for this report (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

Table 2—Characteristics of the GMD2 index well sites.

Site	2021 WL elev. (ft)[a]	2021 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2019 water use (ac-ft)		
					1 mi radius	2 mi radius	5 mi radius
Bentley	1,372.3	207.3	216	b	664	1,904[c]	18,703[d]
Harvey	1,416.0	167	206	198-208	716	3,261[e]	10,510[f]
McPherson	1,400.3	90.3	184	139-183	1,535[g]	6,200[h]	11,202[i]
Mount Hope	1,408.7	160.3	173	166-176	468	1,136[j]	12,981[k]
Pretty Prairie	1,547.8	49.8	71	61-71	748[l]	2,532[m]	8,060[m]

[a] 2021 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html). Bentley estimated from sensor data on 1/11/21 from 0800 to 1700.

[b] Screened interval to be determined by downhole camera survey later in 2021.

[c] Includes 309 ac-ft of municipal water.

[d] Includes 9,849 ac-ft of municipal water, 400 ac-ft of industrial water, and 88 ac-ft of other water.

[e] Includes 197 ac-ft of municipal water.

[f] Includes 197 ac-ft of municipal water and 135 ac-ft of non-irrigation recreation water.

[g] Includes 1,369 ac-ft of municipal water.

[h] Includes 2,897 ac-ft of municipal water, 2,410 ac-ft of industrial water, and 2 ac-ft of non-irrigation stock water.

[i] Includes 2,950 ac-ft of municipal water, 2,591 ac-ft of industrial water, 2 ac-ft of non-irrigation stock water, 88 ac-ft of non-irrigation recreation water, and 546 ac-ft of other water.

[j] Includes 22 ac-ft of non-irrigation recreation water.

[k] Includes 4,750 ac-ft of municipal water, 3 ac-ft of industrial water, 91 ac-ft of non-irrigation recreation water, and 2 ac-ft of other water.

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

[m] Includes 75 ac-ft of municipal water.

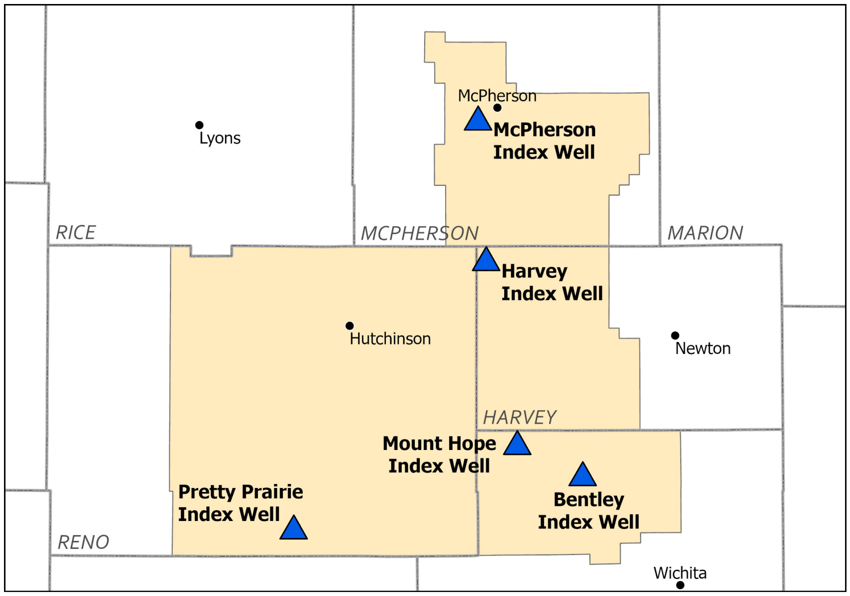


Figure 7—Map of index wells in GMD2. Triangles designate wells with telemetry equipment; data from these wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_ program/index.shtml).

3.2.1 Bentley Index Well

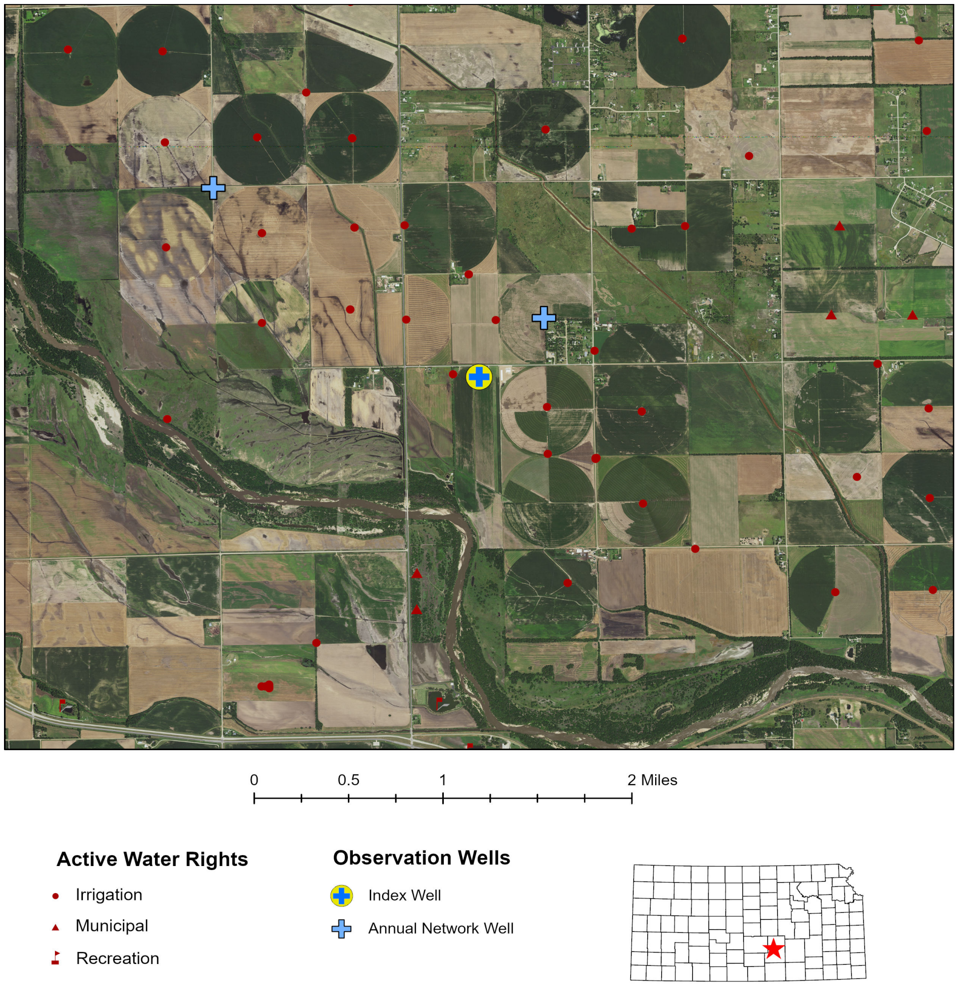


Figure 8—Aerial view of the Bentley index well and nearby annual wells and points of diversion.

Figure 8 is an aerial view of the Bentley index well site (T. 25 S., R. 02 W., 26 BAA 01) at a scale that shows the site of the index well, two additional annual program wells, the nearby wells with active water rights, and the Arkansas River. The site has a single well adjacent to a weather station. The well apparently has not previously been monitored. GMD2 personnel measure water levels at a three-well nest approximately 630 ft to the north-northwest of the Bentley well.

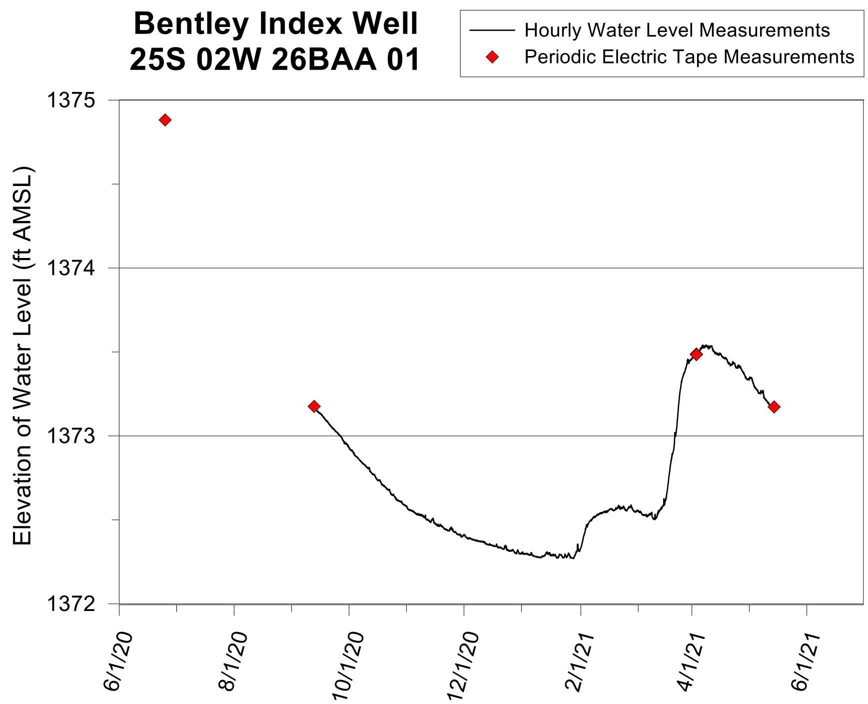


Figure 9—Bentley index well hydrograph—total data run to 5/14/21. A water-level elevation of 1,373 ft corresponds to a depth to water of 8.0 ft below lsf. The screened interval has yet to be determined. The bottom of the aquifer is approximately 216 ft below lsf (elevation of 1,165 ft) and the bottom 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 in late winter and spring of 2021 are likely produced by precipitation and stage changes in the nearby Arkansas River.
- There is little indication of nearby pumping activity.
- Transducer readings are in good agreement with manual measurements.

3.2.2 Harvey County Index Well

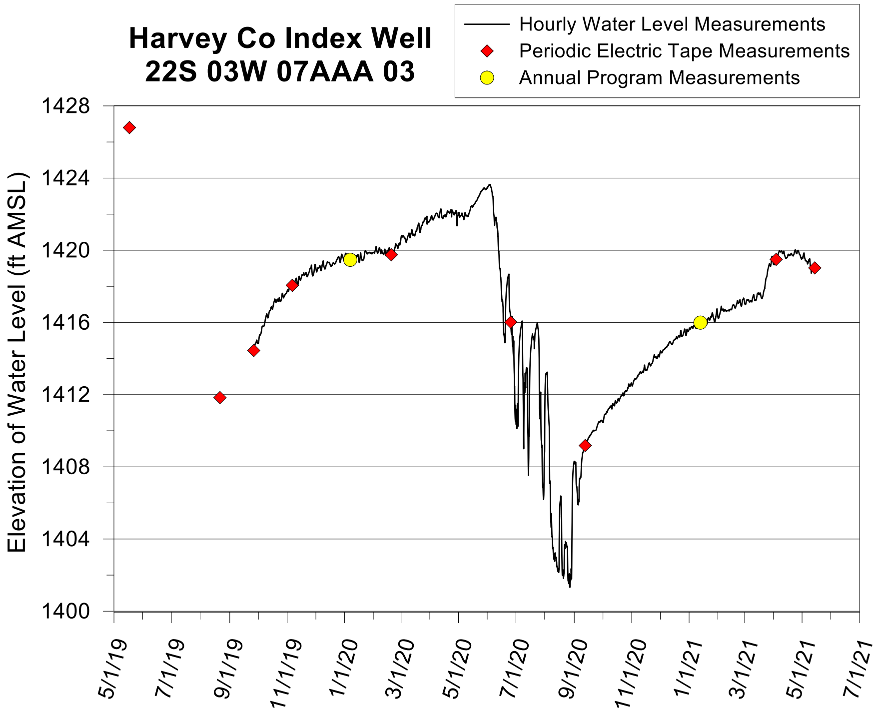


Figure 10—Harvey County index well hydrograph—total data run to 5/14/21. A water-level elevation of 1,418 ft corresponds to a depth to water of 37.0 ft below lsf. The top of the 10 ft screen is 198 ft below lsf (elevation of 1,257.0 ft), and the bottom of the aquifer is 206 ft below lsf (elevation of 1,249.0 ft).

Major Points

- The hydrograph form and the relatively large amplitude fluctuations superimposed on the water levels indicate 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

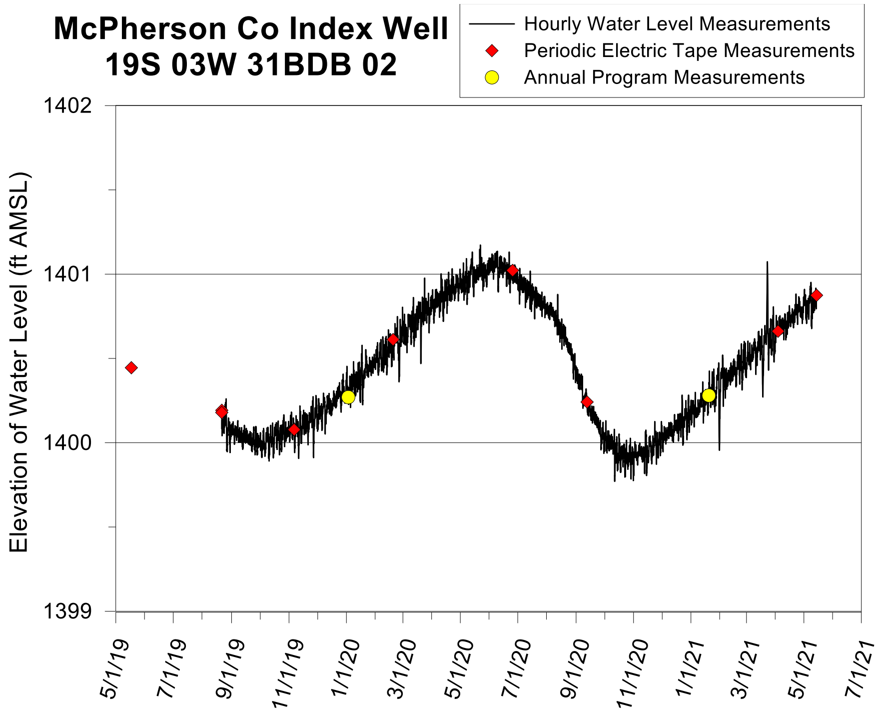


Figure 11—McPherson County index well hydrograph—total data run to 5/14/21. A water-level elevation of 1,400 ft corresponds to a depth to water of 94.0 ft below lsf. The top of the 44 ft screen is 139 ft below lsf (elevation of 1,355 ft), and the bottom of the screen is 183 ft below lsf (elevation of 1,311 ft). The bottom of the aquifer is 1 ft below the bottom of the screen (1,310 ft).

Major Points

- The relatively large amplitude fluctuations superimposed on the water levels indicate unconfined 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 5/14/21 download.
- 2019 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 a water-level rise similar to that seen in the other GMD2 index wells in late March 2021 indicates that overlying clay layers are shielding the screened interval from short-term effects of recharge.

3.2.4 Mount Hope Index Well

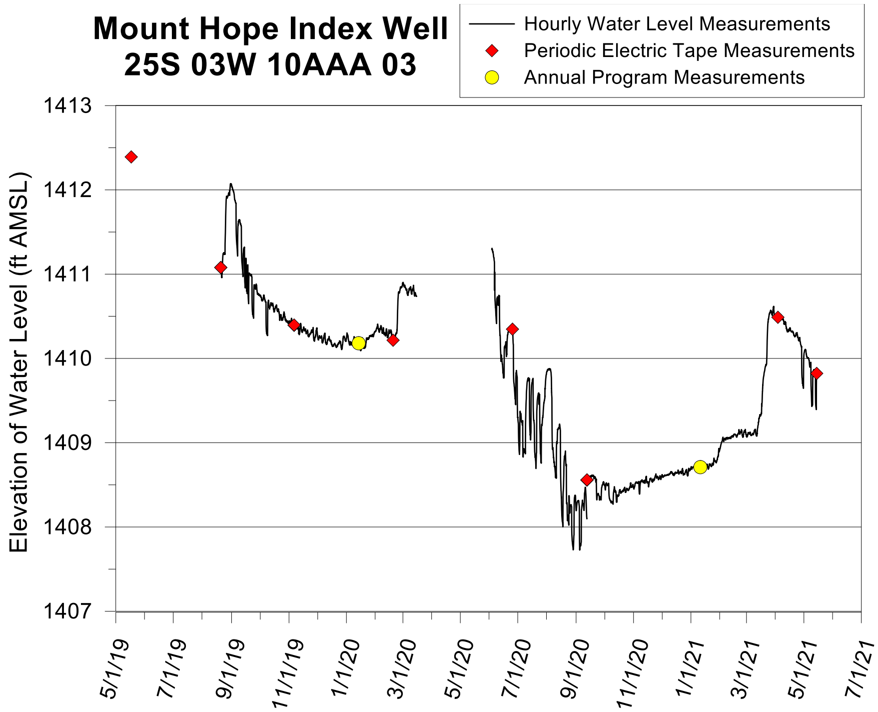


Figure 12—Mount Hope index well hydrograph—total data run to 5/14/21. A water-level elevation of 1,411 ft corresponds to a depth to water of 10.4 ft below lsf. The top of the 10 ft screen is 163 ft below lsf (elevation of 1,258.4 ft), and the bottom of the aquifer is 173 ft below lsf (elevation of 1,248.4 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

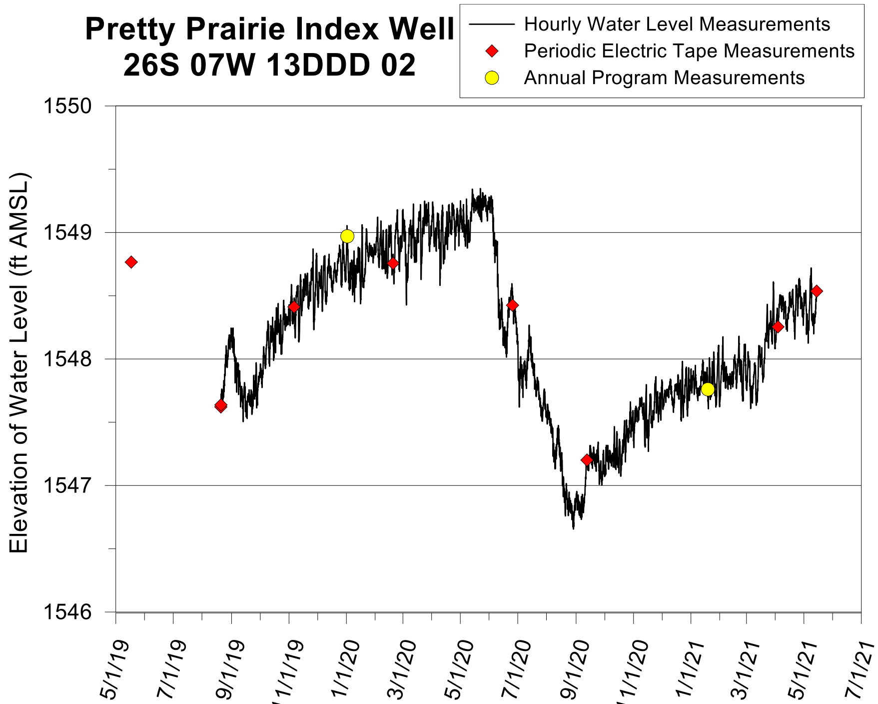


Figure 13—Pretty Prairie index well hydrograph—total data run to 5/14/21. A water-level elevation of 1,548 ft corresponds to a depth to water of 21.0 ft below lsf. The top of the 10 ft screen is 61 ft below lsf (elevation of 1,508 ft), and the bottom of the screen and aquifer is 71 ft below lsf (elevation 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. 14). The Haskell index well was one of the original 2007 index wells; monitoring began at the Cimarron, Hugoton, Liberal, and Rolla well sites in 2012–2013, at the Willis Technology Farm index well in the summer of 2016, 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	2021 WL elev. (ft)[a]	2021 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)[b]	Screened interval (ft below land surface)[b]	2019 water use (ac-ft) 1 mi radius	2019 water use (ac-ft) 2 mi radius	2019 water use (ac-ft) 5 mi radius
Cimarron 210	2,473.89[c]	289.92	345	200–210	0	0	8,467
Haskell	2,527.93	123.06	433	420–430	310	4,471	27,469
Hugoton 313[d,e]	2,905.08[c,d]	440.11	635	303–313	441	2,584	35,416[f]
Hugoton 495	2,900.68	435.74	635	485–495			
Kearny-Finney	2,787.40	186.38[g]	360[g]	70–266[h]	1,174	3,600	26,131[i]
Liberal 436	2,653.13	407.13	576	426–436	0.01	1,627[j]	30,305[k]
Rolla 366	3,186.87	210.86	399	356–366	162[l]	996[m]	7,422[n]
Willis Tech Farm	2,630.79	192.79	502	262–482	989	5,469	34,757[o]

[a] 2021 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] 2021 water-level measurements from hand measurements taken 2/2/2021 and 2/3/2021.
[d] Not part of the annual water-level measurement network.
[e] Well originally on a USGS telemetry system; the systems was removed in 2017 because of a lack of funding.
[f] Includes estimated 17,989 ac-ft water use in Oklahoma based on "permitted" quantities.
[g] Based on logs of nearby wells to bedrock.
[h] Measurements estimated from borehole camera log.
[i] Includes 523 ac-ft of non-irrigation stock water, 219 ac-ft of municipal water, and 89 ac-ft of industrial water.
[j] Includes estimated 675 ac-ft water use in Oklahoma based on "permitted" quantities.
[k] Includes 6,832 ac-ft of non-irrigation water for city of Liberal and an estimated 20,909 ac-ft water use in Oklahoma based on "permitted" quantities.
[l] Includes 25 ac-ft of non-irrigation stock water.
[m] Includes 88 ac-ft of non-irrigation stock water.
[n] Includes 261 ac-ft of non-irrigation stock water and 86 ac-ft of municipal water.
[o] Includes 406 ac-ft of industrial water.

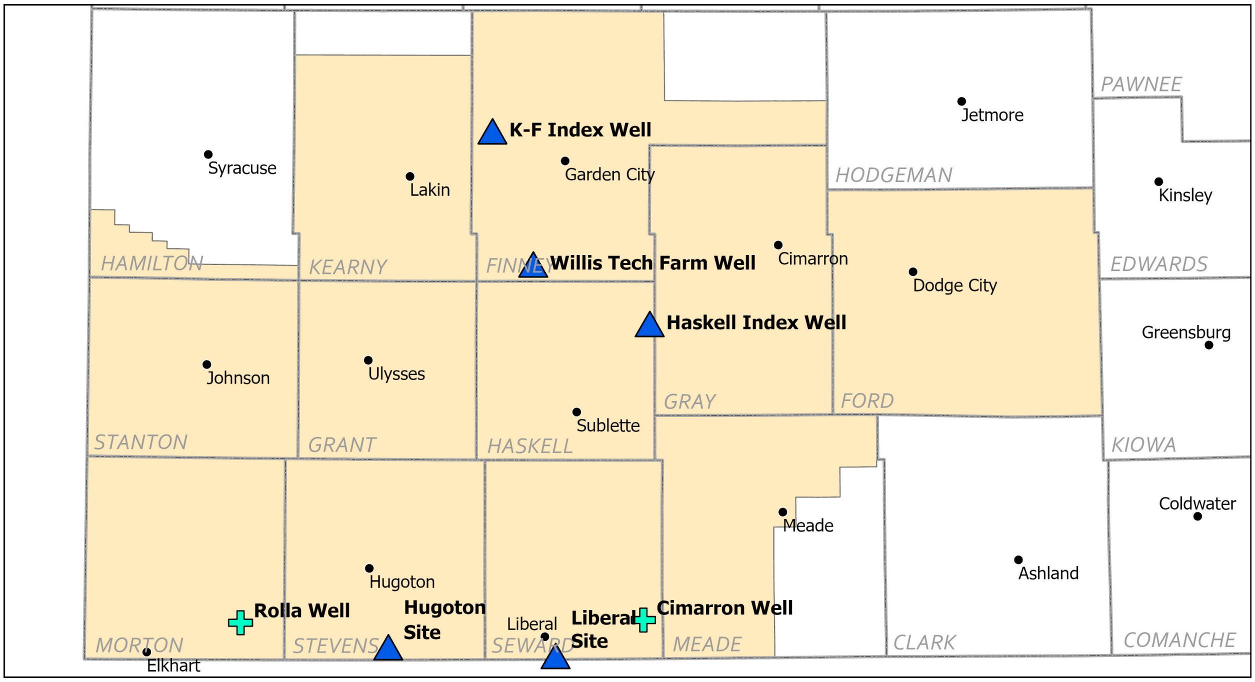


Figure 14—Map of index wells in GMD3. Triangles designate wells with telemetry equipment, whereas plus signs designate wells without telemetry equipment. Data from wells with telemetry equipment can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml); data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

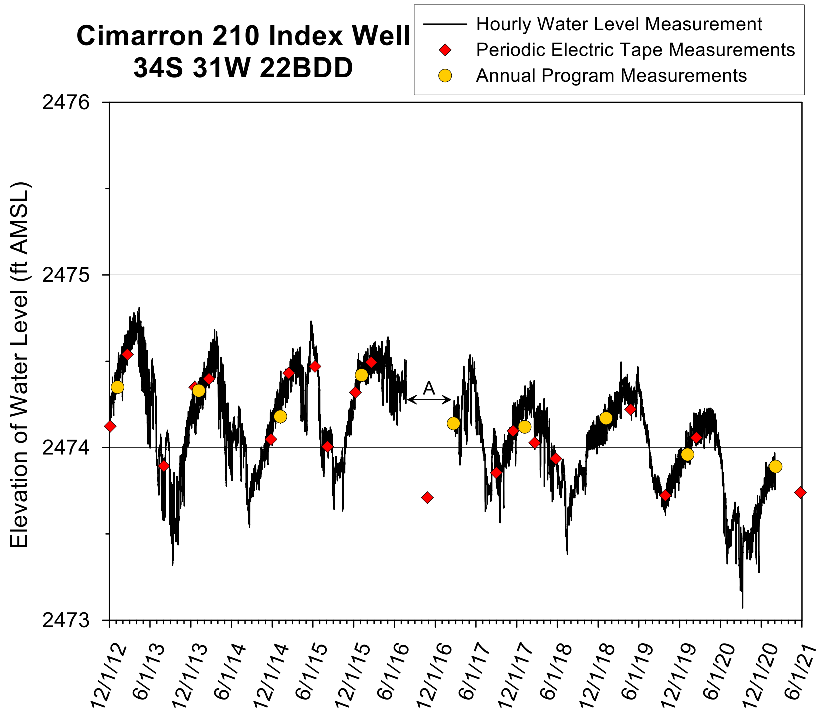


Figure 15—Cimarron 210 index well hydrograph—total data run to 5/25/21; hourly measurements until 2/3/21. A water-level elevation of 2,474 ft corresponds to a depth to water of 55.0 ft below lsf. The top of the 10 ft screen is 200 ft below lsf (elevation of 2,329 ft), and the bottom of the aquifer is 345 ft below lsf (elevation of 2,184 ft); A 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 gap (A) in hydrograph record. Sensor failed again in early February 2021 and will be replaced in the summer of 2021.
- Water use within a 2 mi radius of the well is the lowest of any of the index wells.
- Water level has declined 2.1 ft since January 2000 (decline rate of 0.1 ft/yr); see 2016 annual report (Butler, Whittemore et al., 2017) for further details.
- Transducer readings are in good agreement with manual measurements.

