Kansas Geological Survey

High Plains Aquifer Index Well Program: 2018 Annual Report

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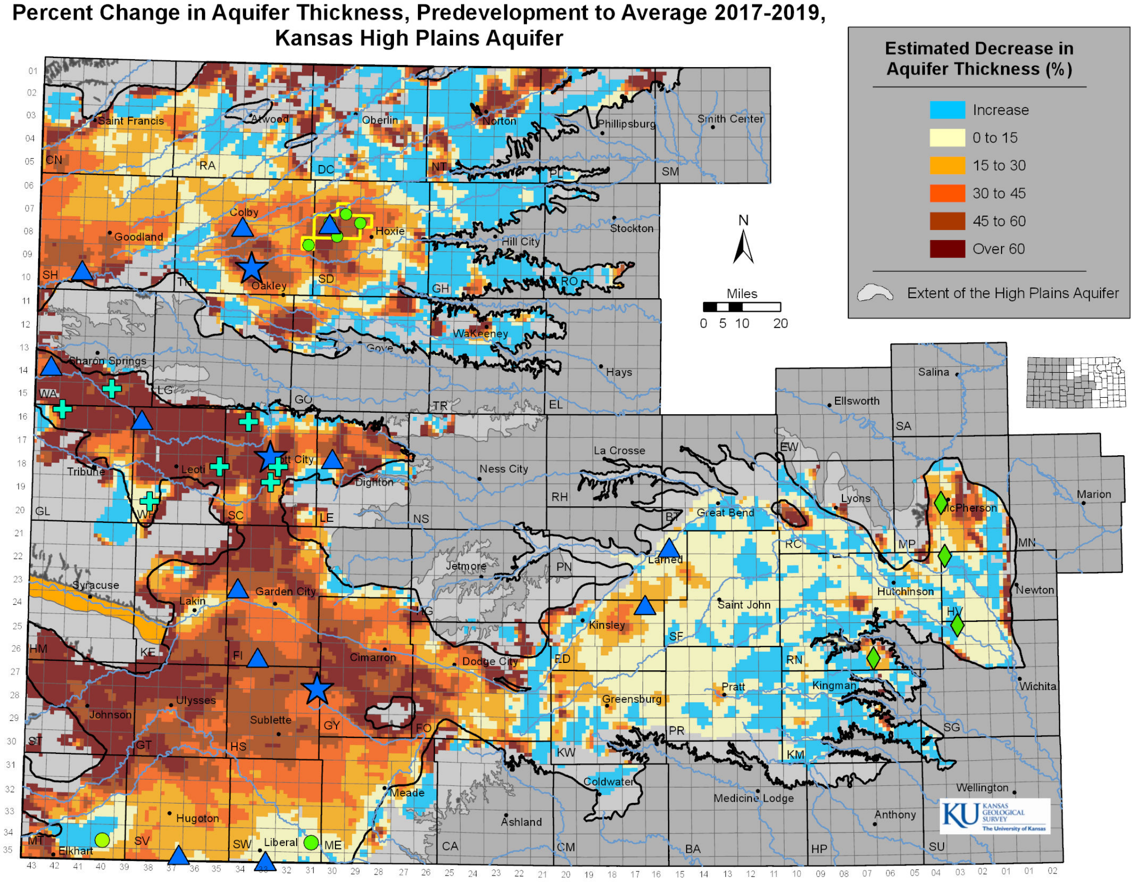
Percent Change in Aquifer Thickness, Predevelopment to Average 2017-2019,
Kansas High Plains Aquifer



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Acknowledgments

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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 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, 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 late summer 2007. Each well has a transducer 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 continuously added to the network. The index well network now consists of 15 wells with telemetry equipment and real-time data access from the KGS website and 8 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 other wells 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 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 are also used to develop a better understanding of the major mechanisms affecting water levels in the Kansas HPA. This improved understanding is then incorporated into the groundwater models of the aquifer.

This report provides a concise description of conditions as of late winter to early spring of 2019. 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, 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 are presented.

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

1. Water-level data collected using a pressure transducer and data logger 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 no indication of episodic recharge at any of 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 impact of management decisions on the township and larger scale using a new 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 to the concise description in this report, these findings are discussed in previous program reports, a recent KGS publication (Whittemore et al., 2018), and scientific journal articles resulting from program work (Butler et al., 2013; Whittemore et al., 2016; Butler, Whittemore, Wilson, and Bohling, 2016, 2018).