3.3.2 Haskell County Index Well

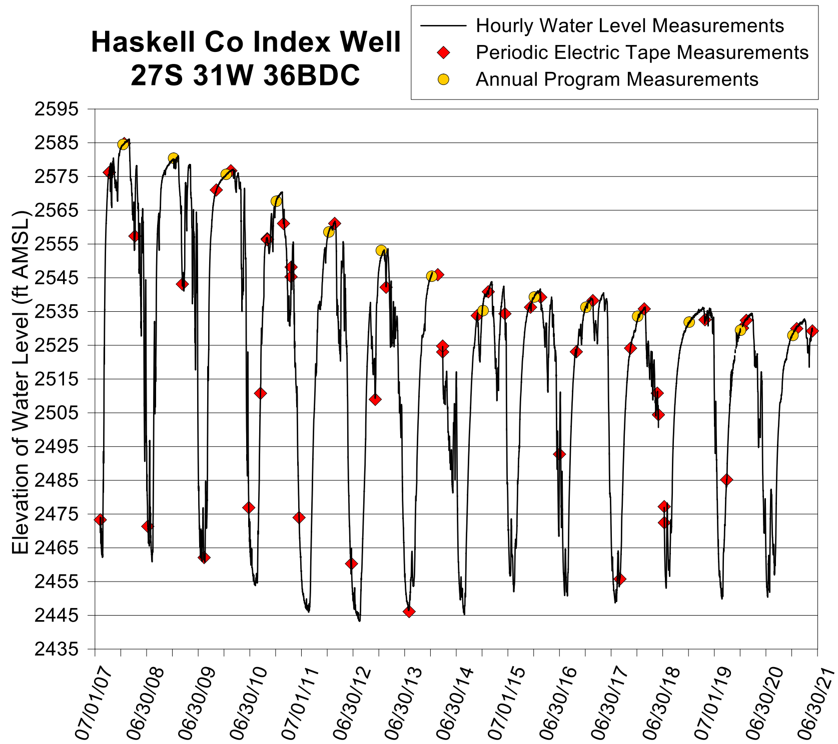


Figure 16—Haskell County index well hydrograph—total data run to 5/25/21. A water-level elevation of 2,445 ft corresponds to a depth to water of 392.85 ft below lsf. The top of the screen is 420 ft below lsf (elevation of 2,417.85 ft), and the bottom of the aquifer is 433 ft below lsf (elevation of 2,404.85 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.
- 2019 water use (2 mi radius centered on well) was the lowest since the start of monitoring (2007) at the Haskell index well.
- Transducer readings are in reasonable agreement with manual measurements.

3.3.3 Hugoton Site

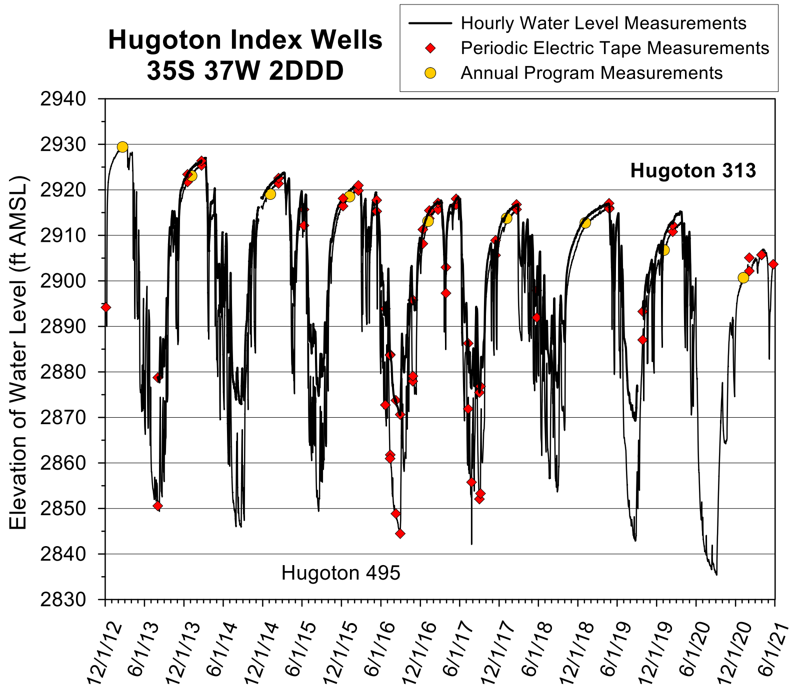


Figure 17—Hydrographs of Hugoton index wells—total data run to 5/24/21 for Hugoton 495 and 5/19/20 for Hugoton 313. A water-level elevation of 2,930.0 ft corresponds to a depth to water of 170.0 ft below lsf. For the Hugoton 495 well, the top of the 10 ft screen is 485 ft below lsf (elevation of 2,615 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 will be replaced in summer 2021.

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 69.3 ft since January 2000 (decline rate of 3.3 ft/yr); see 2016 annual report (Butler, Whittemore et al., 2017) for further details.
- Transducer readings are in good agreement with manual measurements.

3.3.4 Kearny-Finney Index Well

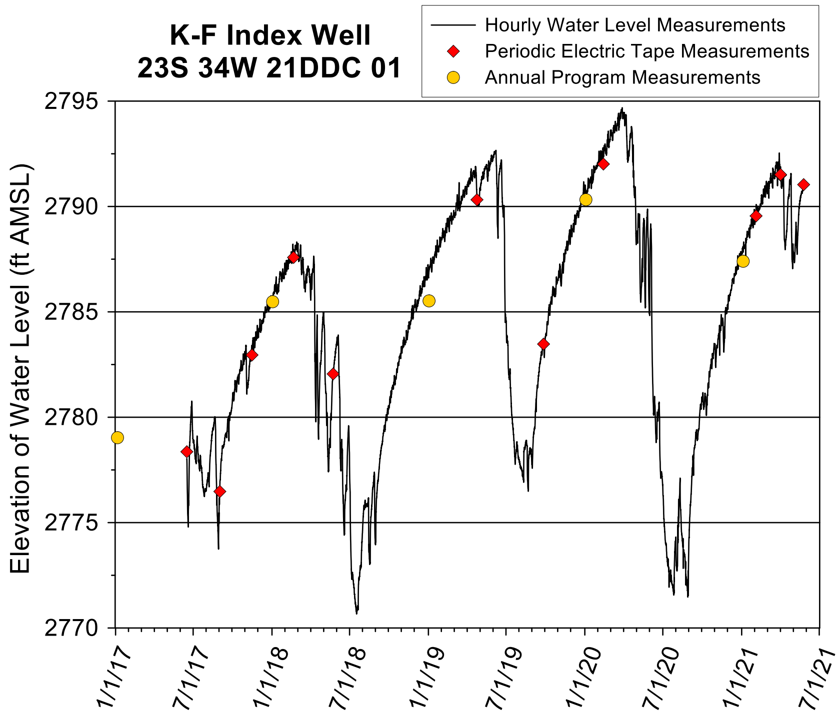


Figure 18—Kearny-Finney (K-F) index well hydrograph—total data run to 5/25/21. A water-level elevation of 2,790 ft corresponds to a depth to water of 171 ft below lsf. Nominal bottom of well is 300 ft below lsf (elevation of 2,661 ft), but the well is currently filled with sediments to 266 ft below lsf (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 50.8 ft since January 2008 (over half of that total decline occurred in 2011 and 2012).
- Minimum water-level elevation for 2020 was 5.0 ft lower than that of 2019 and the apparent maximum recovered water level for 2021 was 2.2 ft below the maximum recovered level for 2020.
- Transducer readings are in relatively good agreement with electric-tape measurements; 2019 annual measurement appears to be in error.

3.3.5 Liberal Index Well

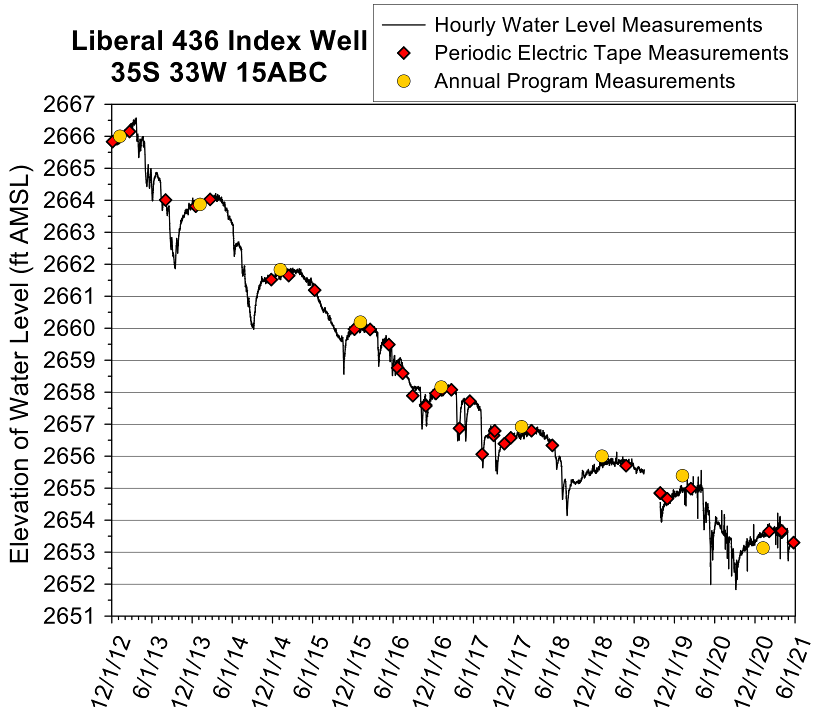


Figure 19—Hydrograph of Liberal 436 index well—total data run to 5/25/21. A water-level elevation of 2,664 ft corresponds to a depth to water of 157 ft below lsf. The top of the 10 ft screen is 426 ft below lsf (elevation of 2,395 ft). Sensor failed on July 6, 2019; a new sensor was installed on September 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] paper).
- The water level in Liberal 436 has declined 29.4 ft since January 2000 (decline rate of 1.4 ft/yr).
- Transducer readings are in good agreement with electric tape measurements but annual program measurements recently appear to have greater error.

3.3.6 Rolla Index Well

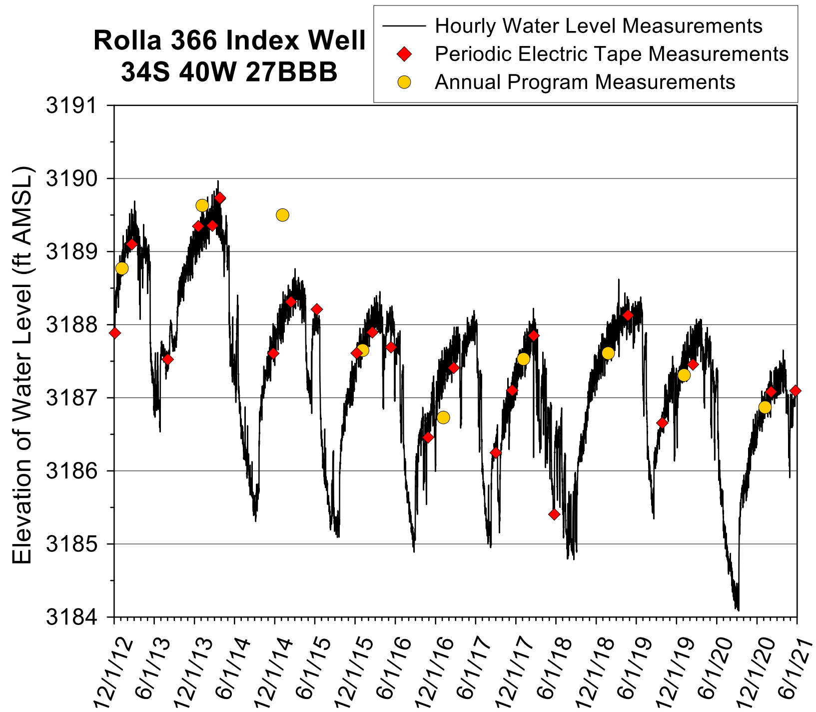


Figure 20—Rolla 366 index well hydrograph—total data run to 5/24/21. A water-level elevation of 3,188 ft corresponds to a depth to water of 187 ft below lsf. The top of the 10 ft screen is 356 ft below lsf (elevation of 3,019 ft), and the bottom of the aquifer is 399 ft below lsf (elevation of 2,976 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 2020 and the apparent maximum water level in 2021 were the lowest since monitoring began in late 2012.
- The water level has declined 10.1 ft since January 2000 (decline rate of 0.48 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

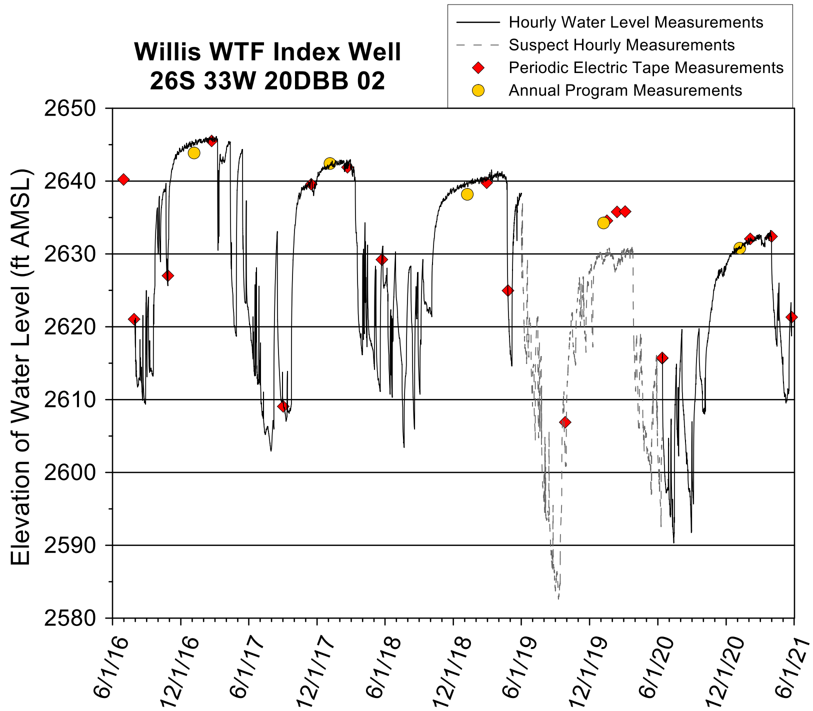


Figure 21—Willis Water Technology Farm (WTF) index well hydrograph—total data run to 5/25/21. A water-level elevation of 2,640 ft corresponds to a depth to water of 300 ft below lsf. The top of the 220 ft screen is 262 ft below lsf (elevation of 2,678 ft), and the bottom of the aquifer is 502 ft below 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. Telemetry ceased operating in 2/9/21 due to cable damage; repaired cable will be installed in well in early July 2021.

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.
- At the end of an 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. Water level has fallen approximately 13.4 ft since February 2017 – rate of decline 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

Eight index wells are located in GMD4, five of which have telemetry equipment that allows real-time viewing of data (fig. 22). 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, and Steiger SD-6 LEMA index wells in 2015, 2016, 2017, and 2021, respectively. Table 4 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 4—Characteristics of the GMD4 index well sites.

Site	2021 WL elev. (ft)[a]	2021 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2019 water use (ac-ft) 1 mi radius	2 mi radius	5 mi radius
Colby	3,024.4	97.4[b]	250–300	156–175	399[c]	1,708[d]	7,227[e]
SD-6 Baalman	NA[f]	NA	262	260–270	388	1,170	8,308[g]
SD-6 Beckman[h,i]	2,679.9[h]				489	1,817[j]	8,077[k]
SD-6 Moss[h]	2,624.4[h]	51.4	243	205–245	168	1,445	8,891[l]
SD-6 Seegmiller	2,738.5	70.5	265	225–265	425	1,674	8,593[m]
SD-6 Steiger[h]	2,850.7[h]	62.7	177	145–185	146	670[n]	5,293[o]
Sherman	3,614.5	143.5	323	310–320	1,263	2,543	8,656
Thomas	2,969.8	66.4	284	274–284	572	1,536	6,405

[a] 2021 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html).
[b] Based on bedrock depth of 250 ft below lsf.
[c] Includes 212 ac-ft of municipal water.
[d] Includes 1,002 ac-ft of municipal water and 220 ac-ft of other water.
[e] Includes 1,158 ac-ft of municipal water, 220 ac-ft of other water, 1 ac-ft of industrial water, and 17 ac-ft of non-irrigation stock water.
[f] Annual measurement on 01/07/2021 is likely in error. Transducer measurements not available as sensor failed after 6/5/2020 and wasn't replaced until 3/20/2021.
[g] Includes 766 ac-ft of non-irrigation stock water.
[h] Not an annually measured index well; 2021 water-level measurements from hand measurements taken 01/7/2021 at Moss and Steiger.
[i] Well construction information not available.
[j] Includes 438 ac-ft of non-irrigation stock water.
[k] Includes 691 ac-ft of non-irrigation stock water.
[l] Includes 659 ac-ft of non-irrigation stock water, 1 ac-ft of industrial water, and 278 ac-ft of municipal water.
[m] Includes 691 ac-ft of non-irrigation stock water.
[n] Includes 30 ac-ft of non-irrigation stock water.
[o] Includes 50 ac-ft of non-irrigation stock water and 2 ac-ft of recreation water.

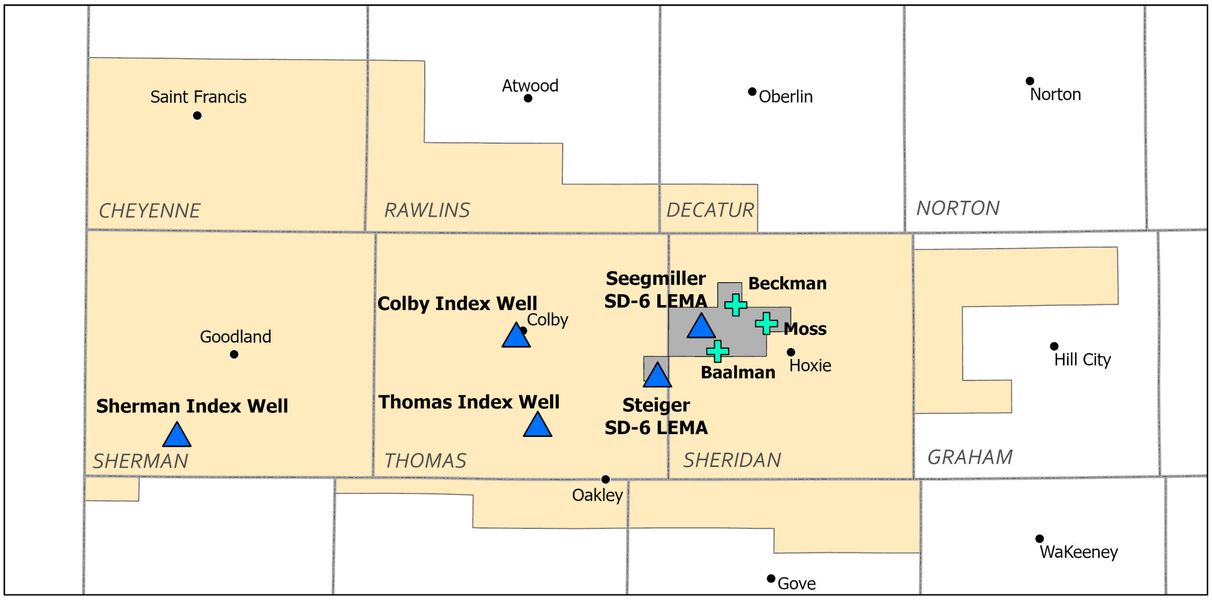


Figure 22—Map of index wells in GMD4. Triangles designate wells with telemetry equipment, whereas plus signs designate wells without telemetry equipment. Data from wells with telemetry equipment can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml); data from wells without telemetry equipment are periodically downloaded (typically quarterly) and posted on the KGS website. Shaded area is the Sheridan-6 LEMA.

3.4.1 Colby Index Well

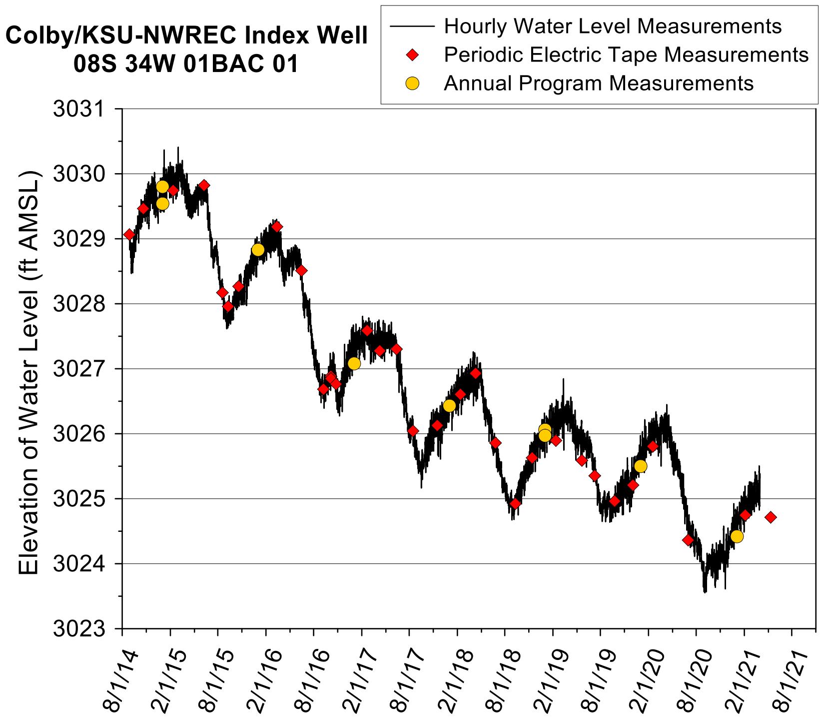


Figure 23—Colby index well hydrograph—total data run to 5/12/21. A water-level elevation of 3,029 ft corresponds to a depth to water of 148 ft below lsf. Total depth of the well is 175 ft below lsf (elevation of 3,002 ft). The screened interval extends from 156 to 175 ft below lsf. The base of the aquifer 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 0.88 ft/yr over the monitoring period and a total of 38.5 ft since January 1948.
- Transducer readings are in good agreement with manual measurements.