The focus of activities in 2019 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 four existing wells in GMD2; exploring the possibility of adding additional wells to the network; and further assessment of the relationships among radar precipitation data, 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 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—hereinafter, local or subunit) 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, 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 the 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 eleven 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 a pressure transducer and data logger 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 no indication of episodic recharge at any of 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 subunit and larger scale using a new 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.

The index well network was enlarged in 2018 by the installation of real-time monitoring equipment in an existing well in GMD5 near the Arkansas River channel east of Larned in Pawnee County. Note that the term "index well" is used here to designate a well at which monitoring is anticipated to continue for many years. There are additional wells, designated here as "expansion wells," at which monitoring is not likely to continue over the long term because of constraints imposed by well depth (i.e., water level is anticipated to drop below the bottom of the well screen), logistics, or management issues. Both types of wells are considered in this report.

This report provides a concise description of conditions as of late winter to spring of 2019. The majority of the report consists of an update and interpretation of the hydrographs for all of the index wells and the GMD1 expansion wells. In addition, this report discusses the relationships among precipitation (as characterized by radar data), annual water-level changes, and nearby water use at the three original index wells and three additional wells, and the implications of those relationships for efforts to moderate water-level declines by pumping reductions.

2 Program History

The index well program began in late 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 the first week of 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 at each site for monitoring 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. In the spring of 2019, telemetry equipment was added back to the Hugoton well in the main body of the HPA; we anticipate adding telemetry equipment back to the Liberal well in the main body of the HPA in late summer of 2019. 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. A transducer-datalogger unit and telemetry equipment were installed in July 2014. As described in the 2014 report (Butler 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 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. The existing equipment was replaced 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). Real-time data from this well are now accessible from the KGS website. Data from the four 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.

The current state of the index well network is shown in fig. 1. There are now 15 wells in the network with telemetry equipment and real-time data access from the KGS website and 8 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. At least four existing wells in GMD2 will be added to the network in 2019.

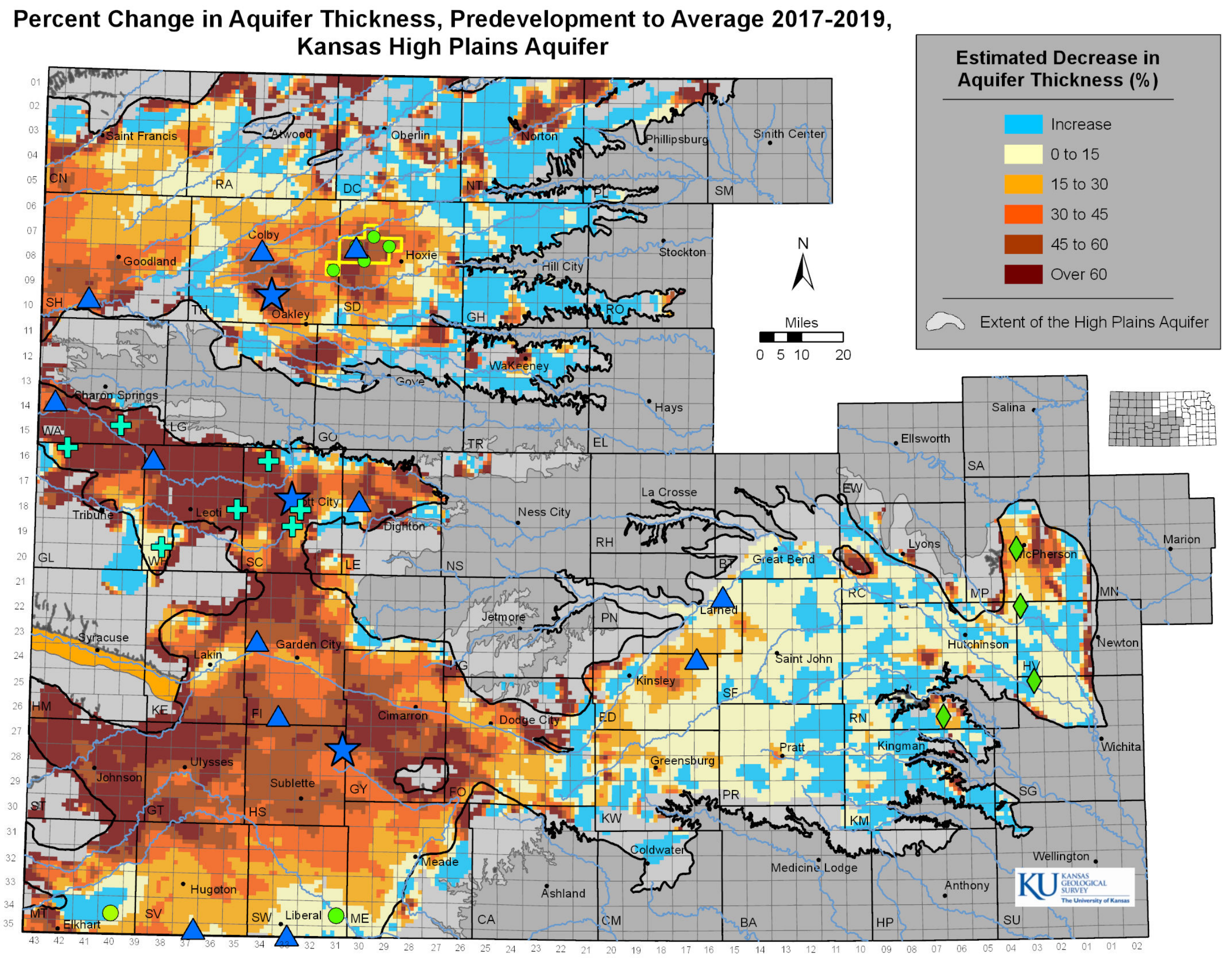

Figure 1—The Kansas portion of the High Plains aquifer, with aquifer and county boundaries shown. Each colored pixel represents one section (1 mi^2), coded for the degree of groundwater depletion from the beginning of large-scale development to the average of conditions in 2017–2019. The blue stars indicate the locations of the original three index well site, the blue triangles indicate additional telemetry-equipped wells, the green circles are the index wells without telemetry equipment for which data are downloaded quarterly, the yellow polygon indicates the Sheridan-6 Local Enhanced Management Area, and the green diamonds indicate the locations of the index wells in GMD2 that will begin acquiring data in the summer of 2019. 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 23 index wells and 7 GMD1 expansion wells currently in operation. The duration of monitoring ranges from more than 11¾ 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, unless the well was added to the program in 2018, 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, whereas the Lane, Wallace, and Wichita wells were installed 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 et al., 2017) and the online appendices for this report (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml). Section 3.5.1 discusses GMD1 expansion wells.

Table 1—Characteristics of the GMD1 index well sites.

Site	2019 WL elev. (ft)[a]	2019 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2017 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Lane	2,767.0	33.0	118	105–115	434	1,073	2,732[b]
Scott	2,827.2	83.1	223	215–225	696	2,226	12,171[c]
Wallace	3,561.9	127.9	394	375–385	528[d]	3,492[d]	11,423[d]
Wichita	3,288.1	30.1	190	175–185	130	2,377	8,651

[a] 2019 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html).
[b] Includes 56 ac-ft of municipal water and 32 ac-ft of non-irrigation stock water.
[c] Includes 697 ac-ft of municipal water and 332 ac-ft of non-irrigation stock water.
[d] Includes 46 ac-ft of municipal water.