3.4.2 SD-6 Baalman Index Well

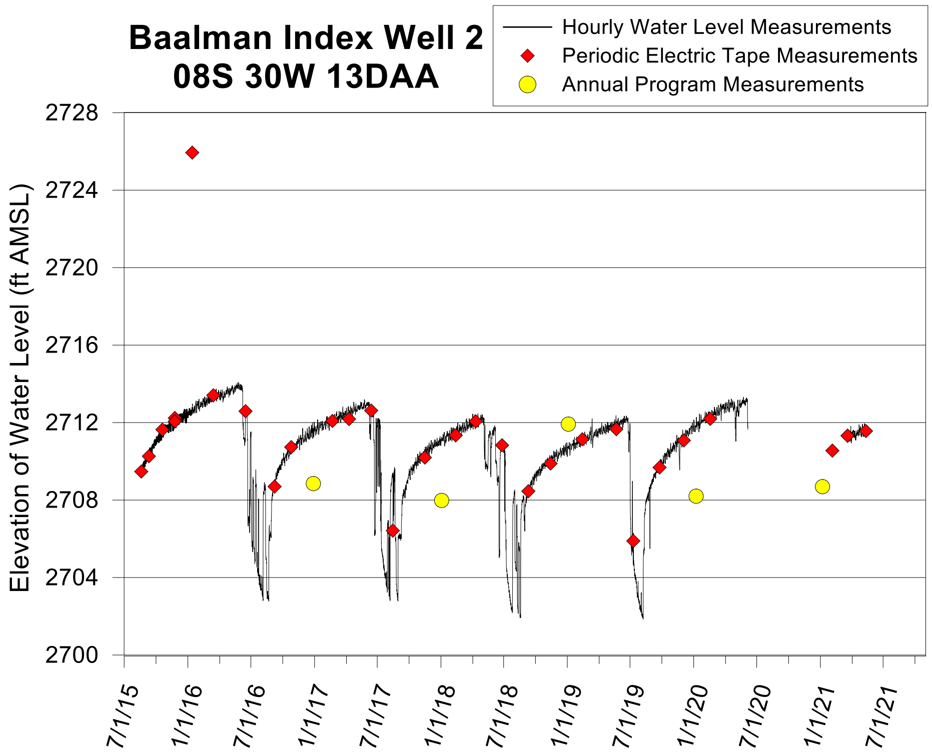


Figure 24—Baalman index well hydrograph—total data run to 5/12/21. A water-level elevation of 2,712 ft corresponds to a depth to water of 185 ft below lsf. The top of the 10 ft screen is 260 ft below lsf (elevation of 2,637 ft), and the bottom of the aquifer is 262 ft below lsf (elevation of 2,635 ft). 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 2020 was above the previous three years as a result of the relatively small amount of pumping in 2019 (lowest pumping total and shortest pumping season [44 days] in the vicinity of the Baalman well [2 mi radius] since the establishment of the SD-6 LEMA).
- Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.69 ft (8.3 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

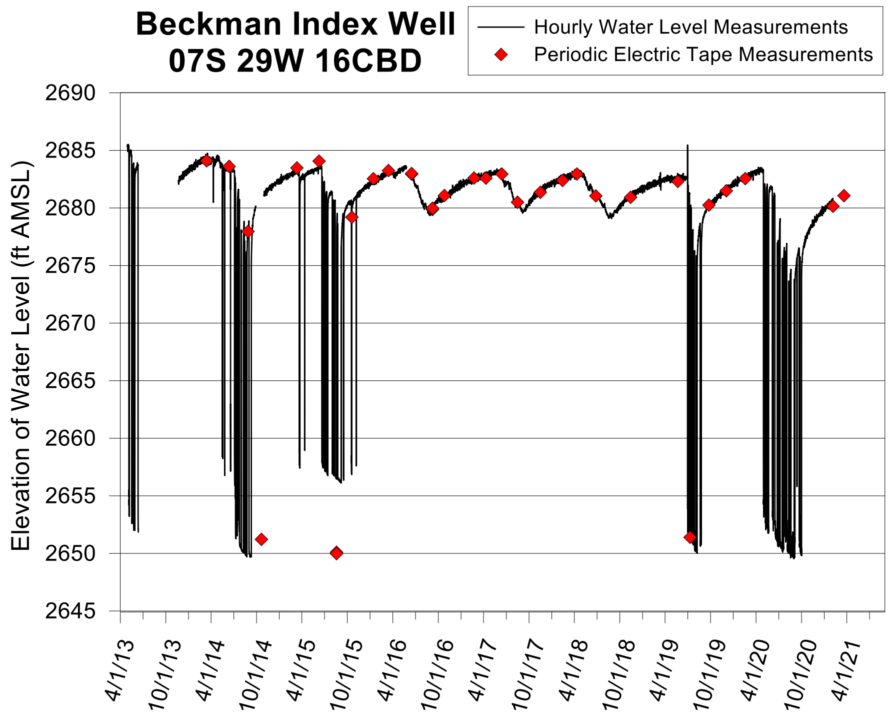


Figure 25—Beckman index well hydrograph—total data run to 3/20/21. A water-level elevation of 2,680 ft corresponds to a depth to water of 200.15 ft below lsf. The data gaps in 2013 and 2014 were caused by datalogger battery problems. The difference between the electric-tape measurement in the summer 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 second time in the last five irrigation seasons and the fifth 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 0.69 ft (8.3 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. However, the sensor could not be downloaded during the 5/12/21 visit because the site could not be accessed without damaging the winter wheat crop.
- 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

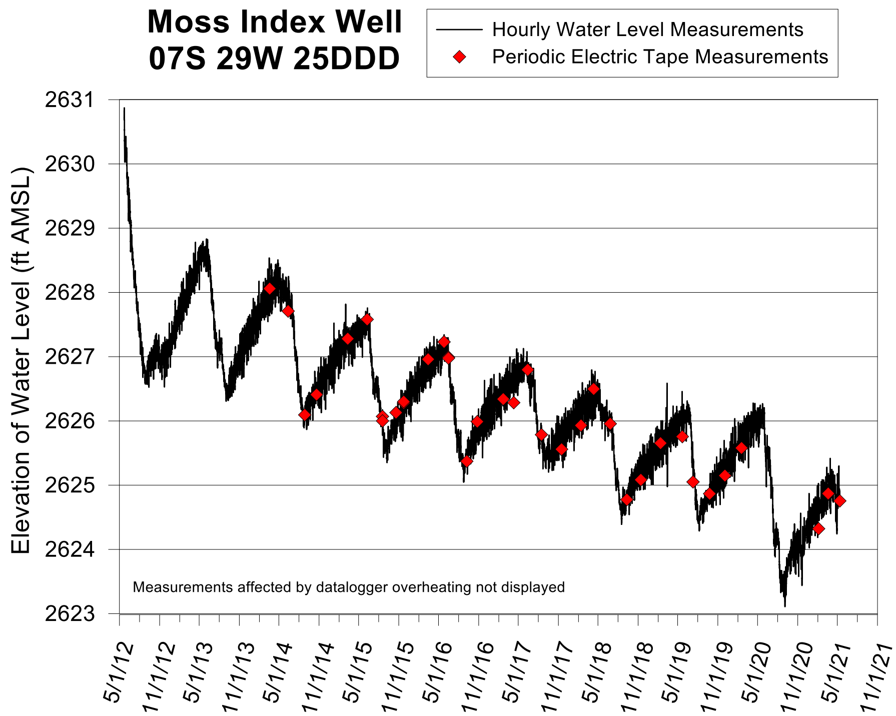


Figure 26—Moss index well hydrograph—total data run to 5/12/21. A water-level elevation of 2,627 ft corresponds to a depth to water of 189.0 ft below lsf. The top of the 40 ft screen is 205 ft below lsf (elevation of 2,611.0 ft), and the bottom of the aquifer is 243 ft below lsf (elevation of 2,573.0 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 0.79 ft (9.5 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

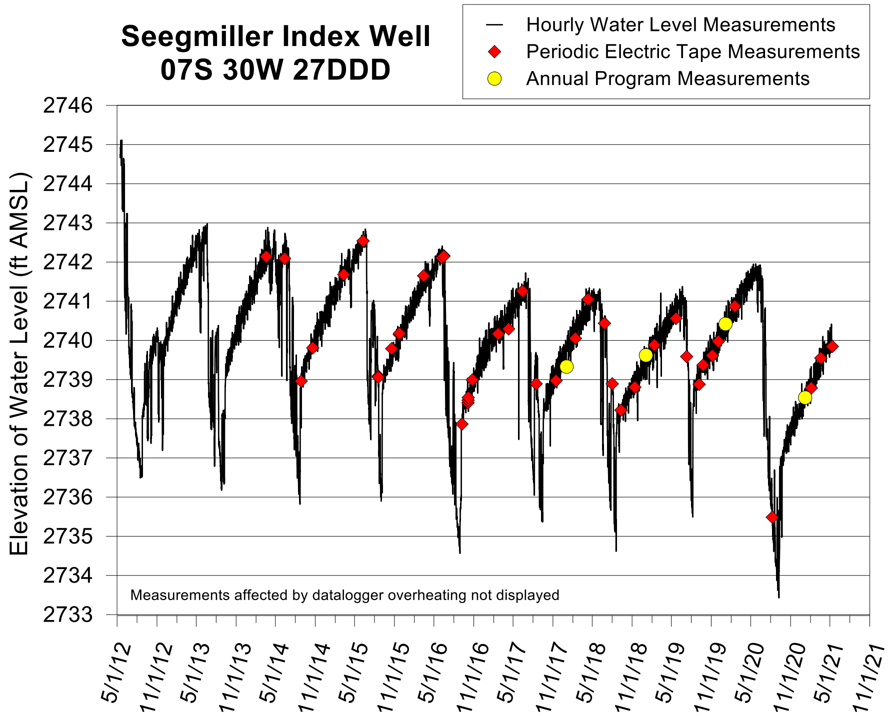


Figure 27—Seegmiller index well hydrograph—total data run to 5/12/21. A water-level elevation of 2,740 ft corresponds to a depth to water of 193.0 ft below lsf. The top of the 40 ft screen is 225 ft below lsf (elevation of 2,708.0 ft), and the bottom of the aquifer is 265 ft below lsf (elevation of 2,668.0 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 2020 was 2.1 ft below that of 2019 and 1.2 ft below that of 2018, which was the previous lowest level observed during the monitoring period. The increase in maximum water-level elevations between 2019 and 2020 was the largest (0.6 ft) observed during the monitoring period because of the small amount of pumping in 2019 (lowest during the monitoring period and about 24% lower than the previous low [2017]).
- Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.71 ft (8.5 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

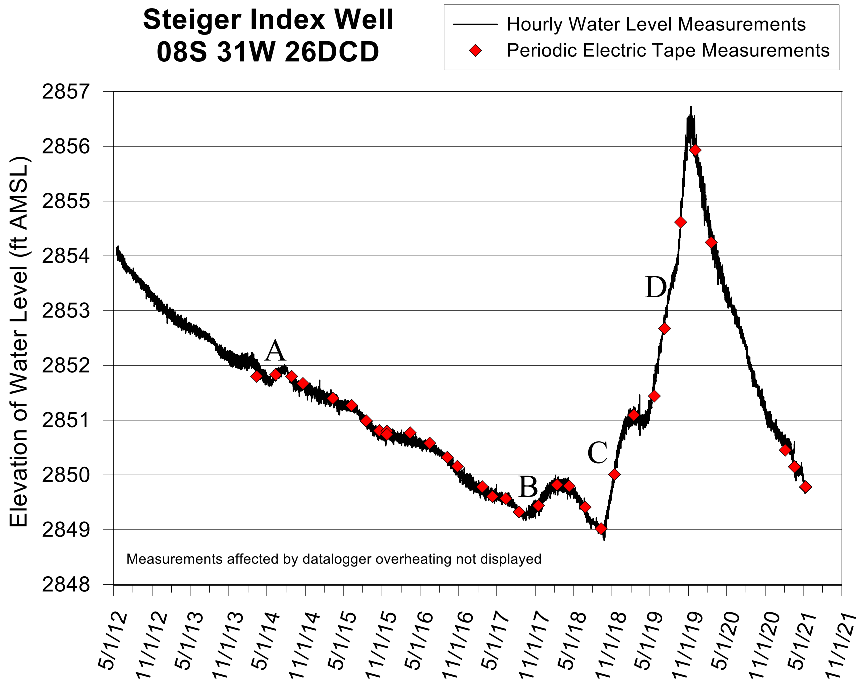


Figure 28—Steiger index well hydrograph—total data run to 5/12/21. A water-level elevation of 2,851 ft corresponds to a depth to water of 114.0 ft below lsf. The top of the 40 ft screen is 145 ft below lsf (elevation of 2,820.0 ft), and the bottom of the aquifer is 177 ft below lsf (elevation of 2,788.0 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 0.78 ft (9.3 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

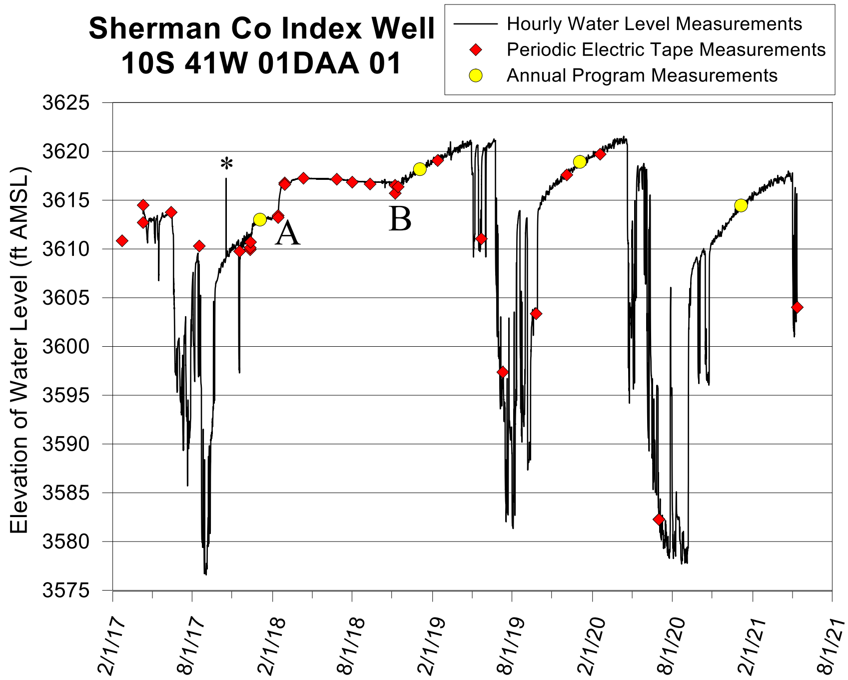


Figure 29—Sherman County index well hydrograph—total data run to 5/13/21. A water-level elevation of 3,617 ft corresponds to a depth to water of 177 ft below lsf. The top of the 10 ft screen is 310 ft below lsf (elevation of 3,484 ft), and the bottom of the aquifer is 323 ft below lsf (elevation of 3,471 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 very 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 Thomas County Index Well

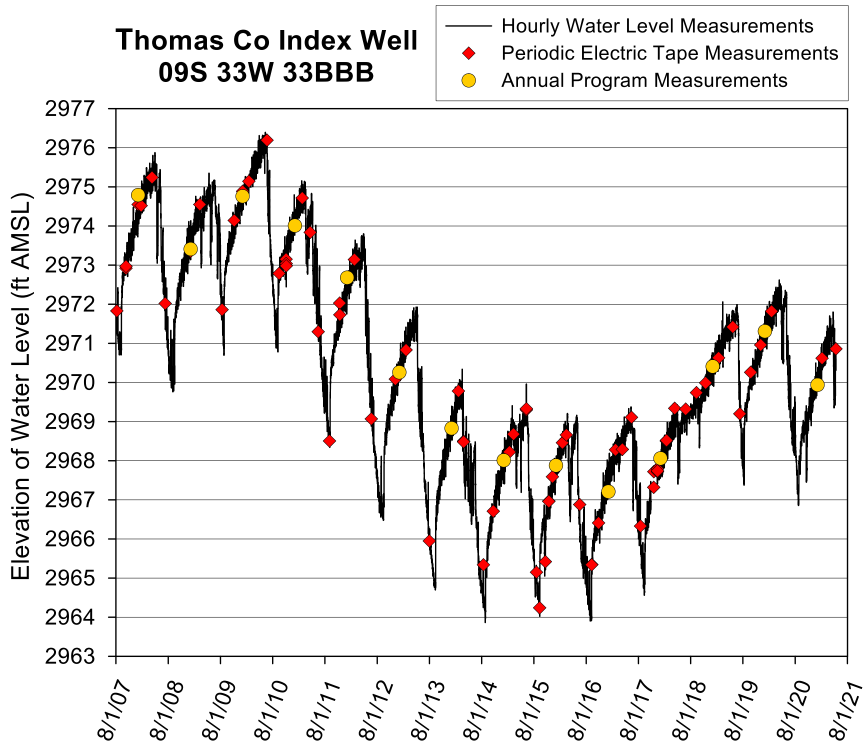


Figure 30—Thomas County index well hydrograph—total data run to 5/12/21. A water-level elevation of 2,968 ft corresponds to a depth to water of 219.56 ft below lsf. The top of the screen is 274 ft below lsf (elevation of 2,913.6 ft), and the bottom of the aquifer is 284 ft below lsf (elevation of 2,903.6 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 maximum water level in 2020 was 0.5 ft above that in 2019 and the highest since 2012.
- 2018 water use 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. 2019 water use was the second lowest for the monitoring period and 1.9 times greater than that in 2018.
- Transducer readings are in good agreement with manual measurements.

3.5 GMD5 Index Wells

Two index wells, both of which have telemetry equipment that allows real-time viewing of data, are located in GMD5 (fig. 31). Table 5 summarizes characteristics of these two wells. Further details concerning the Belpre well are given in the 2016 annual report (Butler, Whittemore et al., 2017), and further information about both 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	2021 WL elev. (ft)[a]	2021 saturated thickness (ft)	Bedrock depth (ft below land surface)	Screened interval (ft below land surface)	2019 water use (ac-ft) 1 mi radius	2 mi radius	5 mi radius
Belpre	2,043.46	137.8–163.5[b]	175–200[b]	89–109	412	1,887	14,842
Larned	1,944.95	60.63	71	66–71	318	2,559	15,394

[a] 2021 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html).

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

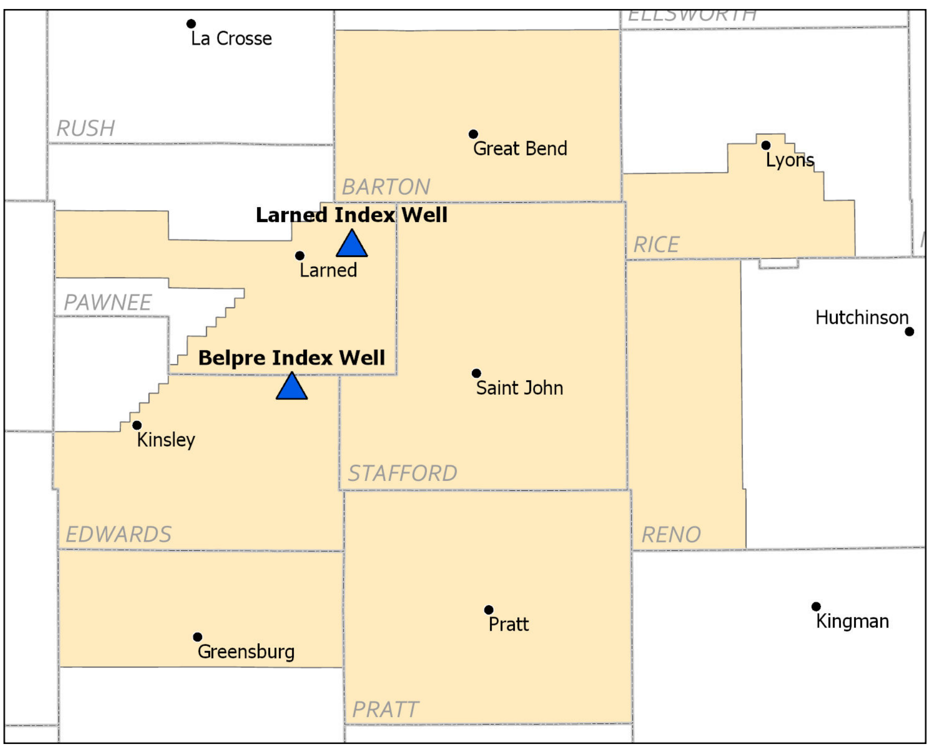


Figure 31—Map of GMD5 with Belpre and Larned index wells (blue triangles). Data from both wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

3.5.1 Belpre Index Well

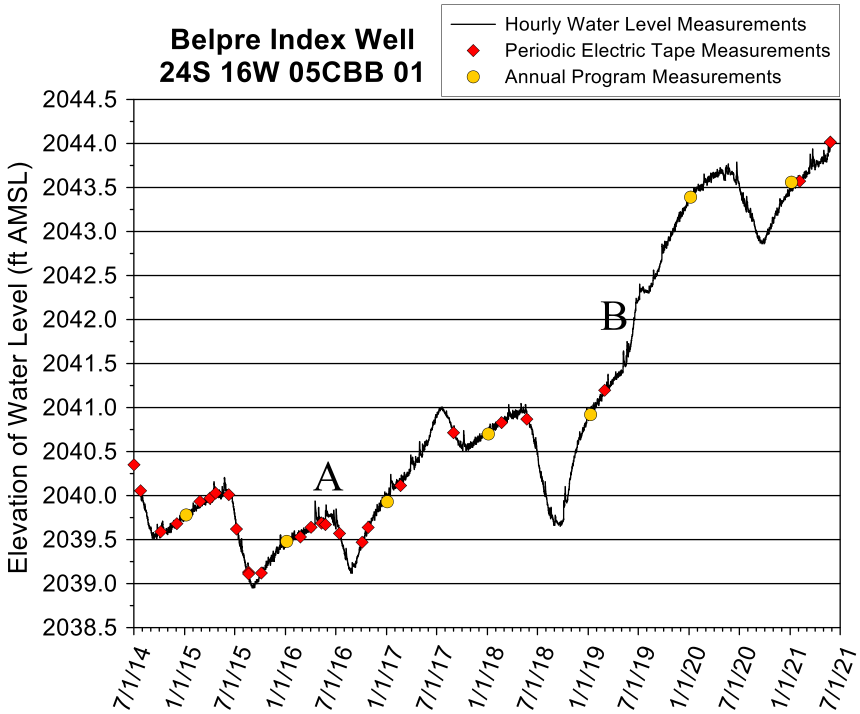


Figure 32—Belpre index well hydrograph—total data run to 5/26/21. A water-level elevation of 2,040 ft corresponds to a depth to water of 40 ft below lsf. The top of the 20 ft screen is 89 ft below lsf (elevation of 1,991 ft), and the bottom of the screen is 109 ft below lsf (elevation of 1,971 ft). The base of the aquifer is estimated to be 175–200 ft below lsf (elevation of 1,905–1,880 ft). A and B defined in text.

Major Points

- Small amplitude fluctuations superimposed on water levels indicate unconfined conditions with a relatively shallow depth to water.
- The effect of individual pumping wells cutting on and off is difficult to discern; the water-level response to pumping appears to be more integrated than at most of the index wells. Given the proximity of nearby pumping wells, this indicates that those wells are extracting water from intervals that are not in good hydraulic connection with the index well, which 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 2019 were the highest for the monitoring period. At the time of this report, the water level is the highest since the start of continuous monitoring.
- The water level has declined 6.77 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

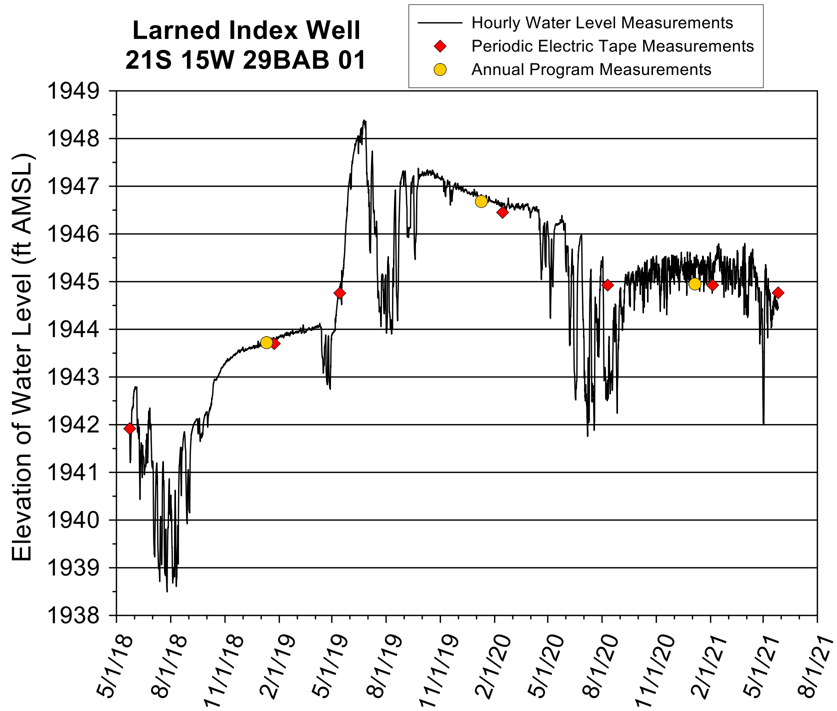


Figure 33—Larned index well hydrograph—total data run to 5/26/21. A water-level elevation of 1,944 ft corresponds to a depth to water of 11.3 ft below lsf. The top of the 5 ft screen is 66 ft below lsf (elevation of 1,889.3 ft), and the bottom of the screen, which is at the base of the aquifer, is 71 ft below lsf (elevation of 1,884.3 ft).

Major Points

- Hydrograph form and small amplitude fluctuations superimposed on water levels indicate confined conditions.
- 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 irrigation season.
- Transducer readings are in reasonable agreement with manual measurements, but transducer noise has significantly increased over the last 12 months for reasons that are not clear.

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. 34). 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. A barometer has been placed a short distance below lsf at expansion well 3. More information about these 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).

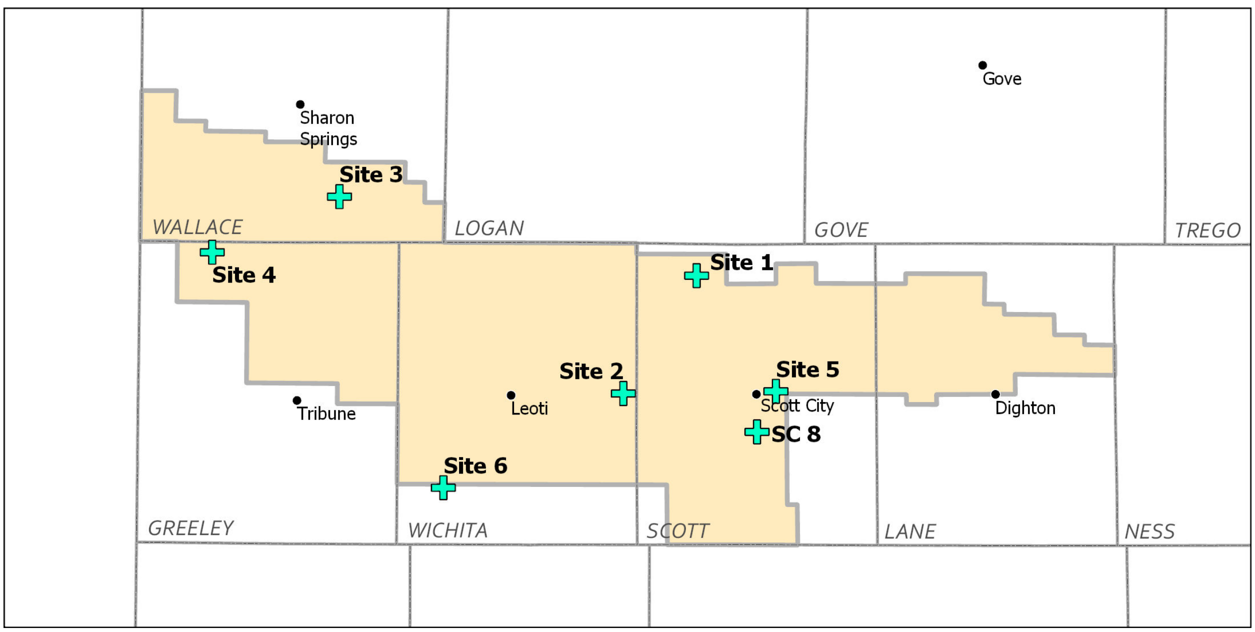


Figure 34—Map of GMD1 expansion wells.

Table 6—Characteristics of the GMD1 expansion well sites.

Site	2021 WL elev. (ft)[a]	2021 saturated thickness (ft)[b]	Bedrock depth (estimated ft below land surface)[b]	Screened interval (ft below land surface)	2019 water use (ac-ft)		
					1 mi radius	2 mi radius	5 mi radius
SC-8	2,848.5[a]	85.5	174	[c]	469	1,298	7,634[d]
Site 1	2,929.3[a]	26.3	195	[c]	439[e]	1,044[e]	3,438[e]
Site 2	3,053.1[f]	42.1	160	[c]	0	167	2,368[g]
Site 3	3,425.1[a]	22.1	220	[c]	78	936	8,356[h]
Site 4	NA[i]	[j]	[j]	[c]	413	1,936	5,225[k]
Site 5	2,845.3[l]	27.3	158	[c]	343[m]	2,122[n]	8,348[o]
Site 6	NA[i]	NA[i]	184	[c]	0	266[p]	1,030[q]

[a] 2021 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 906 ac-ft of municipal water, 3 ac-ft of industrial water, 5 ac-ft of domestic water, and 287 ac-ft of non-irrigation stock water.

[e] Includes 70 ac-ft, 154 ac-ft, and 300 ac-ft of non-irrigation stock water for 1 mi, 2 mi, and 5 mi circles, respectively.

[f] Annual measurement on 1/5/21 likely in error; 2021 water-level measurements from average of transducer measurements from 8 a.m. to 4 p.m. on that day.

[g] Includes 104 ac-ft of non-irrigation stock water.

[h] Includes 17 ac-ft of municipal water and 41 ac-ft of non-irrigation stock water.

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

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

[k] Includes 554 ac-ft of non-irrigation stock water.

[l] Not an annually measured index well; 2021 water-level measurements from average of transducer measurements from 8 a.m. to 4 p.m. on that day, 1/5/21.

[m] Includes 24 ac-ft of non-irrigation stock water.

[n] Includes 435 ac-ft of municipal water, 3 ac-ft of industrial water, 5 ac-ft of domestic water, and 24 ac-ft of non-irrigation stock water.

[o] Includes 3 ac-ft of industrial water, 906 ac-ft of municipal water, 5 ac-ft of domestic water, and 134 ac-ft of non-irrigation stock water.

[p] Includes 246 ac-ft of non-irrigation stock water.

[q] Includes 388 ac-ft of non-irrigation stock water.

3.6.1.1 SC-8 Site – Scott County

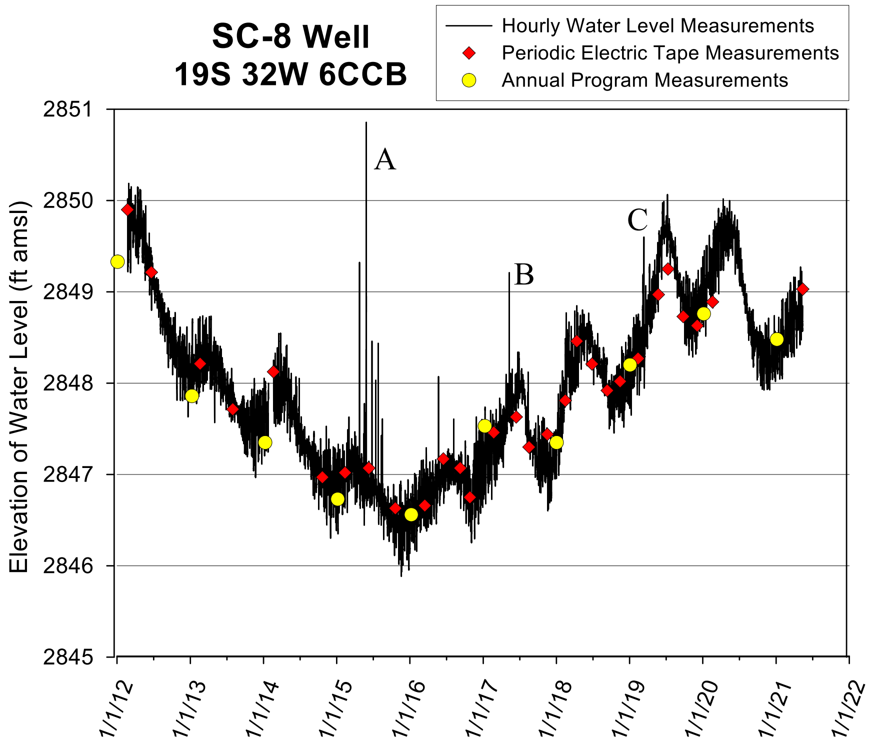


Figure 35—SC-8 well hydrograph—total data run to 5/13/21. A water-level elevation of 2,847 ft corresponds to a depth to water of 89 ft below lsf. Bottom of well is approximately 102 ft below lsf (elevation of 2,834 ft). Transducer measurements have been corrected from earlier reports for an incorrect 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. A-C 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 casing; the added water is then dissipated quickly through lateral flow to the aquifer (Butler, Whittemore et al., 2017). On August 15, 2017, (B), GMD1 staff sealed openings in the side of the casing at the land surface; no large spikes that can be attributed to runoff flowing down the well have been recorded since that time. 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

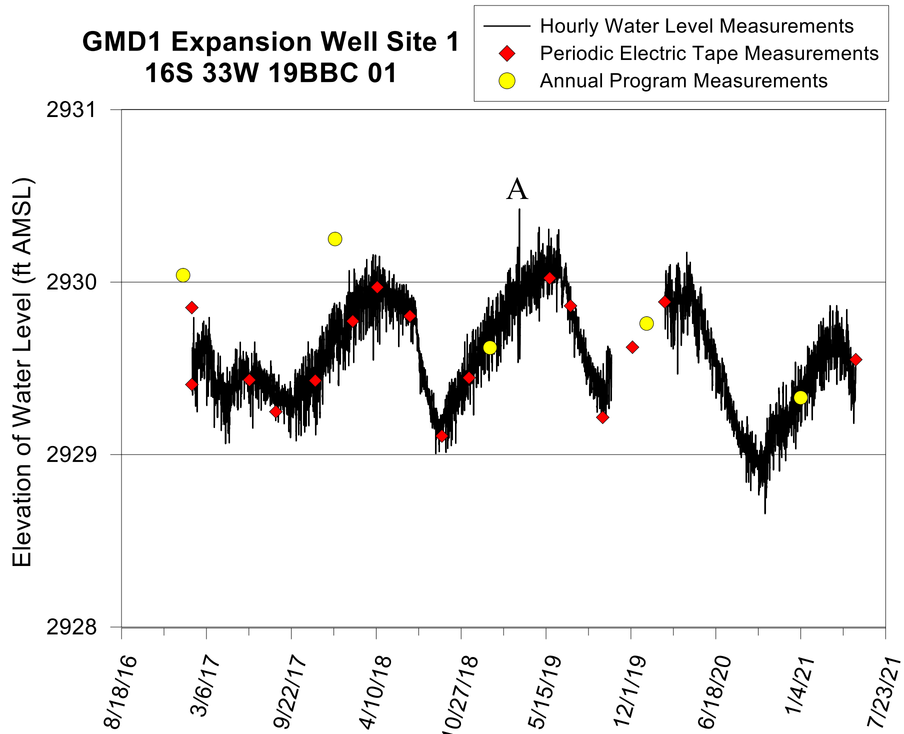


Figure 36—GMD1 Expansion Site 1 well hydrograph—total data run to 5/13/21. A water-level elevation of 2,930 ft corresponds to a depth to water of 168 ft below lsf. Bottom of well is 193.2 ft below lsf (elevation of 2,904.8 ft).

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 for 2020 was the lowest during the monitoring period.
- The water level spike on March 13, 2019, (A) was produced by a bomb cyclone (Butler, Knobbe et al., 2021).
- Transducer readings are in good agreement with electric-tape measurements after commencement of monitoring but not with 2018 annual program measurement.

3.6.1.3 Expansion Site 2 – Wichita County

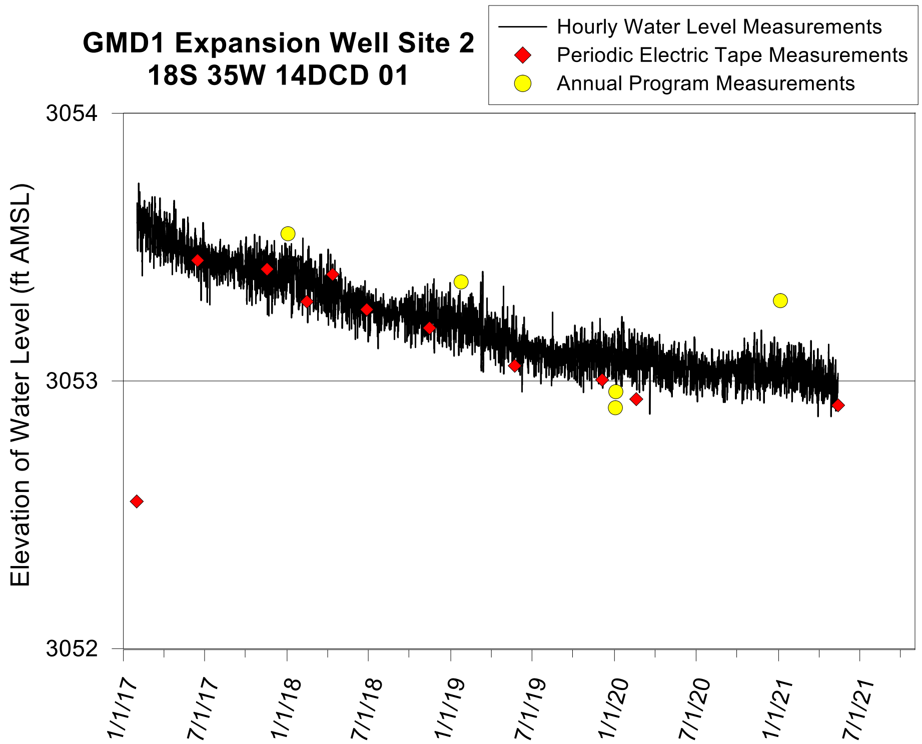


Figure 37—GMD1 Expansion Site 2 well hydrograph—total data run to 5/13/21. A water-level elevation of 3,053 ft corresponds to a depth to water of 118 ft below lsf. Bottom of well is 130.9 ft below lsf (elevation of 3,040.1 ft). First electric-tape measurement may be a transcription error.

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.
- Water level changed 35.6 ft between December 1958 and January 1982 but has only changed about 4.0 ft since January 1982. Water levels declined 1.75 ft between January 2014 and January 2020, but the decline rate has diminished since 2019.
- Transducer readings are generally in reasonable agreement with manual measurements except for the first electric-tape measurement and the last annual program measurement. Except for the last annual measurement, the most recent manual measurements are near the lower boundary of the water-level band (likely a sensor calibration issue).

3.6.1.4 Expansion Site 3 – Wallace County

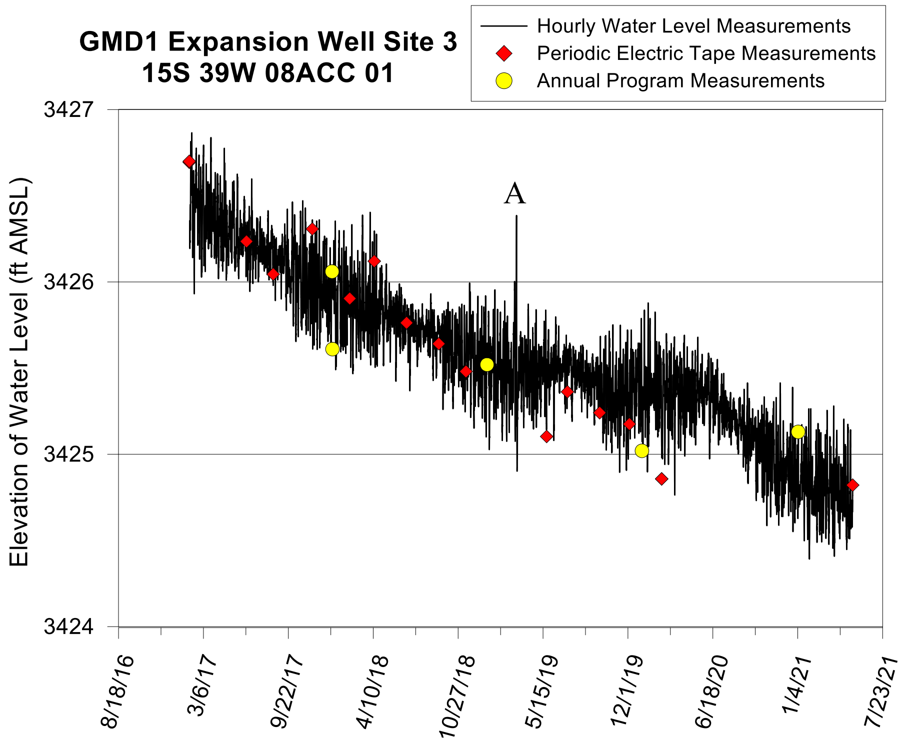


Figure 38—GMD1 Expansion Site 3 well hydrograph—total data run to 5/13/21. A water-level elevation of 3,426 ft corresponds to a depth to water of 197 ft below lsf. Bottom of well is 219.9 ft below lsf (elevation of 3,403.1 ft). A defined in text.

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.
- Water level has declined 77.9 ft since 1964 (1.4 ft/yr) and 7.5 ft since 2011 (0.8 ft/yr). Decline rate diminished in 2019 as a result of the lower level of pumping due to the wet conditions. The decline rate increased in 2020 as a result of more pumping due to the 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.

3.6.1.5 Expansion Site 4 – Greeley County

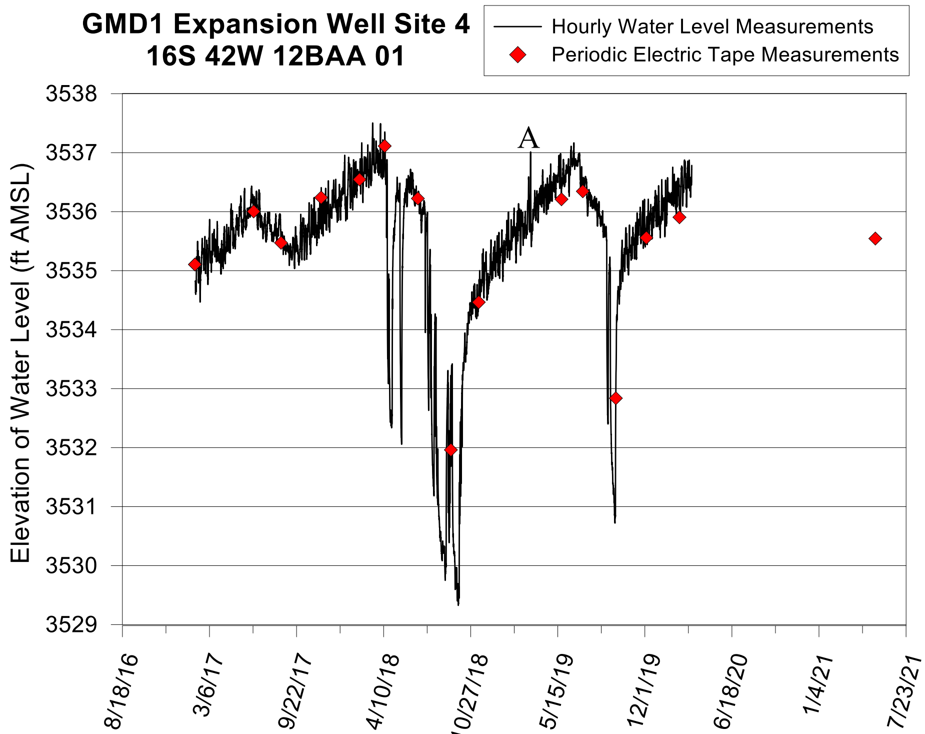


Figure 39—GMD1 Expansion Site 4 well hydrograph—total data run to 5/13/21, hourly measurements until 3/17/20. A water-level elevation of 3,537 ft corresponds to a depth to water of 236 ft below lsf. Bottom of well is 264.5 ft below lsf (elevation of 3,508.5 ft). A defined in text.

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 in 2018 and 2019. 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).
- Transducer readings are in reasonable agreement with manual measurements. The more recent manual measurements are near the lower boundary of the water-level band (likely a sensor calibration issue).
- Sensor 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 will be replaced shortly.

3.6.1.6 Expansion Site 5 – Scott County

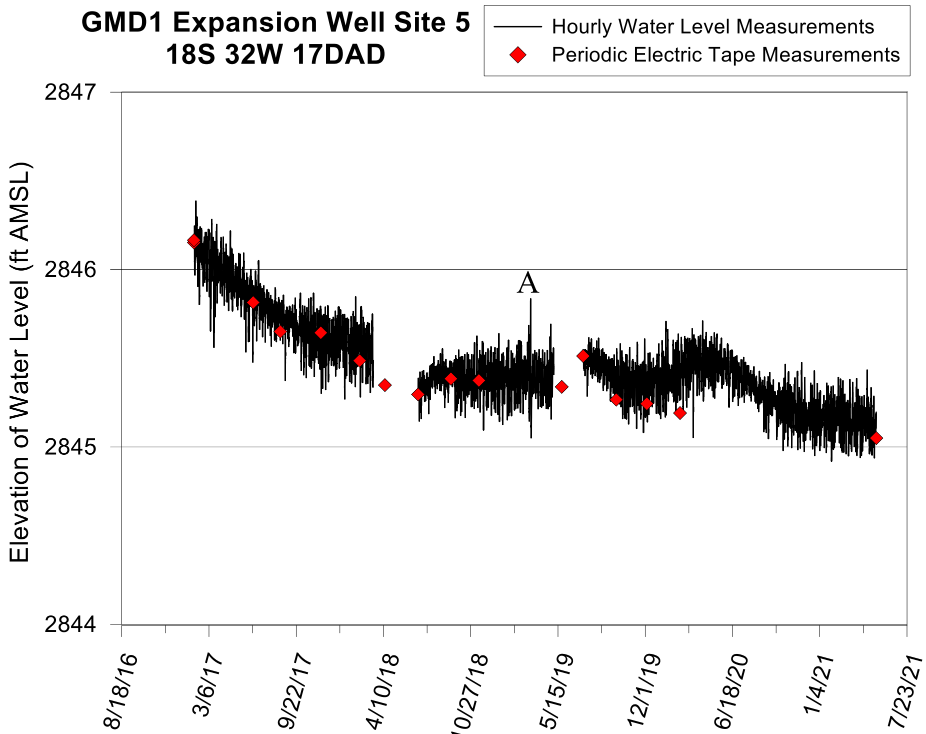


Figure 40—GMD1 Expansion Site 5 well hydrograph—total data run to 5/13/21. A water-level elevation of 2,846 ft corresponds to a depth to water of 130 ft below lsf. Elevation of well bottom is not known. A defined in text.

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 8.5 ft since 2011 (0.9 ft/yr) and 34.8 ft since 1981 (0.9 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 generally in good agreement with manual measurements.

3.6.1.7 Expansion Site 6 – Wichita County

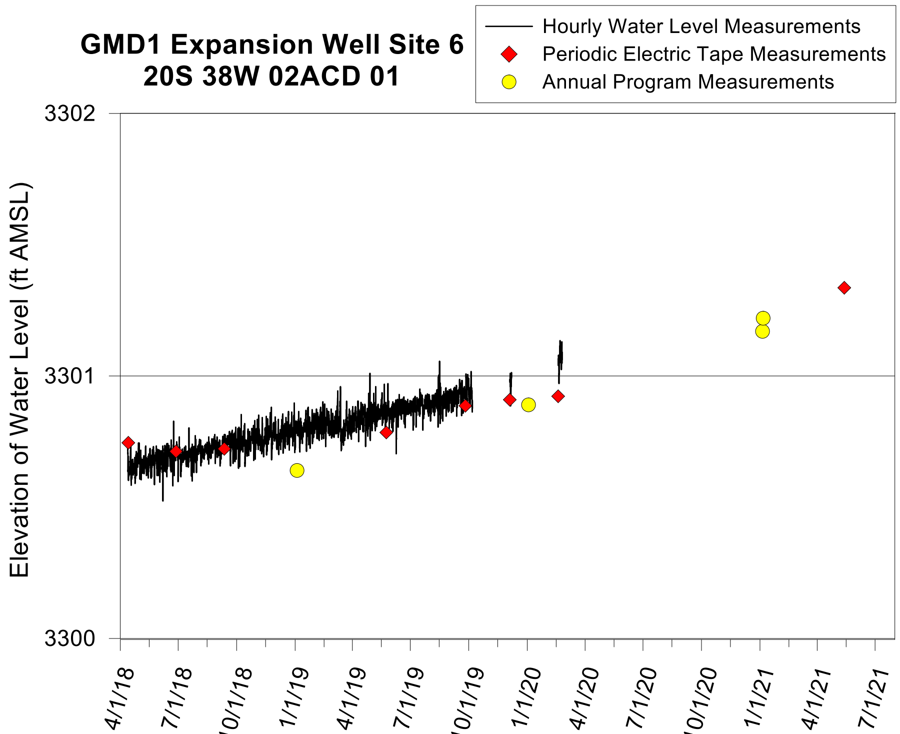


Figure 41—GMD1 Expansion Site 6 well hydrograph—total data run to 5/13/21; continuous hourly measurements ended on 10/6/19. A water-level elevation of 3,301 ft corresponds to a depth to water of 104 ft below lsf. Elevation of well bottom is not known. Bottom of aquifer is at an elevation of 3,221 ft (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. The sensor has been removed from the well, and a decision will be made shortly on whether to continue hourly monitoring at this well.
- 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 2019 water use in 1 mi radius centered on well; smallest 2019 water use for 5 mi radius of any index or expansion well.
- Transducer readings are in relatively good agreement with manual measurements.

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 2020 were 855, 902, and 1,074, respectively. The number of these added after 1997 were 26 (3.1% increase), 17 (1.9% increase), and 0 for these three counties, respectively. Thus, for the last 20+ years, the main driver for water-level changes in the HPA in western Kansas was 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 the Sheridan-6 LEMA, where the crop type and application rate have been altered the last eight 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 42 shows an image of the percent of normal annual precipitation during 2020 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 2020 was substantially less than in the prior several years 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 GMD5 generally had less than normal rainfall (especially GMD4), while most of GMD5 received near normal to somewhat above normal precipitation, although the amount was substantially less than in the last two years.

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 2020 values of this SPI for Kansas climatic divisions 1, 4, 7, and 8, in which are located GMDs 4, 1, 3, and 2 and 5, respectively, are -1.29, -0.77, -0.66, and -0.06, respectively, in comparison to 0.94, 0.47, 0.28, and 1.56 for 2019. 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 2020 climate for the extended irrigation season in GMD4 was dry, for GMDs 1 and 3 was on the dry side of average, and the combined area of GMDs 2 and 5 was close to average. Although this pattern generally fits the appearance of the radar precipitation in fig. 42, radar precipitation data indicate that GMD2 was drier than GMD5.

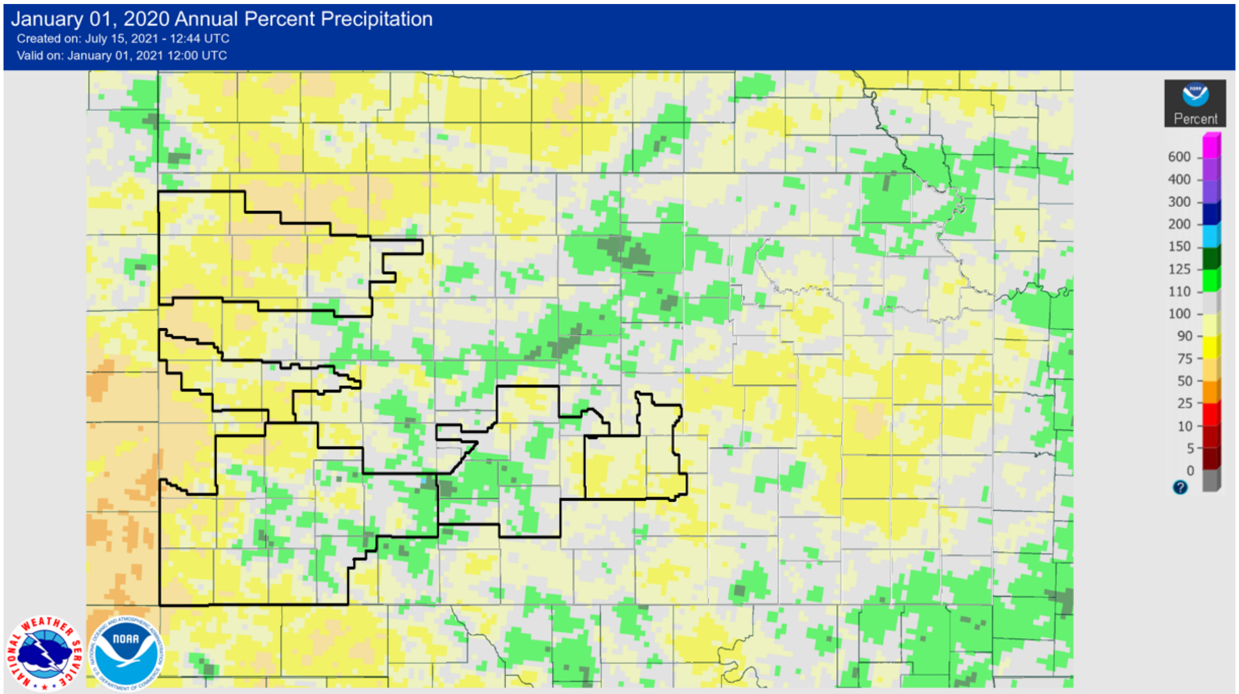


Figure 42—Percent of normal radar precipitation for Kansas in 2020. County lines and the GMD boundaries (bolded) are displayed.

4.4 Water-Level Change in the Groundwater Management Districts

Figure 43 displays the mean annual year-to-year changes in winter water levels during 2005–2020 for the GMDs involved in the index well program prior to 2019; these values are based on wells for which measurements were made every winter from 2005 to 2021. 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 +3.2 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 these four GMDs generally mimic the variations in radar precipitation (March–October sum), which are also displayed on fig. 43. The annual water-level changes for the four GMDs in 2020 were all moderate declines (< -1 ft) in comparison to GMD2 (not shown) which was -1.7 ft. All of the 2020 changes were negative relative to 2019, which is consistent with the substantial decrease in precipitation from 2019 to 2020. However, the water-level declines in the districts were not as great as for the drought of 2012 in GMDs 4 and 1 and the drought of 2011 in GMDs 3 and 5. The water levels did not decline as much as might be expected in GMDs 1 and 3 given the low 2020 precipitation. Possible reasons for this are the greater soil moisture due to the wetter conditions in 2019 than in the years prior to 2011 and 2012, which resulted in more early soil moisture in 2020 and, thus, less required irrigation in the early spring, and the increasing effect of water conservation in the growing number of LEMAs and WCAs.

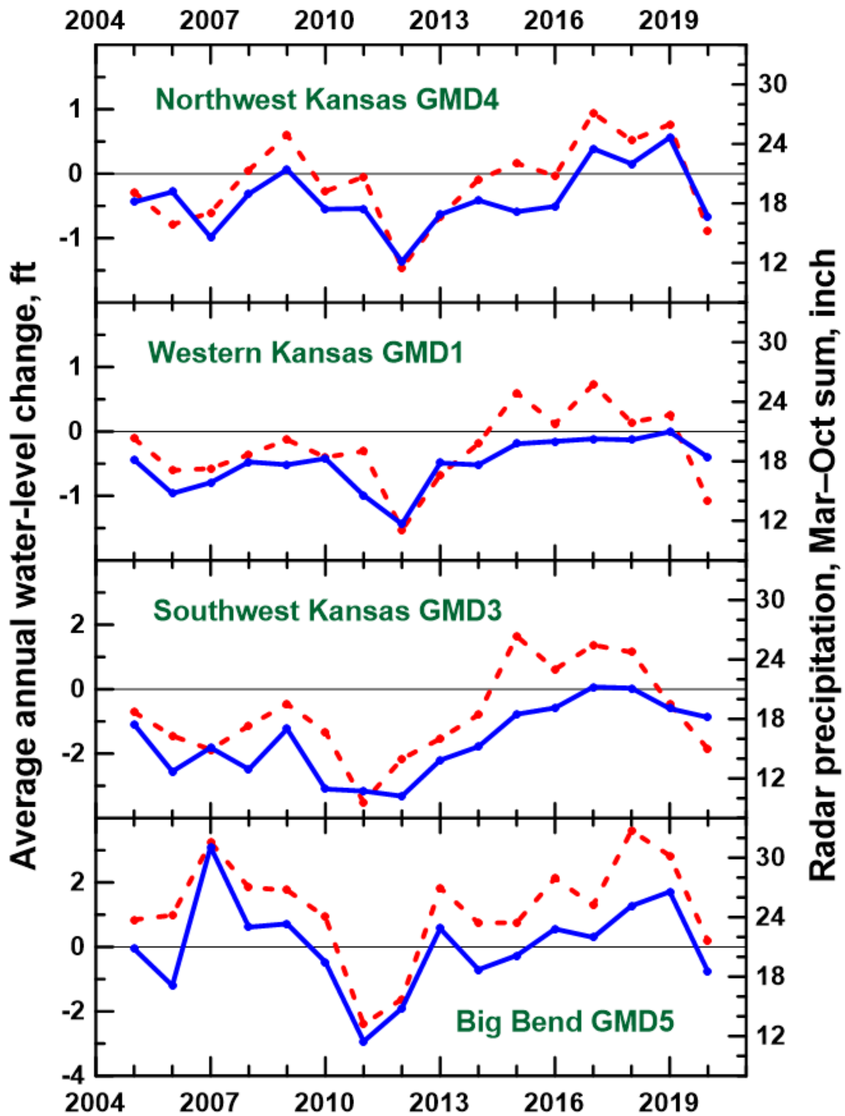


Figure 43—Mean annual water-level change and radar precipitation (sum of March–October precipitation) for GMDs 4, 1, 3, and 5 during 2005–2020. The water-level change for a particular year is the water-level difference between the following year and that year for continuously measured wells for 2005–2021. 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 the upper two plots are half those of the lower two plots. The ranges in the y-axes for radar precipitation are the same for all four 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 44 shows the annual water-level changes for both the tape and transducer values for January 2008–2020 (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. 43). 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 2008–2020 (fig. 44). 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, 2018, and 2019 change in the Thomas 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.

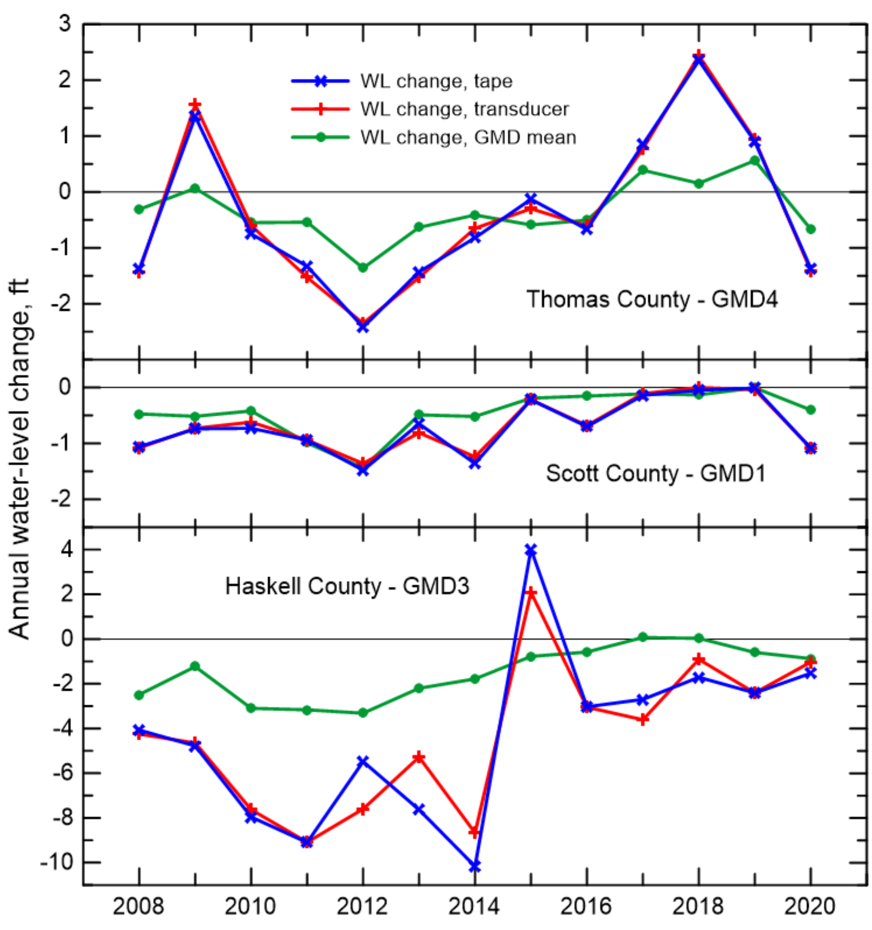


Figure 44—Annual winter (January) water-level changes in the original three index wells and the mean annual changes in the three GMDs in western Kansas in which they are located. Note the different y-axis range for Haskell County versus that for Thomas and Scott counties; suspect 2013 tape measurement 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.

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 were often substantially different from those for that 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 have generally lessened in the Haskell well in comparison to a small increase in declines for GMD3.

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), 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 45 displays the correlation between annual water-level change and annual water use in the vicinity of the Thomas index well for 2008–2019. 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 7.4%, which is lower than the 14.4% for 2008-2017 that omits the hail year of 2018 and the following wet year (2019), and considerably smaller than the 17% for all of GMD4 for 2005–2019. The average annual water use during 2008–2019 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 drainage from the newly formed unsaturated zone.

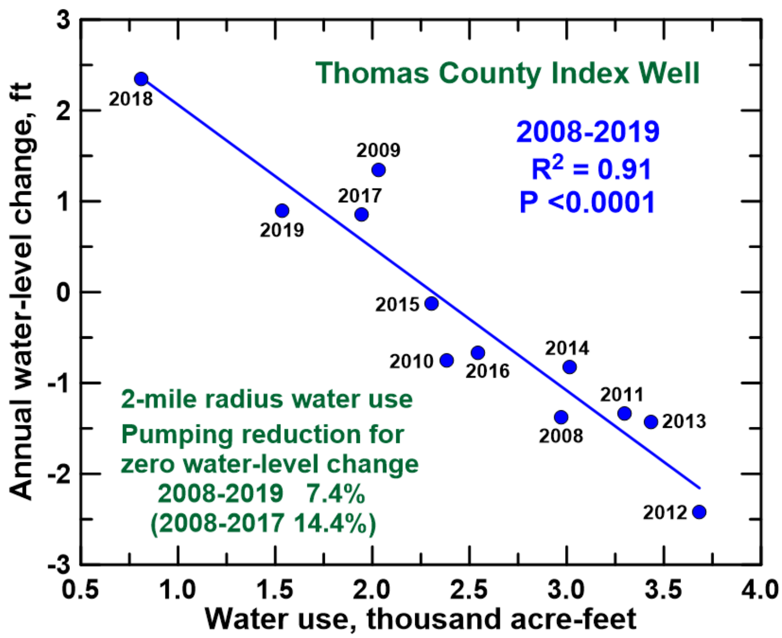


Figure 45—Correlation of annual water-level change based on manual measurements in the Thomas County index well with annual water use within a 2 mi radius around the well during 2008–2019.

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

Figure 46 displays the correlation between annual water-level change and annual water use in the vicinity of the Scott index well for 2008–2019. The pumping reduction for stable water levels is 33%, which is about the same as 34% for all of GMD1 for 2005–2019. The water-level decline in 2019, which was near zero, was the smallest decline for the monitoring period; the water use was also the smallest observed. 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 3.0 in/yr for the 2 mi radius area, which again is substantially greater than the 1.2 in/yr for the entire GMD1 area. As with the Thomas index well, the greater density of water use may have produced a locally depressed water table that induces more lateral groundwater inflow, as well as resulting in more irrigation return flow and drainage from the newly formed unsaturated zone.

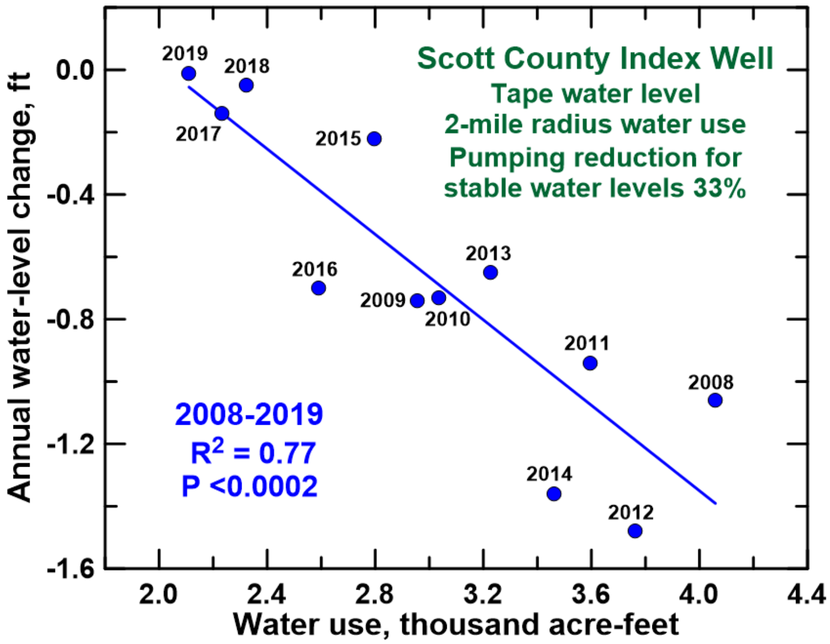


Figure 46—Correlation of annual water-level change based on manual measurements in the Scott County index well with annual water use within a 2 mi radius around the well during 2008–2019.

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

Figure 47 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 2008–2019. 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 2013–2019 (especially during 2015–2019) 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 2013–2019 in comparison to that during 2008–2012 in GMD3 (see fig. 43). The pumping reduction for stable water levels for the average annual water use before the court-ordered pumping shutdowns (2008–2012) is 72% (using the linear regression for 2008–2019 and the average annual water use for 2008–2012), which is much larger than the 24% for all of GMD3 for 2005–2019. The pumping reduction for stable water levels for the average annual water use after the shutdowns (2013–2019) is 55% (again using the linear regression for 2008–2019), which, although much greater than the reduction for all of GMD3, is appreciably less than for the period before the shutdowns. The average annual water-use rates were 14.3 in/yr and 9.0 in/yr for the 2 mi radius area centered on the well during 2008–2012 and 2013–2019, 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 4.8 in/yr for the 2 mi radius area based on the 2008–2019 data, which again is substantially greater than the 3.0 in/yr for all of GMD3. As with the Thomas and Scott index wells, these values indicate that the area of the Haskell well is more heavily pumped than average for GMD3, thereby resulting in a greater net inflow. In this case, the greater density of water use may have induced upward vertical flow from the underlying Dakota aquifer as well as leakage from the thick clay interval overlying the sand unit at the bottom of the HPA in the vicinity of the Haskell well.

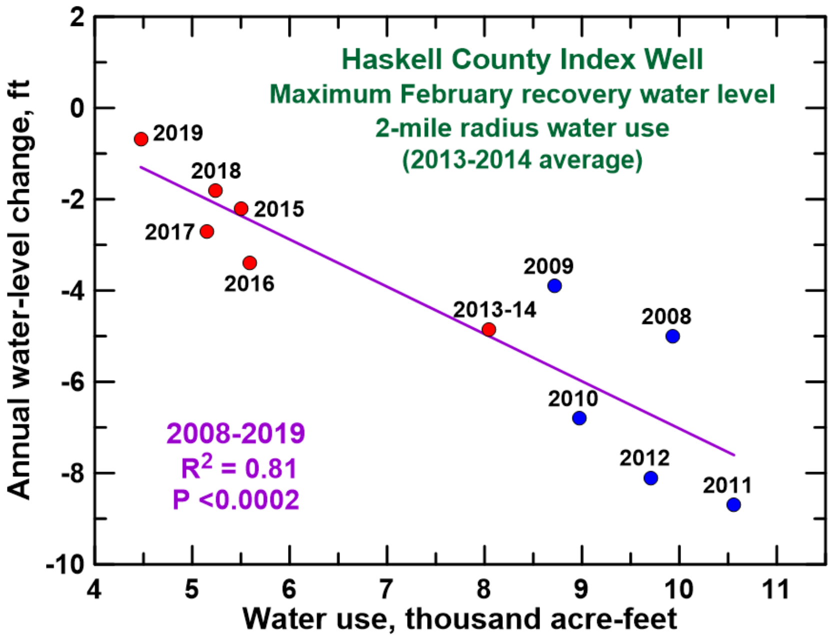


Figure 47—Correlation of change in maximum recovery water level during February based on transducer measurements in the Haskell County index well with annual water use within a 2 mi radius around the well during 2008–2019. Red points designate values after the court-ordered shutdowns (see section 3.3.2); 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. 48). 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 (53%) is the largest of any of the index wells for which relationships have been developed in the GMD4 and GMD1 areas. The average annual water use was 3.1 in/yr for the 1 mi radius area centered on the well, which is less than that in the vicinity of the Thomas index well (3.4 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. 48). 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 (33% 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 (3.0 in/yr for 2 mi radius) but much greater than the 1.2 in/yr for all of GMD1.

The correlation for the water-level change versus water use relationship at the Belpre well is higher for the 2 mi than the 1 mi radius area centered on the well (fig. 48). The percent pumping reduction to attain stable water levels was negative (-1.3%), meaning that that system could have sustained slightly greater pumping for the generally wet period of 2005–2019, and is close to the -1.0% for all of GMD5 for the same period. The smaller pumping reductions 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.

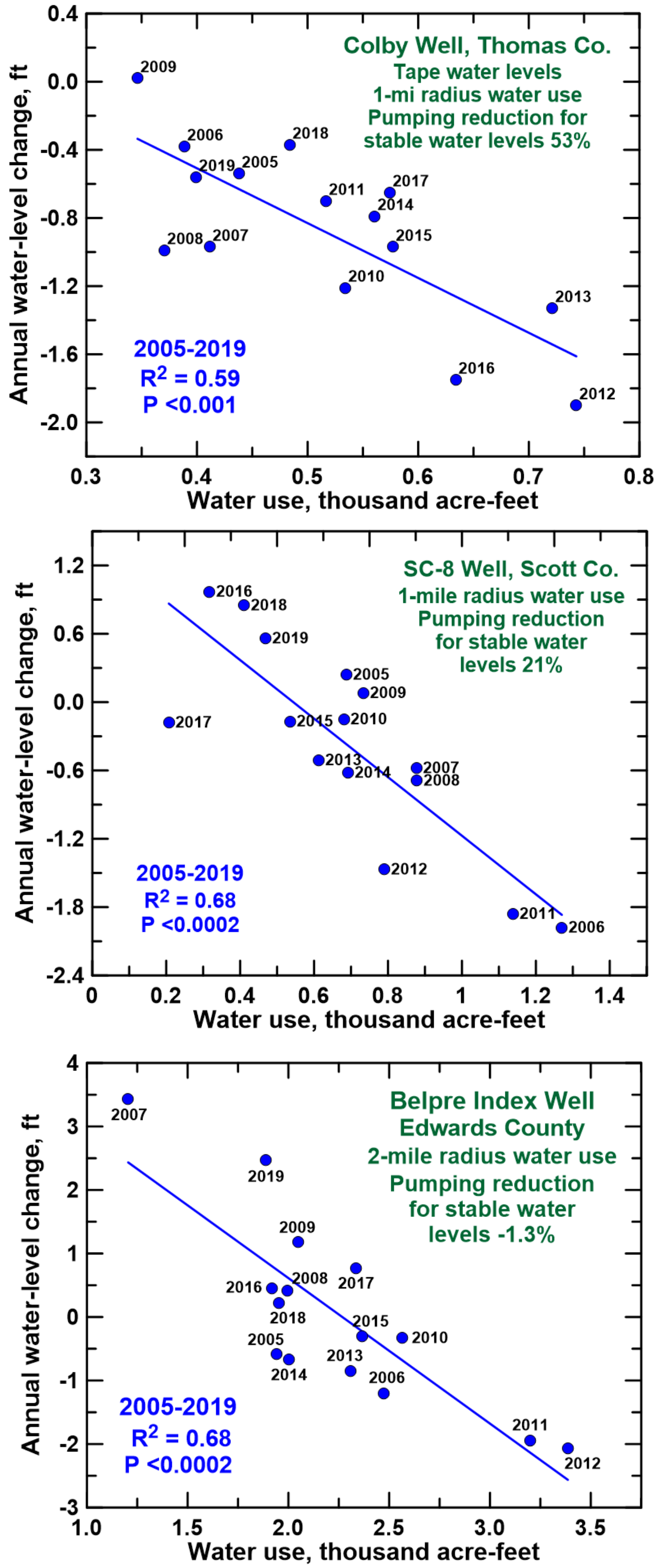


Figure 48—Correlation of annual water-level change in the Colby, SC-8, and Belpre wells with annual water use within a 1 or 2 mi radius around the wells during 2005–2019.

4.6 Relationship of Water Use and Climatic Conditions

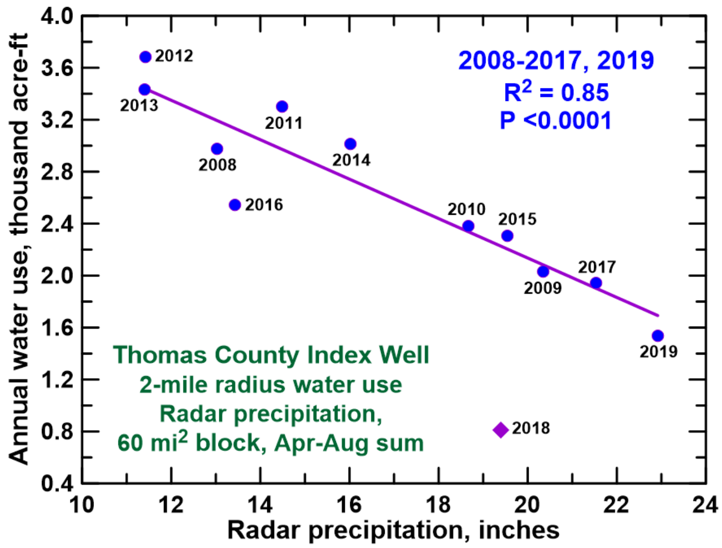
As indicated earlier, climatic conditions have generally had the greatest influence on water-use variations over the last few decades because the irrigated acreage, crop type, and application rate have not changed substantially over the HPA in Kansas. We have found that the sum of the radar precipitation 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 43 includes the variation in radar precipitation versus time since 2005 for the GMDs that were involved in the index well program prior to 2019. 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 around 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 of the wells except a plot for the Haskell well, for which both the 1 mi and 2 mi radii for water use and the 6.6 mi^2 and 60 mi^2 areas for radar precipitation are used. The generally high statistical correlations found for the relationships show that annual water use can usually be predicted relatively well by radar precipitation around the index wells nearly a year before reported water-use data are available for that year.

The monthly precipitation sums that give optimum correlations for the Thomas County and Scott County index wells are April–August and March–September, respectively (fig. 49), which essentially span the main part of the irrigation season. The 2017 precipitation was the greatest during 2008–2019 for both index well locations. 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, 2019 are used for the regression line in fig. 49. 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 was also lower than expected given the precipitation, suggesting that either decreasing aquifer thickness or conservation measures might have been an influence.

Two plots are shown for the water use and radar precipitation relationship for the Haskell index well (fig. 50). The first plot (a) for a 1 mi radius of water use gives the best correlation for the data before the court-ordered shutdown of nearby irrigation wells (see section 3.3.2.); the second plot (b) for a 2 mi radius gives a better correlation for post-shutdown data. The plots show the 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.



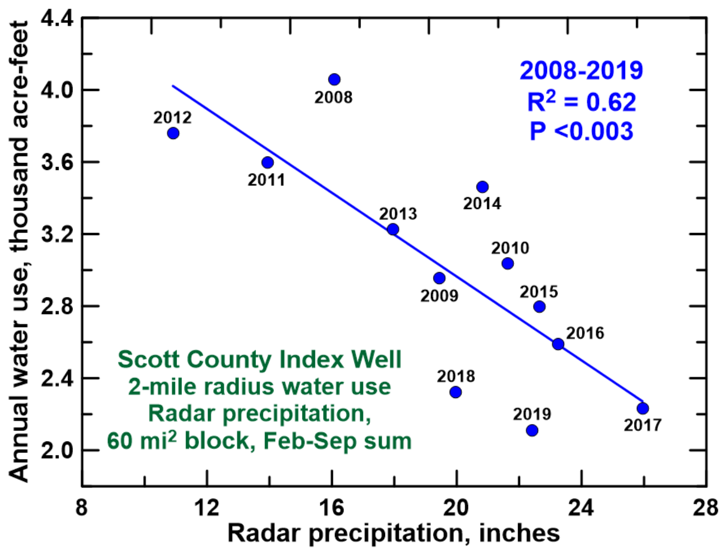


Figure 49—Correlation of annual total groundwater use with radar precipitation at the Thomas and Scott index wells for 2008–2017, 2019 (Thomas) and 2008-2019 (Scott).

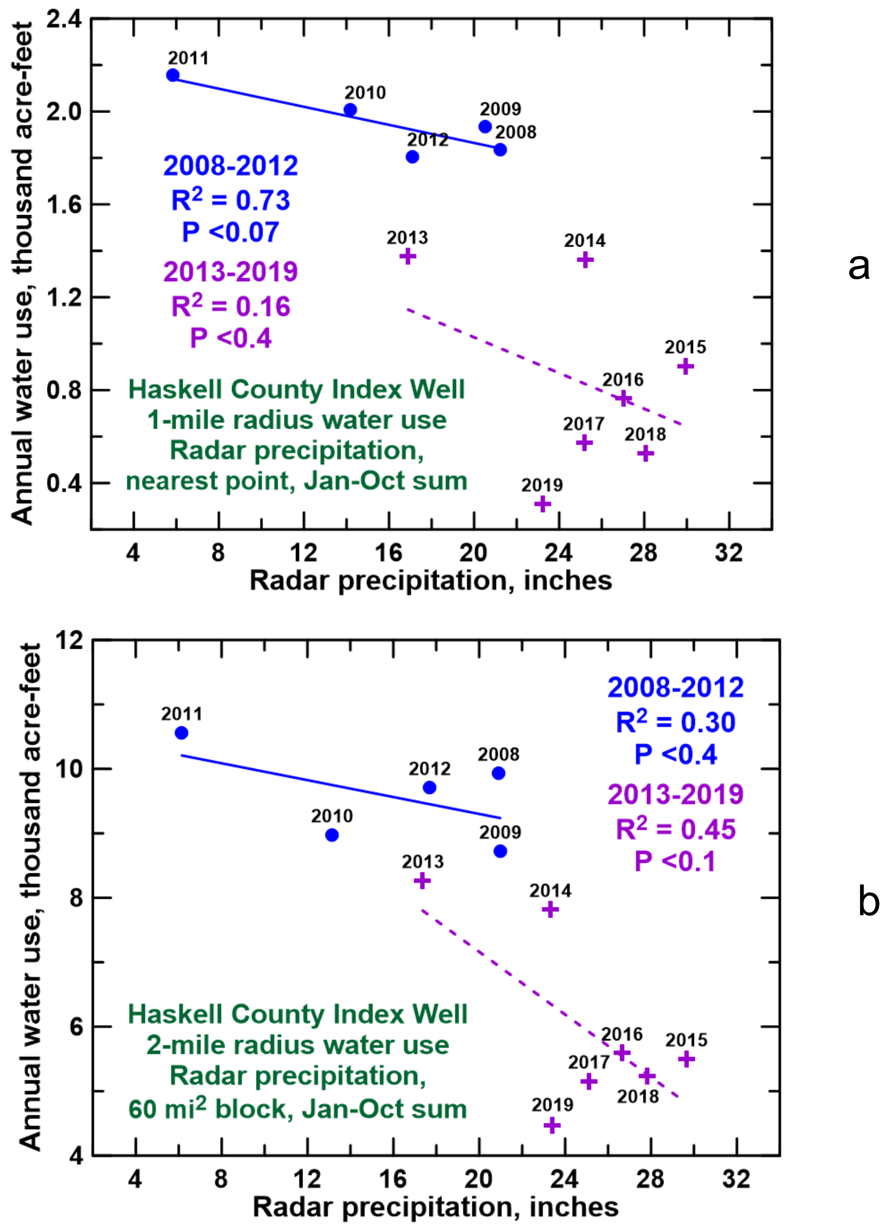


Figure 50—Correlation of annual total groundwater use with radar precipitation at the Haskell index well for 2008–2019 for a) a 1 mi radius and b) a 2 mi radius of water use. The 2008–2012 and 2013–2019 periods represent years before and after a court-ordered shutdown of nearby irrigation well pumping.

Figure 51 shows the correlations between water use and radar precipitation for the three additional wells (Colby, SC-8, and Belpre). The water-use values for 2005–2007 appear to be high for the Colby well (possibly as a result of conversion of rate meters to total flow meters); the correlation is better if only the data for 2008–2019 are used. The month range for the precipitation summation that gives the optimum correlation (March–October) is longer than that for the Thomas County well (April–August). The water use for 2018 and 2019 surrounding the Colby well is anomalously low in comparison with other years given the precipitation. It is unknown at this time whether any storm damage to crops occurred in the area of the Colby well as it did around the Thomas County well to cause the water use to be substantially lower than expected for 2018. The May precipitation around the well was the highest of any month of 2018, although not as anomalously high as for the Thomas County well. Municipal water use contributes appreciably to the total water use in the Colby area. The substantial rainfall during May–July may have been distributed beneficially for crops (and lawn watering) to keep irrigation and municipal water use lower than expected. An alternative possibility for the lower use during 2018 and 2019 than predicted by the regression is conservation measures being implemented since the establishment of the district-wide LEMA in GMD4 in April 2018.

The water-use data for 2005–2007 for the SC-8 well also appear to be high; as for the Colby well, a higher correlation is obtained using the 2008–2019 data. The monthly precipitation range for the SC-8 well optimum correlation is the same as for the Scott County index well. The water use in 2018 and 2019 around the SC-8 well was significantly below the regression line, just as occurred for the Scott County well. Given that the SC-8 and Scott County index wells are relatively near one another, the possibility exists that either decreasing aquifer thickness or conservation measures might have been an influence in 2018 and 2019 for both wells.

The water-use data for the Belpre well during 2005–2007 falls within the band of variation of the 2008–2019 data; thus, the longer time span of 2005–2019 was used in the plot for this well in fig. 51. Just as for the SC-8 well, the optimum month range for precipitation for the Belpre well started in February. This early monthly start may indicate that pre-irrigation, which is typically done in an effort to enhance soil moisture, is important enough to affect the correlation. The precipitation around the Belpre well in 2018 falls above the regression line, in contrast with below for the wells in GMDs 1 and 4, and the point for 2019 is nearly on the line.

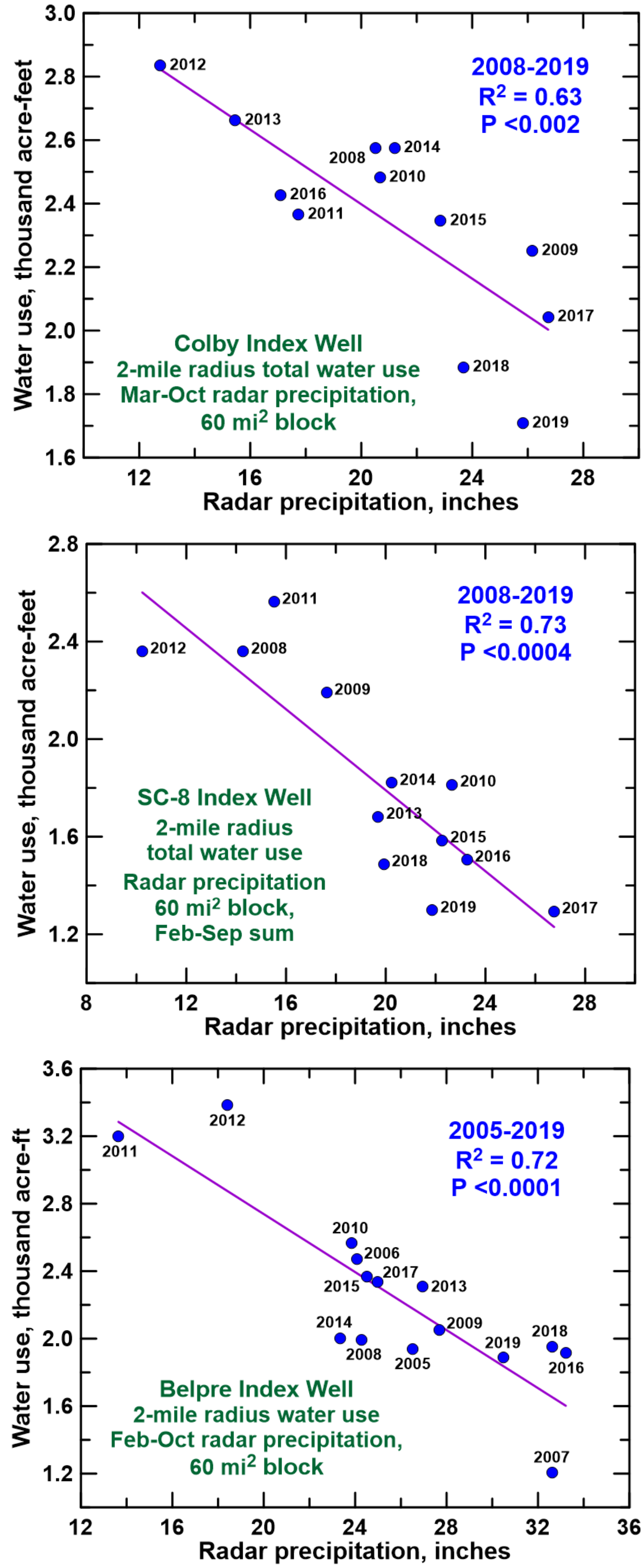


Figure 51—Correlation of annual total groundwater use with radar precipitation at the Colby, SC-8, and Belpre wells for 2008–2019 (Colby and SC-8) and 2005–2019 (Belpre).

4.6.2 Prediction of 2020 Water Use from Radar Precipitation

The availability of water-level data for the index wells is either near real time for wells with telemetry or on a frequency of a few months for wells without telemetry. However, water-use data are typically not available until several months or more after the end of the year. Figures 49–51 indicate that water use can be predicted for most index wells based on the significant correlation with radar precipitation. Thus, these correlations can be used to help understand water-level changes observed in the wells before the water-use data are available. As shown in fig. 43, precipitation was generally much less across the HPA area in 2020 than in 2019 and several prior years. Therefore, as figs. 49–51 indicate, water use is expected to have been greater for the area around index wells where 2020 was drier than during the previous several years. Table 7 lists the water use predicted for 2020 from radar precipitation for a 60 mi^2 block of radar precipitation (nine data pixels) for six index wells, and compares the values to 2019 water use and the range in and average for 2008–2019 water use (data for 2005–2019 were used for the Belpre well in fig. 51 but the comparison in table 7 is shown for 2008–2019 for consistency with the period used for the other wells). For the monthly precipitation sums for which the highest correlations were obtained between water use and radar precipitation (figs. 49–51), 2020 was the year with the lowest precipitation for the Thomas County well, was second lowest for the Scott County and Colby wells, but only the fifth lowest for the Haskell County well and was a little above average for the Belpre well. For 2008–2020, the predicted water use for 2020 would be the second highest for the Thomas County and Colby wells and the fourth highest for the Scott County and SC-8 wells but would be a little less than average for the Belpre well. Although the data generally show the marked contrast between water use predicted during 2020 compared to that observed in wet 2019, they also indicate that local variations in precipitation are expected to produce local variations in water use, which then locally affect groundwater levels.

Table 7—Water use for 2020 within a 2 mi radius for six index wells predicted from radar precipitation based on the linear regressions in figs. 49–51 and compared to 2019 water use and the range and average water use for 2008–2019.

Site	2020 predicted water use (acre-ft)	2019 water use (acre-ft)	2008–2019 water use range (acre-ft)	2008–2019 average water use (acre-ft)
Thomas	3,457[a]	1,536	811[b]–3,683	2,496
Scott	3,485	2,110	2,110–4,059	3,012
Haskell	7,513[c]	4,471	4,471–10,560[d]	7,493
Colby	2,734	1,708	1,708–2,834	2,346
SC-8	2,280	1,298	1,294–2,563	1,830
Belpre	2,238[e]	1,887	1,887–2,386	2,330

[a] Calculated using linear regression for 2008–2017 and 2019 data.

[b] Lowest water use was in 2018 for year with hail storm; next lowest water use was in 2019.

[c] Calculated using 2013–2019 data.

[d] Range calculated for period before and after the court-ordered shutdown of nearby irrigation wells.

[e] Calculated using 2005–2019 data.

5 Summary of 2020 Accomplishments and Plans for 2021

5.1 2020 Accomplishments

- Collected and processed data from the 34 wells currently involved in the index well program. Telemetered data from 21 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 GMD2.
- Installed telemetry equipment at the Steiger index well in GMD4.
- 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 involved in the index well program before 2019.
- 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 interpretation of the index well hydrographs; the paper will be published in the journal Groundwater in the latter part of 2021 and is included as an appendix to this report.

5.2 Planned Activities, 2021

- Continue monitoring and processing water-level data from the 34 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.
- Install sensors and telemetry equipment and initiate monitoring at an existing well in GMD2 and two existing wells in GMD5.
- Continue to seek new wells to add to the network. Areas of particular interest are northern Sherman/southern Cheyenne counties in GMD4 and Grant and Gray counties in GMD3.
- 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.
- Drill and equip a well nest in GMD3 with one well in the HPA and one well in the Dakota aquifer.
- Redevelop and slug test the original three index wells and the Belpre index well.

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7 Appendix

WATER WELL HYDROGRAPHS: AN UNDERUTILIZED RESOURCE

FOR CHARACTERIZING SUBSURFACE CONDITIONS

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Article Impact Statement: We demonstrate the great practical value of information embedded in water-well hydrographs using wells in the High Plains aquifer in Kansas.

Abstract

Many of the world's major aquifers are under severe stress as a result of intensive pumping to support irrigated agriculture and provide drinking water supplies for millions. The question of what the future holds for these aquifers is one of global importance. Without better information about subsurface conditions, it will be difficult to reliably assess an aquifer’s response to management actions and climatic stresses. One important but underutilized source of information is the data from monitoring well networks that provide near-continuous records of water levels through time. Most organizations running these networks are, by necessity, primarily focused on network maintenance. The result is that relatively little attention is given to interpretation of the acquired hydrographs. However, embedded in those hydrographs is valuable information about subsurface conditions and aquifer responses to natural and anthropogenic stresses. We demonstrate the range of insights that can be gleaned from such hydrographs using data from the High Plains aquifer index well network of the Kansas Geological Survey. We show how information about an aquifer’s hydraulic state and lateral extent, the nature of recharge, the hydraulic connection to the aquifer and nearby pumping wells, and the expected response to conservation-based pumping reductions can be extracted from these hydrographs. The value of this information is dependent on accurate water-level measurements; errors in those measurements can make it difficult to fully exploit the insights that water-well hydrographs can provide. We therefore conclude by presenting measures that can help reduce the potential for such errors.

Introduction

Aquifers across the globe are under stress to meet the ever-increasing demand to support irrigated agriculture and provide drinking water for millions (Alley and Alley, 2017). The question of what the future holds for these highly stressed systems is one of global importance. Defining paths forward, however, is fraught with uncertainty. Without better information about subsurface conditions, it will be difficult to reliably assess the aquifer response to management actions, regardless of the impacts of a changing climate (Butler et al., 2020a,b).

One source of data that has not been fully utilized is that from networks of monitoring wells that provide near-continuous records of water levels through time. Most organizations running these networks have to expend most, if not all, of their funding and energy on network maintenance, which is a far from trivial task. The result is that relatively little attention is given to interpretation of the acquired well hydrographs. However, embedded in those hydrographs is valuable information about subsurface conditions and aquifer responses to natural and anthropogenic stresses. That information could significantly enhance the reliability of assessments of future prospects for many systems. Although the value of that information has been recognized for over a century (e.g., Veatch, 1906; Robinson, 1958), it has received relatively little recent attention beyond work on water-level responses to various natural forcings (e.g., Healy and Cook, 2002; Butler et al., 2007; McMillan et al., 2019). The one area in which there has been a considerable amount of recent activity is time series modeling of hydrographs from near-surface aquifers using predefined transform functions (e.g., von Asmuth et al., 2002; Collenteur et al., 2019). Hydrograph interpretation will be an important element of efforts to help clarify appropriate transform functions and inform and extend that modeling process.

The purpose of this paper is to explore the insights that can be gleaned from the interpretation of hydrographs from continuously monitored wells. Previously, we have provided interpretations of hydrographs from wells at three sites in the High Plains aquifer (HPA) in Kansas (Butler et al., 2011, 2013). This paper greatly expands on those earlier analyses in terms of both areal extent and topical coverage. We begin with an overview of the HPA monitoring network of the Kansas Geological Survey (KGS). Following that, we demonstrate how information about an aquifer's hydraulic state and lateral extent, the nature of recharge, the hydraulic connection to the aquifer and nearby pumping wells, and the expected response to conservation-based pumping reductions can be extracted from hydrographs of network wells. We then discuss some of the sources of error in water-level data and present some measures to help reduce the potential for such errors. The paper concludes with a summary of the major findings.

The KGS Index Well Network

The index well network was initiated in the summer of 2007 to enhance understanding of conditions in the HPA in western and south-central Kansas. The network began with the installation of three monitoring wells, each of which had an integrated pressure transducer-datalogger unit (hourly acquisition rate) connected to telemetry equipment that enabled near real-time viewing of water levels on the KGS website. As a result of the insights acquired from the original three wells (Butler et al., 2013), the program expanded into its current state of 20 wells equipped with telemetry and another seven with sensors that are periodically downloaded (Figure 1; Butler et al., 2020c). One of the objectives of the program is to maintain the network for the long term, so most wells are screened at or near the bottom of the aquifer. Sites are visited approximately quarterly for downloading, manual measurements, and equipment maintenance. Vented transducers are used at all sites and a number of sites have barometers to allow assessment of water-level responses to fluctuations in barometric pressure.

Figure 2 is the water-level record from one of the original three wells, the Thomas County index well in northwest Kansas, that displays features that are characteristic of the majority of the network wells. The most prominent of these are a strong seasonal pumping signal, continued water-level recovery until the start of the next pumping season, and a clear water-level response to barometric pressure fluctuations (water-level "band"). In the following section, we show how water level records from this and other network wells can be used to develop insights of considerable practical value.

Interpretation of Water Well Hydrographs

A. <u>Hydraulic conditions</u>

The hydraulic state (confined to unconfined) is a key aquifer characteristic that often may not be known. However, passive monitoring of responses to pumping or natural forcings can clarify the condition in the monitored interval.

Response to pumping: The water-level response to nearby pumping can be a diagnostic indicator of the hydraulic state of the aquifer (in this case, confined versus unconfined). Figure 3a depicts a seven-month period spanning the 2013 irrigation season at the Thomas County index well (dashed ellipsoid in Figure 2). The commencement or cessation of pumping produces a rapid change in water level that quickly transitions to a much more gradual change over time. In an unconsolidated aquifer like the HPA, this behavior, which is most noticeable at the start and end of the irrigation season as in Figure 3a, is simply the hydrograph expression of the two-stage response to pumping observed in unconfined aquifers (Neuman, 1972, 1975). The rapid change in water level occurs during the period when changes are controlled by compressive storage; this is followed by a transition to the period in which changes are controlled by drainable porosity. In contrast, the hydrograph expression of a confined response is much smoother in time (Liberal 436 index well - Figure 3b) as the result of compressive storage being a dominant control on water-level changes at all times in the absence of boundary effects (Theis, 1935; Hantush, 1964). Thus, the hydraulic state of a monitored interval in the HPA can often be recognized through visual inspection of a hydrograph, even when spanning multiple years (Figure 2). The above statements pertain to an unconsolidated formation. In a consolidated formation, a two-phase response similar to Figure 3a could be observed in a double-porosity aquifer where the fractures are the major conduit for flow with the matrix serving as the storage source. Thus, some knowledge of the geology is required for reliable interpretations.

Response to natural forcing: In cases where the pumping-induced response is not clear because of the absence of nearby pumping wells or of a strong hydraulic connection to them, the water-level response to barometric pressure fluctuations will reveal the hydraulic state of the monitored interval (in this case, the full range of confined to unconfined). Although visual inspection of the hydrograph-recorded responses to variations in barometric pressure can often reveal the hydraulic state (e.g., relatively large fluctuations in an unconsolidated aquifer such as in Figure 2), a time- or frequency-domain analysis is required in the general case. The time-domain regression convolution approach yields barometric response functions (BRFs) that have diagnostic forms for unconfined, confined, and semi-confined aquifers (Rasmussen and Crawford, 1997; Spane, 2002; Butler et al., 2011) and can be calculated using public-domain software (e.g., Toll and Rasmussen, 2007; Bohling et al., 2011). Figure 4 shows the BRF responses for the Thomas County and Liberal 436 index wells, which are consistent with the interpretation based on the visual inspection of the pumping-induced responses. The Thomas County BRF is an example of the response in an unconfined aquifer with a deep water table (Weeks, 1979; Spane, 2002); in the case of a shallow water table, there may not be a measureable response to barometric pressure changes or the response can change over time due to varying conditions in the vadose zone (Butler et al., 2011). The Liberal 436 index well is an example of a confined aquifer response in which the BRF stabilizes at larger lags. In a semi-confined setting, the BRF will initially resemble that of a confined system, but then will deviate from it at larger lags (Butler et al., 2011). Frequency-domain methods have been implemented in public-domain software (Schweitzer et al., 2021), but are not fully developed for the general assessment of the hydraulic state of a monitored interval (Rau et al., 2020).

B. Lateral extent

The lateral extent of an aquifer interval is rarely known. Although regional numerical models routinely assume a continuous unit, that often may not be the case. Hydrographs can provide some insight into the lateral extent of the aquifer interval in which the well is screened. Figure 3b depicts a characteristic hydrograph form in a laterally bounded aquifer (the permeable interval in which the pumping and monitoring wells are located is surrounded by units of much lower permeability). The rapid recovery relative to the duration of pumping, the step change across the pumping period, and the stabilization of water levels are diagnostic hydrograph features of a bounded aquifer; Butler et al. (2013) describe the theoretical basis for these features.

A hydrograph in which water levels continue to recover until the start of the next pumping season (Figure 2) can be an indication of a relatively unbounded system. However, it is not necessarily so, as continuing vertical inflow can obscure the bounded hydrograph form of Figure 3b. In that case, the water-level response to pumping can be helpful in clarifying the lateral extent. Linear water level versus time segments during periods of pumping, such as the five-day period marked by A and similar segments in Figure 3b, are an indication that the aquifer is at least partially bounded laterally. However, a longer time interval is needed to establish the extent of the isolation (Butler et al., 2013). Identification of linear intervals in the presence of multiple pumping wells can be difficult because of wells cutting on and off, particularly in the latter stages of the irrigation season. Furthermore, a linear response may be produced by interacting cones of depression, and not the geology. Thus, some knowledge of the area is required for reliable interpretation.

C. Recharge

Recharge is an important component of an aquifer's water budget. However, characterizing the nature of that recharge (i.e. the recharge regime), much less quantifying it, has proven challenging (Healy, 2010). Although episodic recharge (correlated with precipitation and often with large interannual variations) is commonly assumed in regional models, steady recharge (small interannual variations) may often be the rule in aquifers with deep water tables. For example, there are few indications of episodic recharge in the hydrographs from wells in semi-arid western Kansas; in most cases, the hydrographs resemble that in Figure 2 without any of the features that typically would be associated with episodic recharge. Moreover, Butler et al. (2016) use a water-balance approach to show that net inflow (everything flowing into the area minus everything flowing out except pumping) has remained approximately constant in time across the Kansas HPA for close to a quarter of a century. Although recharge is just one component of net inflow, the fact that net inflow changes little from year to year is a strong indication that recharge likely does the same (i.e. steady recharge). Butler et al. (2020c) use the same water-balance approach to show that near-constant net inflow has been observed at the Thomas County index well since monitoring began in 2007. This is not unexpected as a thick vadose zone should act as a low-pass filter on surficial recharge (Stephens, 1996).

In aquifers with deep water tables, episodic recharge should primarily be limited to areas where the recharge has been focused via a variety of mechanisms. That is in the case in western Kansas where episodic recharge has only been observed at sites of focused recharge. The hydrograph from the Steiger index well in northwest Kansas (Figure 5) displays a series of focused episodic recharge events (marked by A-C). The local nature of the recharge events is revealed by the relatively rapid decrease in water level following each peak as water flows laterally to areas that did not receive the vertical recharge. The Steiger well (star in Figure 5 inset) is located near an impoundment behind a small dam over an ephemeral stream channel (circle in Figure 5 inset). The most likely cause of the substantial rises in water level is recharge from the impoundment during the three wetter than normal years from 2017-2019. Aerial photos taken intermittently over the last two decades reveal that the impoundment is typically dry or nearly so. However, the succession of wetter than normal years filled the impoundment and produced a water-level rise at the Steiger well of over 2.2 m; comparison of the substantial rise in water level with area rainfall indicates that the recharge pulse appears to have taken a little over a year to reach the water table. In areas of varied topography, such as northwestern Kansas, where ephemeral stream channels are common, impoundments would likely produce similar focused recharge in wet years. Such impoundments may prove to be one of the only potential avenues for managed aquifer recharge in many semi-arid areas where access to surface water is limited.

Episodic recharge events are commonly observed on hydrographs from wells in areas with relatively shallow depths to water (e.g., Healey and Cook, 2002; Eaton, 2020). For example, recharge events in response to precipitation at different temporal scales are observed in HPA hydrographs in sub-humid south-central Kansas where the water table is much shallower than in areas to the west (average depth to water in northwestern Kansas is over four times that in south-central Kansas [Butler et al., 2016]). The hydrograph from the Belpre index well (Figure 6) illustrates recharge events associated with periods of precipitation ranging from hours to months in duration. The event marked A on Figure 6 and expanded in the inset is an example of the former; a rapid rise in water level in response to rainfall (D) is followed by a recovery (recession) curve (E) as the water is redistributed in the aquifer as described by Healey and Cook (2002) and others (in this case, the well is screened near the center, and not the bottom, of the aquifer). Periods of precipitation lasting weeks (B) and months (C) reveal the recharge response to longer-term events. Water-level responses to wet periods of several months in duration, such as that beginning at C in Figure 6, have been observed in hydrographs across south-central Kansas (e.g., Figure 3 in Butler et al., 2011). As we have shown earlier (Butler et al., 2018), recharge during these infrequent seasonal wet periods plays a critical role in keeping the water levels in the south-central Kansas HPA close to a stable condition. If changing climatic conditions result in a decreasing frequency of such events, the depletion of the aquifer in this area could significantly increase, a situation that is likely true for many other areas as well.

D. <u>Hydraulic connection</u>

The response of water levels to pumping at nearby wells is affected by the nature of the hydraulic connection between the monitored and pumped intervals. At the Thomas County index well (Figures 2 and 3a), the monitored interval appears to be in direct hydraulic connection with the nearby pumped intervals as shown by the two-stage response discussed earlier and the water-level changes associated with cutting on and off nearby irrigation wells (Figure 3a). In contrast, at the Belpre index well (Figure 6), the smooth and relatively small water-level changes during the pumping season indicate that the monitored interval is not in direct hydraulic connection with nearby pumping wells. The small spikes observed during periods of pumping at the Belpre well are all associated with precipitation events, and not the cutting on and off of nearby wells. The average (2014-2017) annual pumping over a circle of 3.22 km (2 mi) in radius centered on the Belpre well was 86% of that for the Thomas well. Thus, despite the density of nearby pumping wells (see photo in Figure 6), the hydrograph indicates that the monitored interval is likely separated from the pumped intervals by units of lower permeability; the Belpre well does appear to be in good hydraulic connection with the monitored interval.

The hydraulic connection between the well and the aquifer can change with time. These changes are typically associated with the buildup of products of biochemical reactions and/or the silting up of the screened interval. Monitoring of water-level responses to barometric pressure fluctuations is a convenient means of identifying when such changes are occurring. The hydrograph from the Sherman County index well in northwest Kansas provides an example of water-level responses to the silting up of the screened interval, which most likely resulted from not developing the well after installation (Figure 7). The inset shows the dampening responses to barometric pressure changes as the upper portions of the screened interval fill with silt and reduce the connection between the well and the aquifer. On December 11, 2017, we discovered that the transducer was being submerged by silt, so we moved it up 0.53 m, producing a six-day period of enhanced water flow into the well. On February 13, 2018, we removed the transducer from the well and found it was completely plugged with silt. We replaced the transducer and positioned it 4.95 m above the original position. Removing and replacing the transducer appeared to disturb the silt column, allowing water to flow in to the well for close to two months. After that, water levels remained nearly stable, with minimal response to barometric pressure changes, for the next seven months. This period included the 2018 pumping season during which the water level gradually declined 13 cm; the typical water-level change during the irrigation season at this well is approximately 10 m. Immediately after the well was thoroughly developed on November 7, 2018, the water-level recovery from the previous pumping season and the fluctuations produced by changes in barometric pressure resumed. Although the near-complete deterioration of the hydraulic connection was apparent from a visual inspection of the hydrograph, smaller changes may not be as easily identified. Thus, in the general case, periodic calculation of the well BRF, or the frequency-domain equivalent, should be used to assess changes in the hydraulic connection and the need for well development. Periodic slug tests are also an effective tool for this purpose, but BRF or frequency-domain calculations are more convenient because identification of deteriorating conditions can be done remotely for wells with telemetry.

E. <u>Response to meteorologic conditions</u>

Water-level responses to large changes in meteorologic conditions, whether they be seasonal variations or extreme events, can provide insights of practical value.

Seasonal variations in barometric pressure: The range over which barometric pressure varies is not constant through the year, as the range in summer is considerably smaller than that in fall and winter in the United States (Herron et al., 1969; Houck et al., 2005). The result is that the magnitude of water-level responses to barometric pressure changes can vary through the year. This seasonal variation is most evident in hydrographs that show little response to pumping, such as that from the Wichita County index well in west-central Kansas (Figure 8). The diminishing water-level fluctuations observed when moving into summer should not be confused with the deterioration of the hydraulic connection between the well and the aquifer.

Hailstorms: A hailstorm can be extremely damaging in agricultural areas as a field can be decimated in a matter of minutes. In areas of groundwater-supported irrigated agriculture, a hailstorm can lead to an abrupt cessation of pumping. In May 2018, a hailstorm hit the fields in the vicinity of the Thomas County index well. The storm ended the pumping season in the immediate vicinity of the well but pumping continued in nearby areas; the 2018 pumping for a circle of 1.6 km (1 mi) centered on the Thomas County index well was 23% of the 2014-2017 average, while the 2018 pumping for a circle of 8.0 km (5 mi) centered on the well was 56% of the 2014-2017 average. The water-level response provides insights into how the aquifer would respond to conservation-based pumping reductions. After the hail-induced cessation of nearby pumping (A on Figure 2), water levels rose at a smaller rate than during the winter recovery period because of pumping continuing in adjacent areas. The pumping in the general area ceased in early October (B on Figure 2), after which the water level rose at a rate similar to that observed during the previous winter recovery. This rise was not produced by enhanced recharge in 2018; it resulted from the steady net inflow to the area. Butler et al. (2020c) have shown (in their Figure 47) that the net inflow in the vicinity of the Thomas County index well during 2018 was approximately the same as each year since monitoring began in 2007. In agricultural areas such as this with deep water tables and a history of near-constant net inflow, the near-term impact of conservation-based pumping reductions should be predictable using the net inflow calculated from the monitoring history (i.e. assuming that the net inflow of the recent past will be the net inflow of the near future). However, what exactly is meant by “near-term” or “near future” has yet to be determined; it could be several years to a few decades or more (Butler et al., 2020b).

Bomb cyclones: A bomb cyclone is a large rapidly deepening extratropical cyclone that typically occurs from autumn to spring in the Northern Hemisphere (Sanders and Gyakum, 1980). The center of the system is at a lower pressure than usual so the movement of the system can cause very rapid and large drops in atmospheric pressure (hence, the term “bomb”). On March 13, 2019, a bomb cyclone formed over Colorado and produced the lowest pressure ever recorded in Colorado (Eagleman, 2021). The storm moved eastward through western Kansas producing a large drop in barometric pressure head across the region. As a result, water levels in wells in the Kansas HPA spiked upward. The * in Figures 2 and 5-9 indicate the upward spikes observed at those wells. The water-level response to a bomb cyclone can be a useful first-order assessment of the hydraulic connection between the well and the aquifer; the lack of a spike or one in the opposite direction than expected would likely be an indication of a poor connection between the well and the aquifer.

F. <u>Measurement error</u>

Gleaning insights into subsurface conditions from water-well hydrographs is dependent on accurate water-level measurements (Rau et al., 2019). Error in those measurements or their timing can make it difficult to fully exploit the information embedded in the hydrographs.

Manual measurement errors: Except in cases of difficult-to-access locations, transducer measurements should not be the sole data source. Sensor performance should be checked with manual measurements on a regular interval, approximately every three months in our case, to ensure the sensor is operating according to specifications. Errors in those manual measurements, however, can make it difficult to assess transducer performance. The Lane County index well in west-central Kansas is measured once a year with a chalked steel tape as part of the annual winter water-level measurement program in the Kansas HPA (Miller et al., 1999), and then more frequently with an electric tape (etape) as part of periodic site visits; the steel tape values are reported to the nearest hundredth of a foot (0.003 m) while the etape values to the nearest millimeter. The well hydrograph (Figure 9) shows that steel tape measurements have proven problematic at this well (average [2017-2020] absolute difference between steel tape and transducer values is 0.238 m). The agreement became much better (2020 deviation < 3 cm) with the assistance of an experienced operator. The etape measurements, which are easier to make and less prone to error in the absence of an experienced operator, are in much better agreement (same etape and same reference point on the casing top used for all measurements).

Transducer drift: Transducers are subject to long-term drift as a result of strain hardening of the diaphragm, bonding deterioration, aging of circuitry, and other factors. The Lane County hydrograph illustrates such a drift; the transducer measurements are below manual measurements in 2016, but then gradually change to be above manual measurements in the second half of 2019 and early 2020 (Figure 9). We see such drift in virtually all of the wells in the HPA network. Transducer manufacturers recommend periodically sending the sensors back for calibration in a controlled setting. Oftentimes, however, an in-field running calibration is a cost-effective means of compensating for the drift if manual measurements are taken carefully.

Plots of water-level change from etape measurements versus water-level change from transducer measurements can characterize the relationship between the manual and transducer measurements for different calibration periods (insets in Figure 9). In the case of the Lane County well, there was a systematic decrease in the slope parameter and a smaller increase in the intercept parameter from 2016 to 2020. This drift can largely be compensated for by applying the calibration equations from the different periods (two of which are shown in the insets in Figure 9) either by periodic adjustments or continuous interpolation (to avoid introducing small steps into the record). A minimum of four to five etape measurements is recommended for each calibration period to reduce errors produced by mismeasurements; the same etape should be used for all measurements at a well.

Impact of solar insolation: Gauge (relative to atmospheric pressure) transducers are commonly used in monitoring networks like that of the KGS. A transducer provides a measurement that is relative to conditions in the chamber behind the pressure-sensitive diaphragm; in the case of a gauge (vented) sensor, the chamber is kept at atmospheric pressure by a small-diameter vent tube that runs the length of the cable. If the cable or the bare vent tube is exposed to direct sunlight, as a result of the setup of the telemetry system, desiccant chamber, etc., then variations in solar insolation can introduce noise (spikes) into the transducer measurements as a result of the heating and cooling of the air in the vent tube producing anomalous back pressures on the pressure-sensitive diaphragm (Cain et al., 2003). The Lane County well (Figure 9) shows a large number of such spikes, particularly during the 2018-19 recovery period; some similar spikes were observed at the Wichita County well (Figure 8). The frequency of spikes at the Lane County well was greatly reduced beginning on May 24, 2019 by attaching loose white fabric to the outside of the exposed section of vent tube. The surface setup at the Lane, Sherman, and Wichita County index wells was recently reconfigured to eliminate the possibility of solar insolation impacting sensor measurements; the original setup at the Thomas County, Liberal 436, Steiger, and Belpre index wells did not expose the cable or vent tube to direct sunlight.

Clock drift: The integrated transducer/datalogger units used for water-level measurements have internal clocks that will slowly drift in time. Traditionally, we have reset the internal clock of a unit during quarterly visits if the clock drifted by more than a few minutes. As indicated in the previous paragraph, we have started reconfiguring the surface setup at the well sites. In addition to removing the spikes produced by solar insolation, the new setup enables us to reset the unit clock to a reference clock every 24 hours. We do not adjust the clock for daylight-savings time.

Discussion and Conclusions

The primary purpose of this paper was to demonstrate the range of insights that can be gleaned from hydrographs from long-term monitoring well networks. This work should thus be considered as a follow-up to a long line of earlier contributions that demonstrated and/or emphasized the importance of long-term monitoring to enhance understanding of hydrologic processes (e.g., Fishel, 1956; Alley et al, 2002; Alley and Alley, 2017). Although the examples discussed here were all drawn from the High Plains aquifer in the state of Kansas, the focus was on general principles that should be widely applicable. The ultimate objective was to show that much information of practical importance is embedded in hydrographs from continuously monitored wells (acquisition intervals of several hours or less). This information can be lumped into two general categories: subsurface conditions (outside of the well) and well conditions.

Subsurface conditions: The hydraulic state of a monitored interval can virtually always be ascertained from the water-level response to nearby pumping or to fluctuations in barometric pressure. In some cases, the bounded nature of the monitored interval can be revealed from the form of the hydrograph or the water-level response during extended periods of pumping. Hints about the heterogeneity in the vicinity of the monitored interval can be gleaned from the response to nearby pumping, while insights into the nature of recharge (steady versus episodic) and the near-term response to proposed pumping reductions can be obtained through visual inspection of hydrographs and calculation of net inflow.

Well conditions: The state of the hydraulic connection between the well and the monitored interval can be assessed from the water-level response to nearby pumping or to fluctuations in barometric pressure. Most importantly, the changes in that connection can be monitored over time using the response to variations in barometric pressure. In wells with telemetry capabilities, this monitoring becomes a convenient means of identifying when well development is needed.

The information obtained from individual wells pertains to conditions in the immediate vicinity of those wells. However, more widely applicable insights can be justified when the same information is obtained from multiple wells. For example, in semi-arid western Kansas, only one well (the Steiger index well – Figure 5) of the 19 sites monitored in that region has a hydrograph that displays episodic recharge. Similarly, only three of the 19 sites have hydrographs that indicate confined conditions. Thus, one can conclude that much of the aquifer in that area is under unconfined conditions with relatively steady recharge that has been significantly smoothed by the lengthy transit through the vadose zone.

Although not emphasized here, there is a rich history of estimating subsurface properties from water-level responses to natural forcings (e.g., Jacob, 1940; Bredehoeft, 1967; Hsieh et al., 1987; McMillan et al, 2019). Many of these methods use water-level responses to earth tides, which are an important natural forcing in consolidated formations, but are more difficult to detect in wells in unconsolidated formations. Xue et al. (2013) demonstrate the potential of these methods for monitoring changes in formation conditions over time. However, deterioration of the connection between the well and the monitored interval can introduce significant error into the parameter estimates determined with these methods.

The secondary purpose of this paper was to emphasize that the insights obtained from well hydrographs depend on high-quality water-level data. As shown here, periodic manual measurements are an essential element of a monitoring program; they are used to ensure that the instrumentation is producing reliable data and to perform running in-field calibrations. Although other instrumentation (depth sounders, capacitance sensors, floats, etc.) can be used, the pressure transducer is the primary instrument of choice for water-level monitoring. Each transducer has a defined pressure range over which it can be used. The resolution, repeatability, and accuracy of the device is a function of that range; sub-millimeter resolutions are common but the repeatability and accuracy specifications (often given in the form of a standard error) are typically on the order of several millimeters to a few centimeters for the transducer ranges commonly used in practice. Ideally, the selection of a transducer range would be based on the expected water-level changes at the well, but pragmatic considerations, such as the need to have transducers with ranges that are appropriate for most wells in the network, may lead to larger-than-needed ranges and, as a result, an increased noise level. The noise level can also be a function of the measurement process; some transducer-datalogger units take the average of a series of measurements over a small time window to reduce noise, while others just take one or very few measurements to maximize battery life. As expected, the noise level is smaller when the measurement is averaged over a time window.

We have discussed the insights that can be gleaned from the calculation of net inflow at several points in this paper. However, the results of that calculation may be questionable outside of mature, seasonally pumped aquifers with high-quality water-level and water-use data. In terms of water-level data, measurements taken three or more months after cessation of irrigation pumping are needed, so that the year-to-year variations in the timing of the end of the irrigation season have a minimal impact. In addition, the measurements should be taken at approximately the same time each year. As we and others have learned, water-level data acquired during the pumping season, shortly after the cessation of pumping, or at greatly varying times from year to year can introduce so much noise into the net inflow calculation that the results are of little use. Ideally, as in the Kansas HPA, all non-domestic pumping wells have totalizing flowmeters and the annual pumping volumes are reported each year and subject to regulatory verification. However, we recognize that Kansas is an outlier in this regard, and in earlier papers (Butler et al., 2016, 2018) have emphasized that greater attention should be paid to the acquisition of high-quality pumping data so that deeper insights can be gleaned into an aquifer's future.

Multi-year datasets from a network of continuously monitored wells operating at acquisition intervals of several hours or less are an example of what is now termed "Big Data". Visual inspection and manual exploration of hydrographs are possible when the network is relatively small and resources for such activities are available, but that will not be the general case. Artificial intelligence could play a valuable role in this regard. Although various approaches have been used to identify groups of hydrographs with similar characteristics (e.g., Winter et al., 2000; Giese et al., 2020), the power of hydrograph interpretation has yet to be fully explored. Machine learning approaches could be developed to scan data from monitoring well networks to identify the hydraulic state and lateral extent of the monitored interval, the primary recharge regime, the deterioration of the connection between the well and the formation, and even estimate some subsurface parameters using the principles discussed here. Such approaches could provide valuable information for modeling investigations and begin to narrow the often sizable gap between the model conceptualization and reality.

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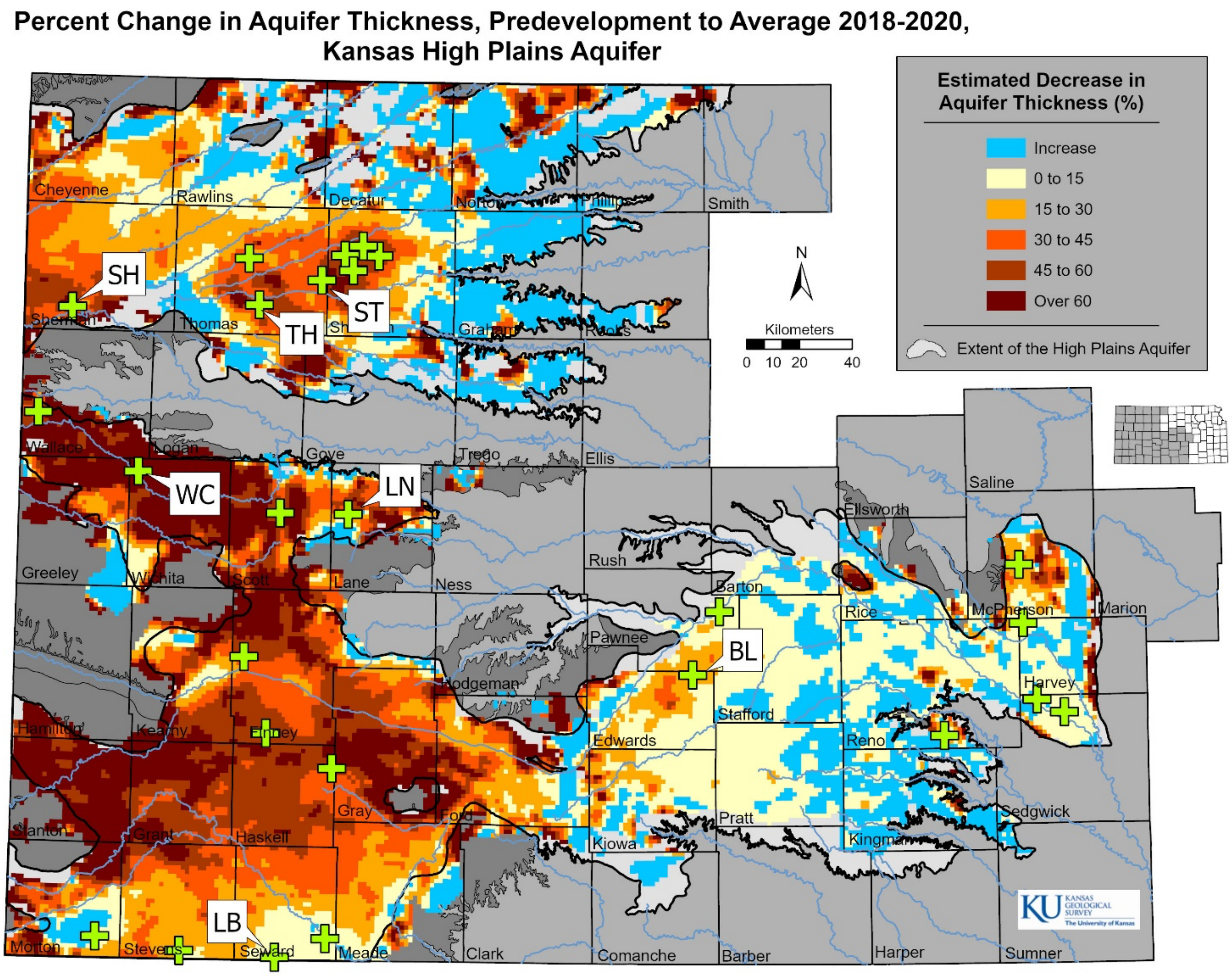

Figure 1 – Map of the percent change in aquifer thickness from predevelopment to present for the High Plains aquifer (HPA) in Kansas (the inset on the right shows the portion of the state pictured here). Wells of the Kansas Geological Survey Index Well Network are indicated with plus signs and those discussed in the paper are labelled (labels defined in text). Predevelopment is defined as period prior to onset of widespread pumping for irrigated agriculture, which occurred between 1940 and the mid-1950s in most of the Kansas HPA; present is defined as average of 2018-2020 winter conditions. The areas of increase in the western third of the figure are areas of thin saturated thickness that are of little practical importance.

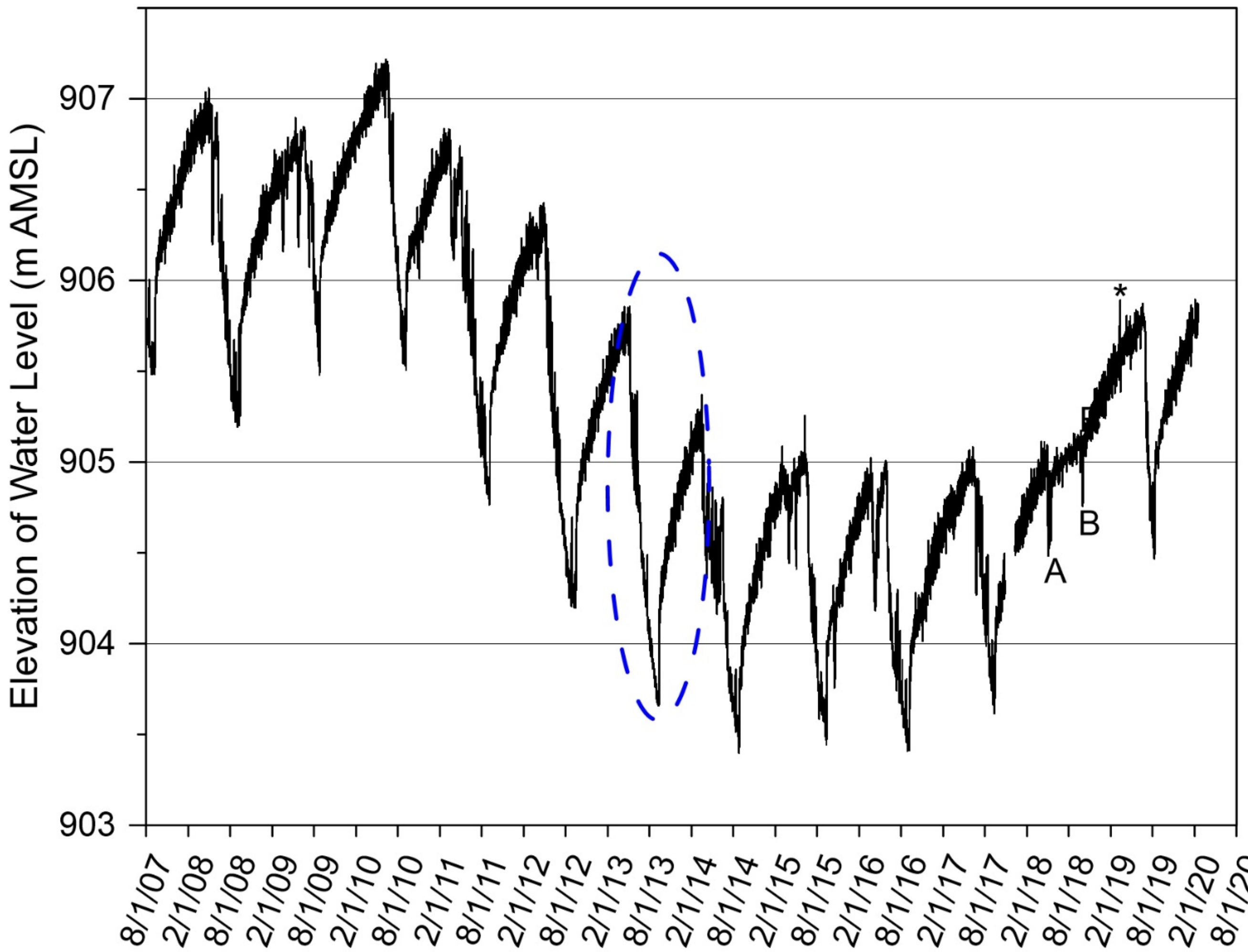

Figure 2 – Elevation of water level versus time for the Thomas County index well in northwest Kansas (TH in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 905 m corresponds to a depth to water below land surface of 66.5 m. The well is screened over 3.05 m at the bottom of the aquifer, which is at an elevation of 885.03 m. Dashed ellipsoid indicates period expanded in Figure 3a; A, B, and * defined in text.

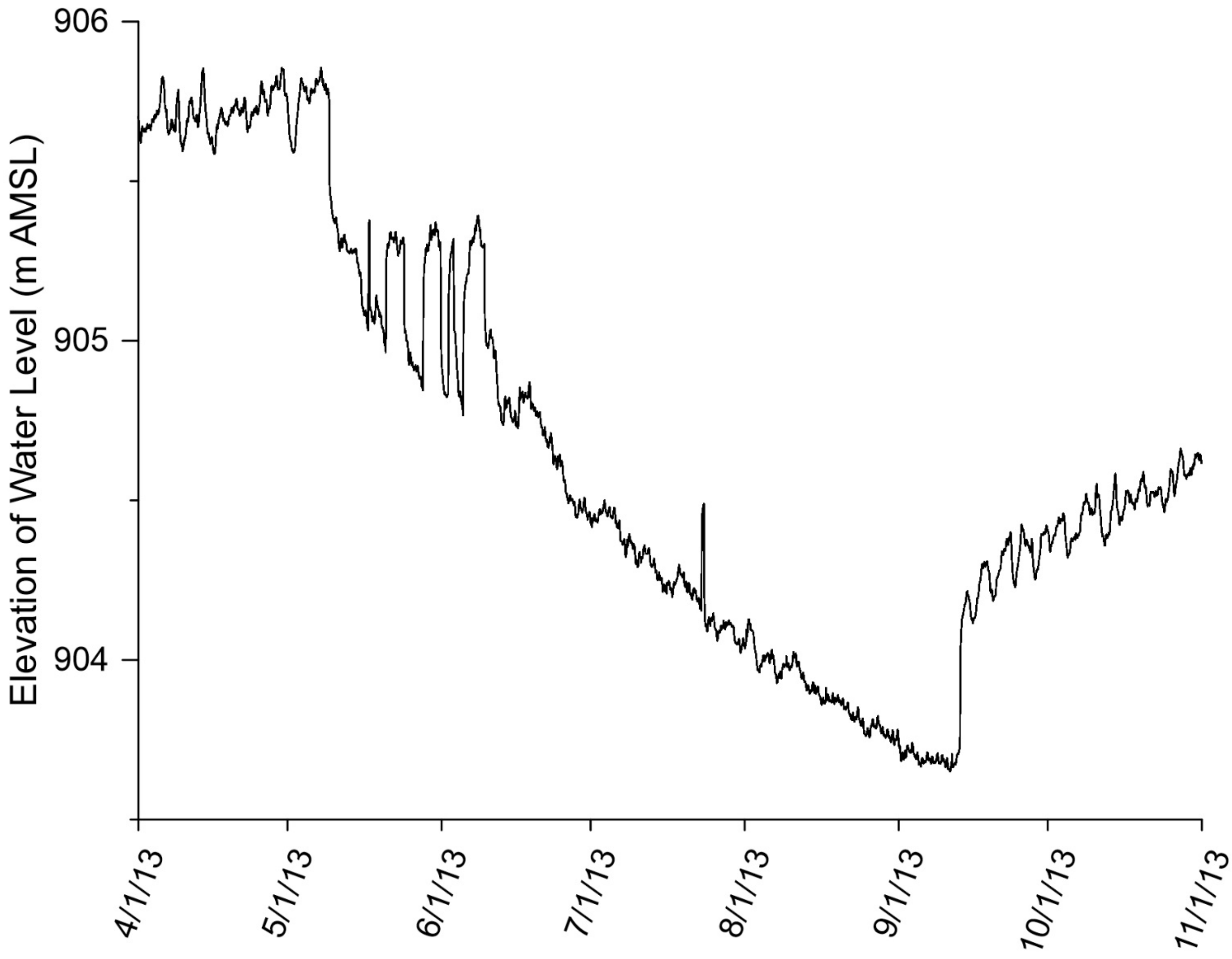

Figure 3a – Expanded view of the 2013 pumping season (marked by dashed ellipsoid in Figure 2) at the Thomas County index well (see Figure 2 caption for further details about well).

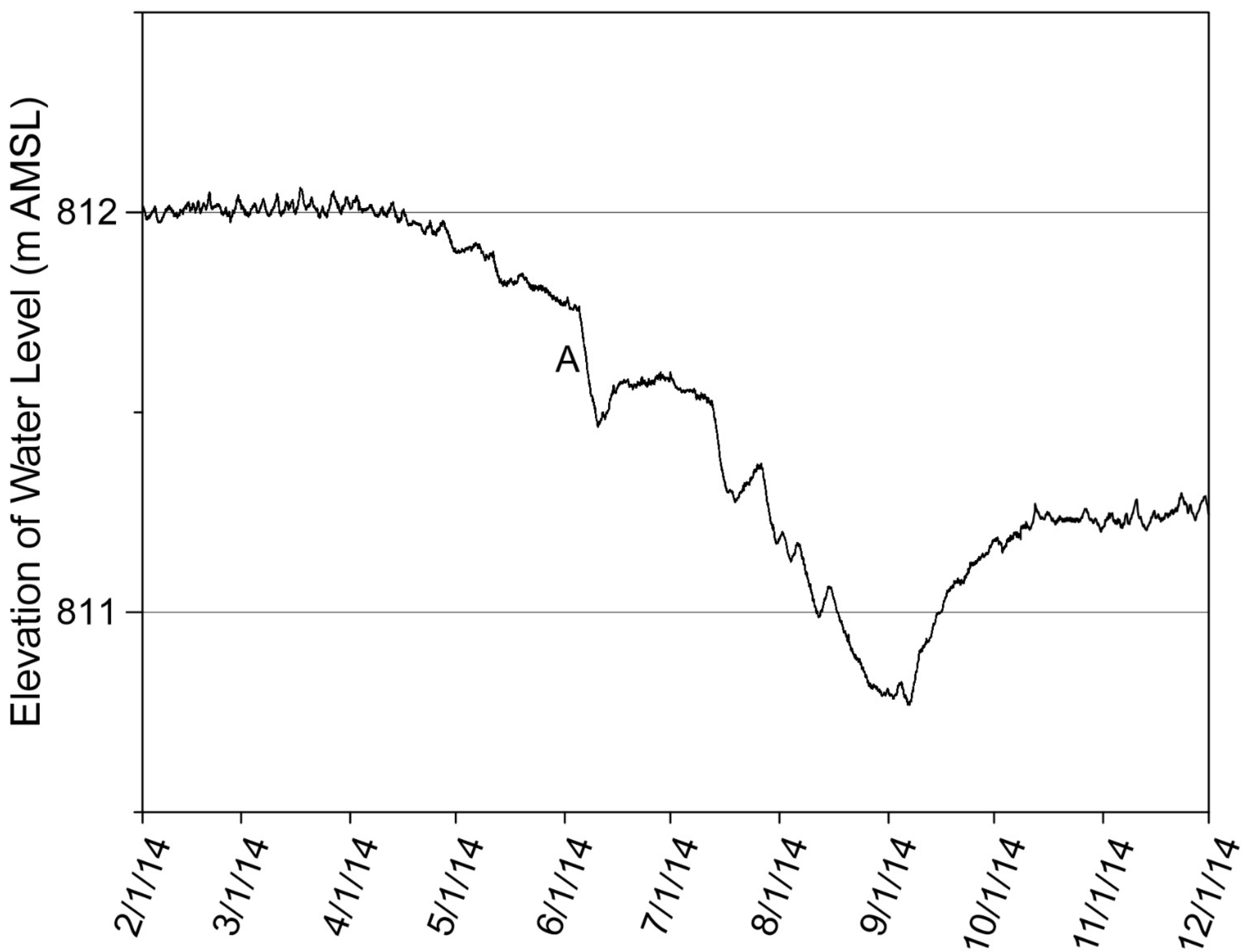

Figure 3b – Elevation of water level versus time for the February through November 2014 period at the Liberal 436 index well in southwest Kansas (LB in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 811 m corresponds to a depth to water below land surface of 48.85 m. The well is screened for 3.05 m with the lower end at an elevation of 726.96 m. The bottom of the aquifer is at an elevation of 684.28 m but the lower portions of the aquifer have higher salinity water of little use for irrigated agriculture; A defined in text.

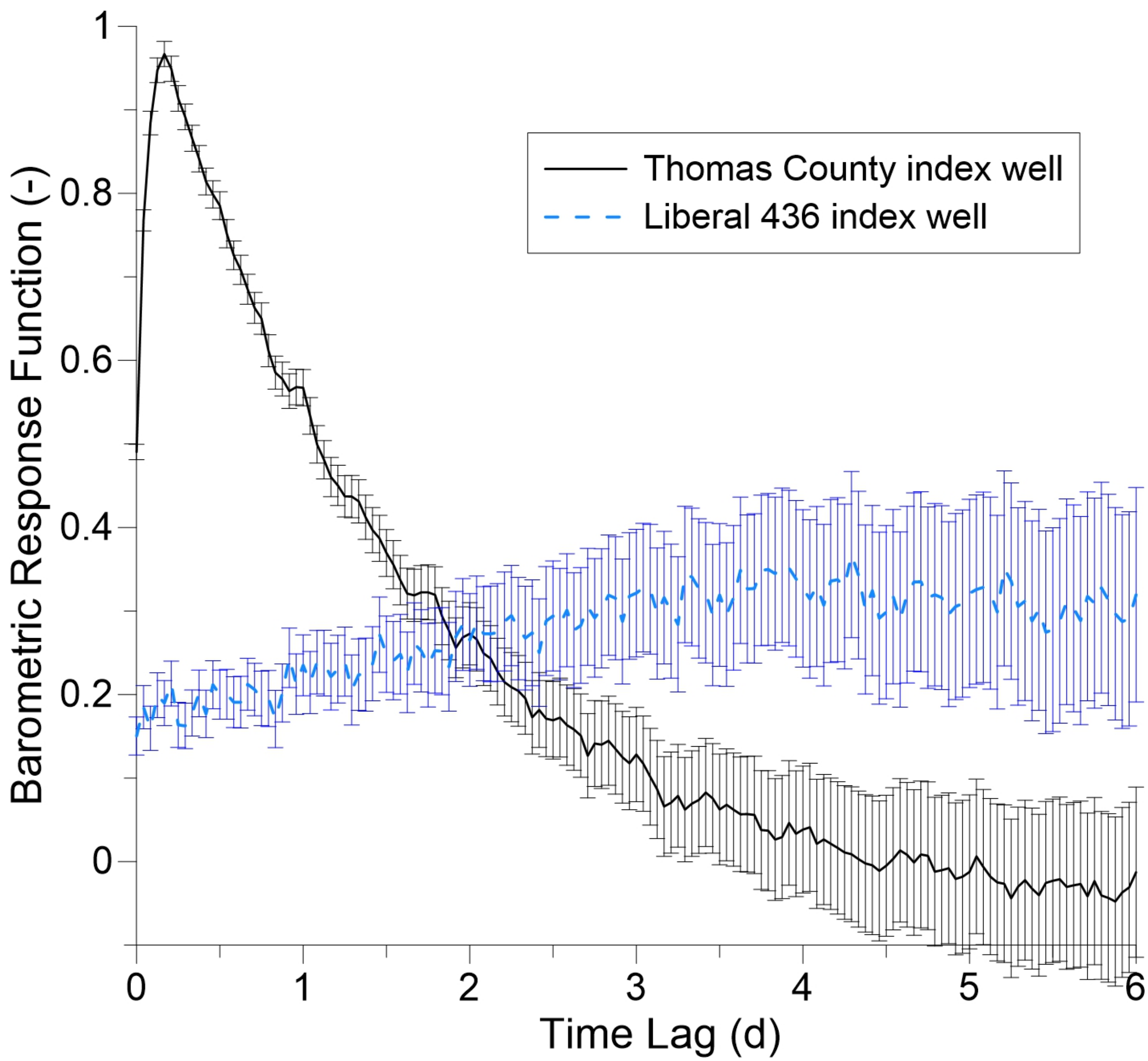

Figure 4 – Six-day barometric response functions (BRFs) for Thomas County and Liberal 436 index wells. Period of analysis is Oct. 30, 2019 to Dec. 30, 2019 for Thomas County well and Dec. 7, 2013 to Jan. 6, 2014 for Liberal well. Given these and analyses of other periods, the BRFs for both wells appear to have changed little from the onset of monitoring (2007 and 2012 for Thomas and Liberal wells, respectively) to present. Error bars indicate one standard error about the estimated functions; linear trend removed from data series prior to BRF calculation. A BRF characterizes the water-level response to a step change in barometric pressure; the time lag is the time since the imposition of that change. The BRFs and their error bars were calculated using Bohling et al. (2011).

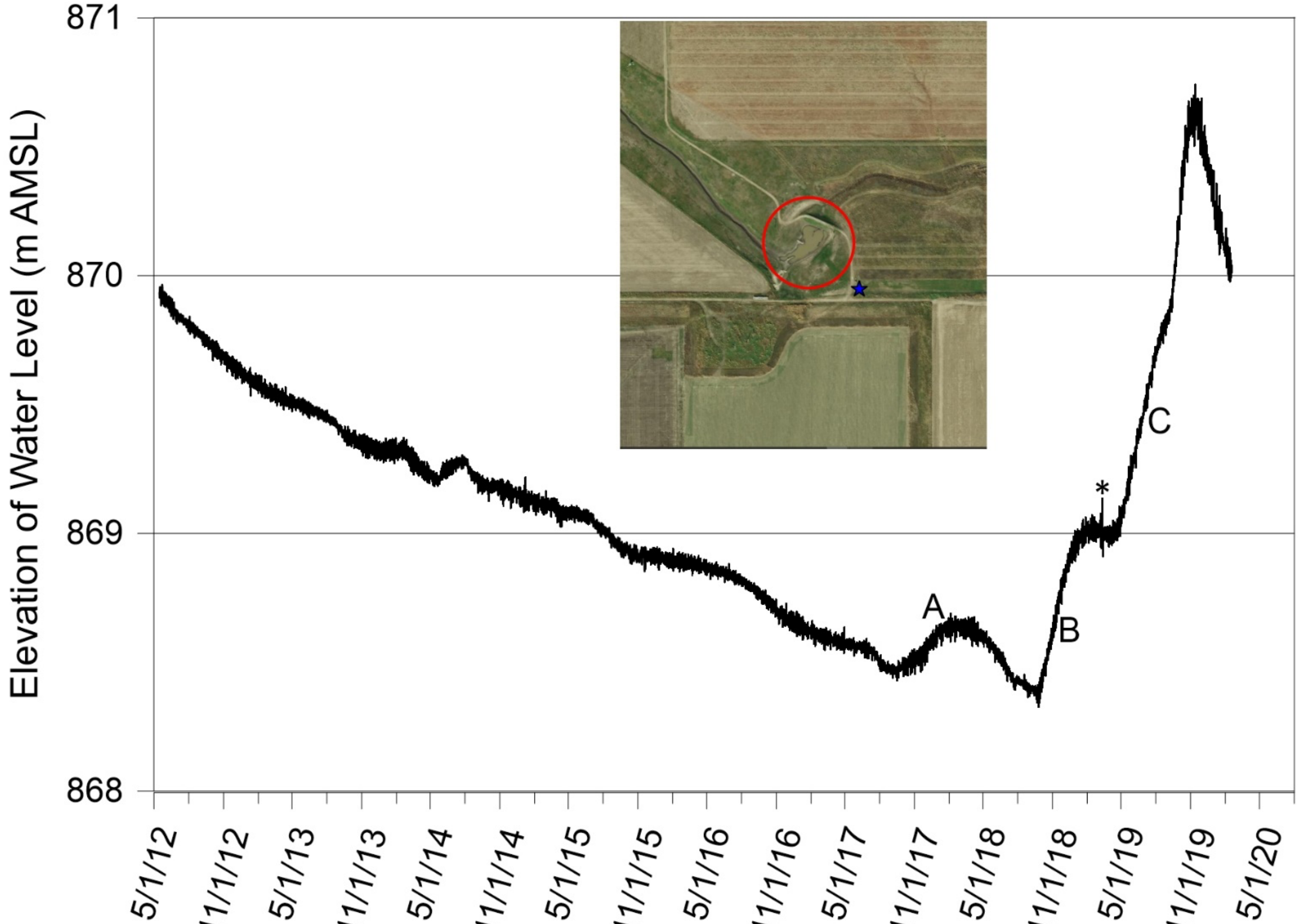

Figure 5 - Elevation of water level versus time for the Steiger index well in northwest Kansas (ST in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 869 m corresponds to a depth to water below land surface of 34.74 m. The well is screened over 9.75 m at the bottom of the aquifer (elevation of 849.79 m), an additional 2.44 m of screen is in the underlying shale and serves as a sump. Inset is an aerial photo of well (star) and nearby impoundment (within circle [radius approximately 76 m]); A-C and * defined in text.

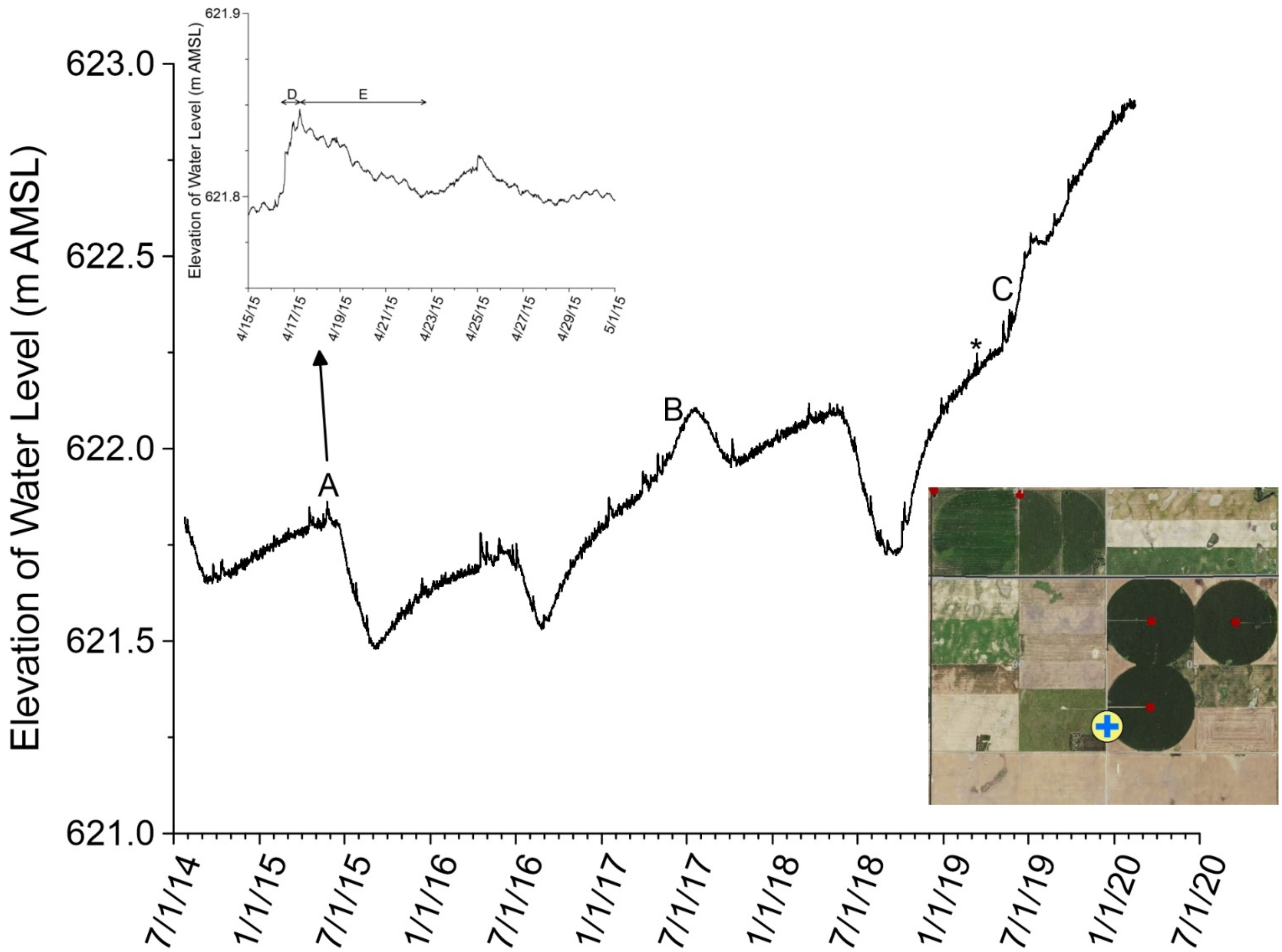

Figure 6 - Elevation of water level versus time for the Belpre index well in south-central Kansas (BL in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 622.0 m corresponds to a depth to water below land surface of 11.99 m. The well is screened over 6.10 m near the center of the aquifer (bottom of the screen is at an elevation of 600.77 m); elevation of the aquifer bottom is estimated to be between 573 and 581 m. Inset plot is an expansion of the water-level record in the vicinity of A; inset aerial photo is of the index well (blue plus sign in yellow circle) and nearby pumping wells (red circles), the irrigation circles are approximately 800 m in diameter; B-E and * defined in text.

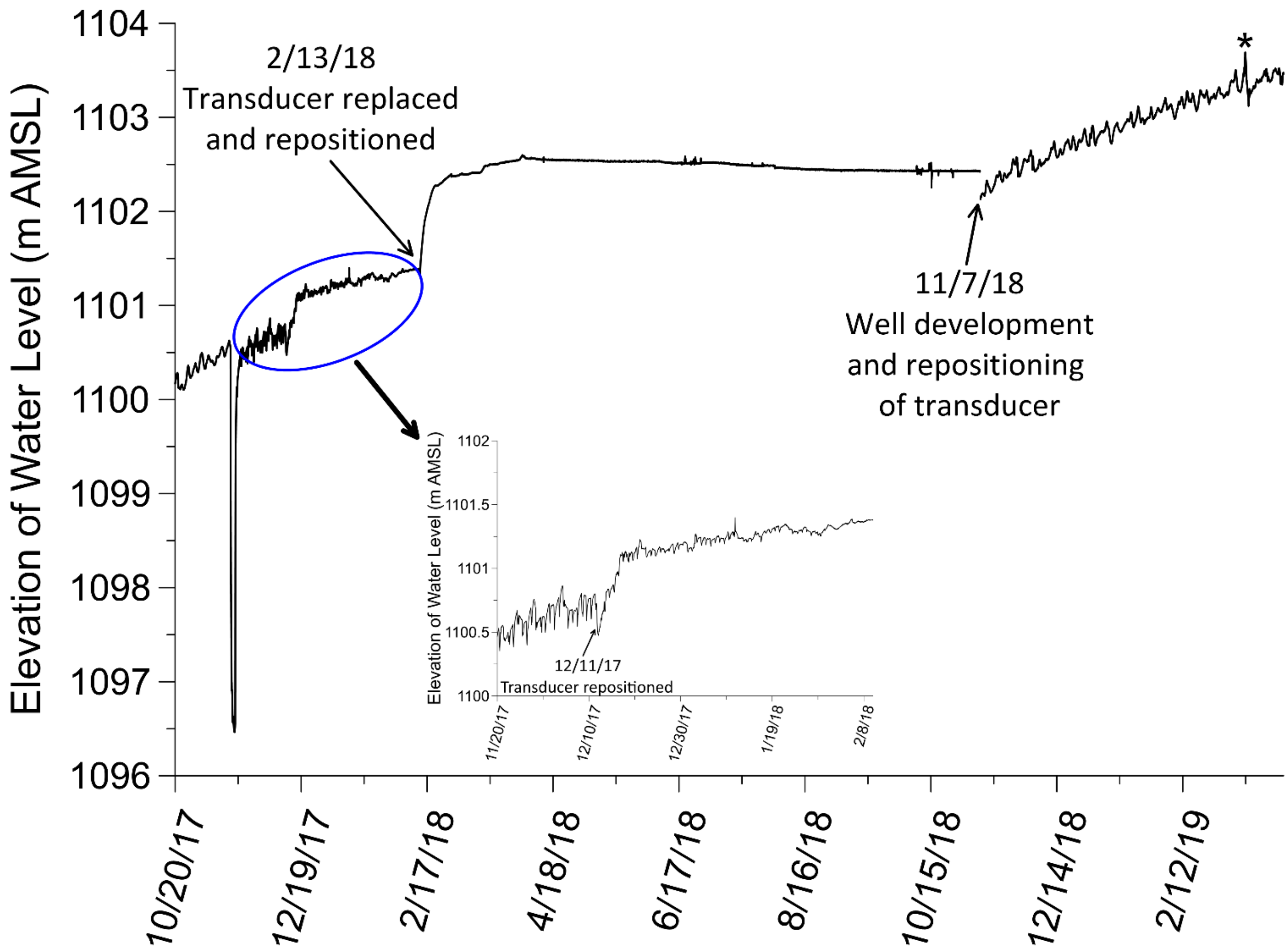

Figure 7 - Elevation of water level versus time for the Sherman County index well in northwest Kansas (SH in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 1,103 m corresponds to a depth to water below land surface of 53.43 m. The well is screened over 3.05 m near the bottom of the aquifer (bottom of the screen is at an elevation of 1,058.89 m, 0.92 m above the aquifer bottom). Inset is an expansion of the water-level record within the ellipse; * defined in text.

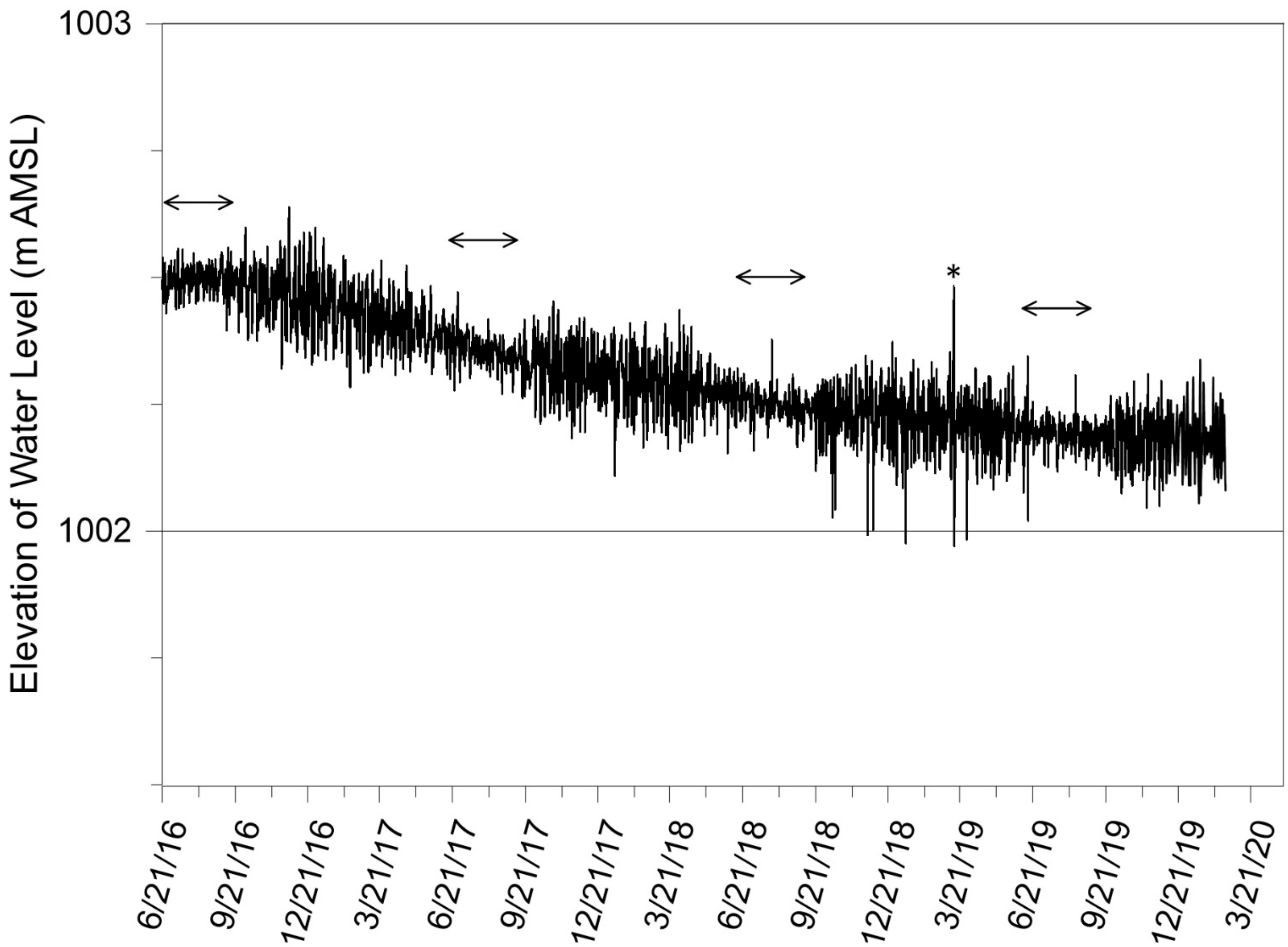

Figure 8 - Elevation of water level versus time for the Wichita County index well in west-central Kansas (WC in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 1,002.5 m corresponds to a depth to water below land surface of 48.46 m. The well is screened over 3.05 m near the bottom of the aquifer (bottom of the screen is at an elevation of 994.57 m, 1.52 m above the aquifer bottom). The double-headed arrows indicate the summer period (June 21 to Sept. 21); * defined in text. Some of the larger spikes are likely spurious readings produced by insolation of the transducer vent tube (Figure 9 and associated discussion).

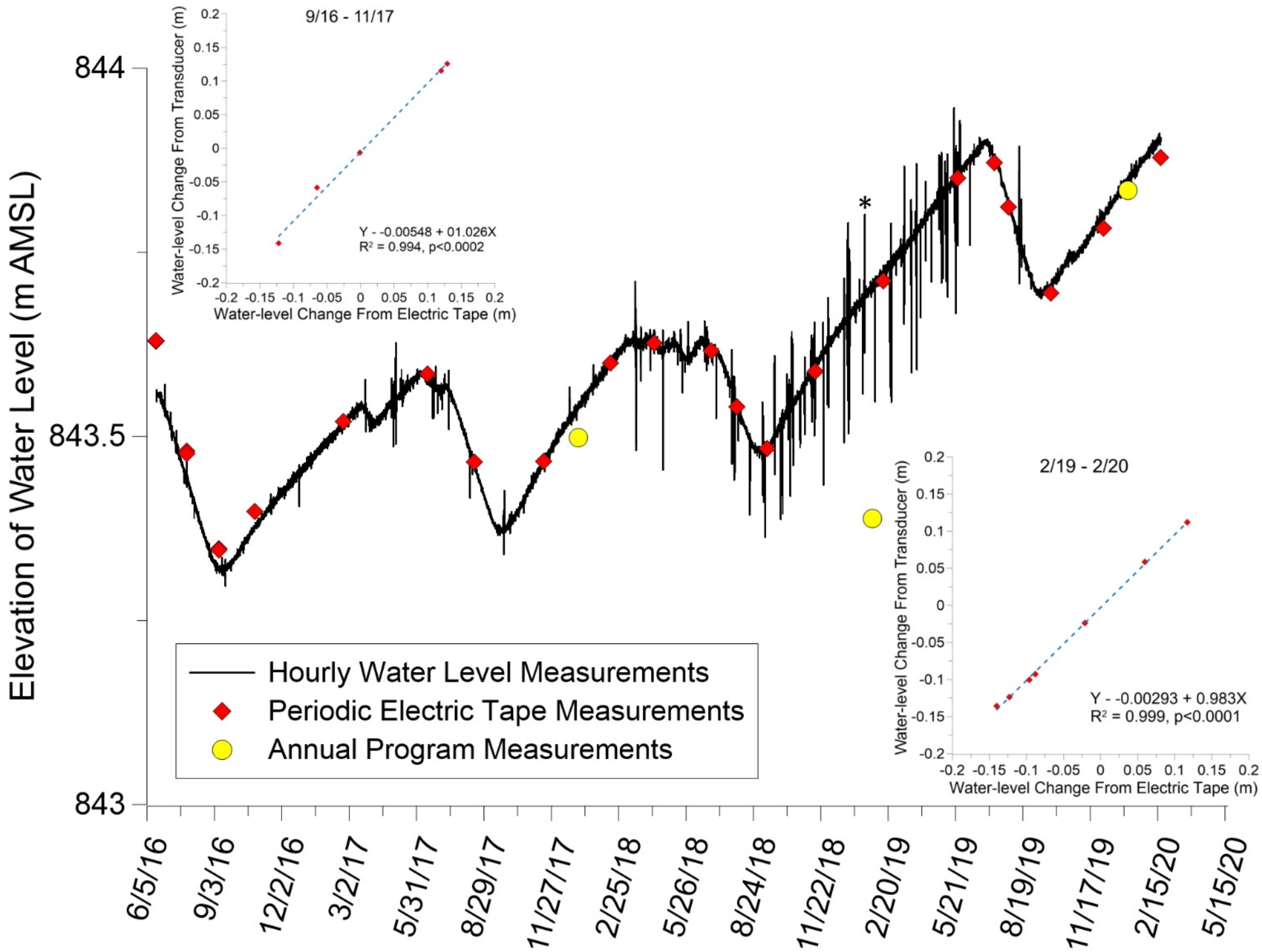

Figure 9 - Elevation of water level versus time for the Lane County index well in west-central Kansas (LN in Figure 1). Measurements taken every hour by a transducer at a fixed position in the water column; an elevation of 843.5 m corresponds to a depth to water below land surface of 25.80 m. The well is screened over 3.05 m near the bottom of the aquifer (bottom of the screen is at an elevation of 834.25 m, 0.92 m above the aquifer bottom). The two insets display the in-field calibration results using measurements from the given periods; * defined in text.