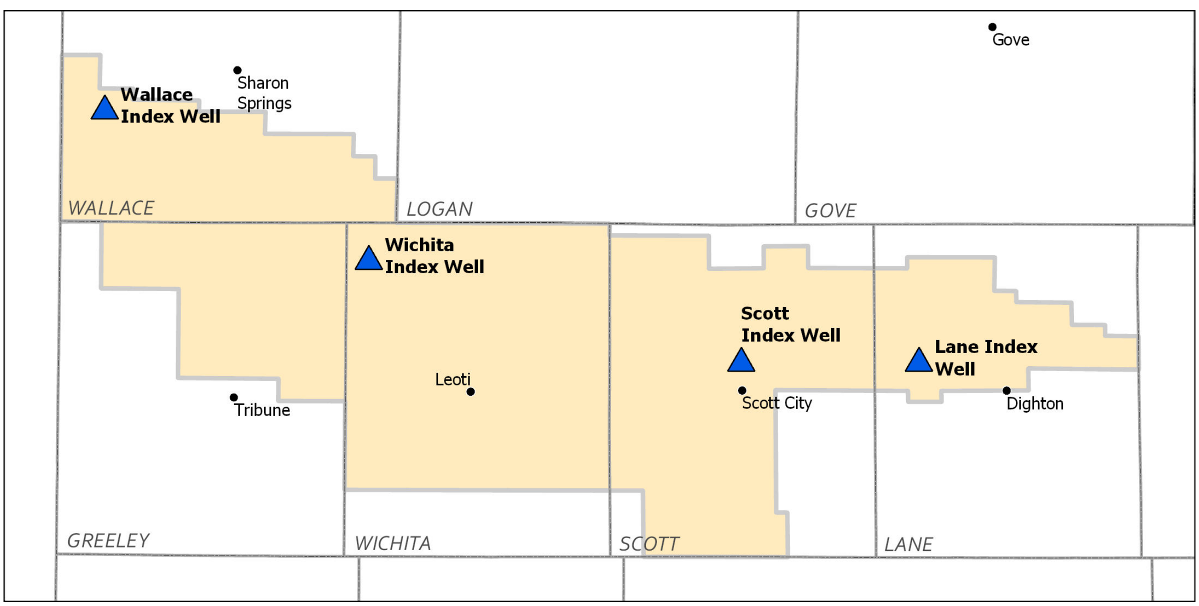

Figure 2—Map of index wells in GMD1. Triangles designate wells with telemetry equipment; data from these wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

3.1.1 Lane County Index Well

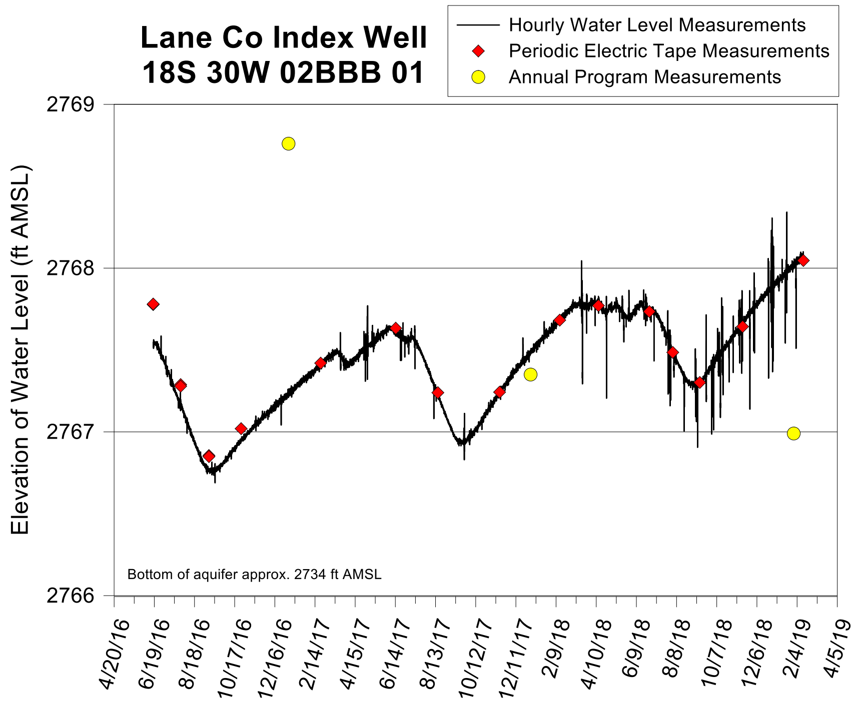

Figure 3—Lane County index well hydrograph—total data run to 2/13/19. A water-level elevation of 2,767 ft corresponds to a depth to water of 85 ft below land surface (lsf). The top of the screen is 105 ft below lsf (elevation of 2,747 ft), and the bottom of the aquifer is 118 ft below lsf (elevation 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 2018 was 0.3 ft above that of 2017, whereas the minimum water level for 2018 was 0.3 ft above that of 2017; such year-on-year increases are rare in the index wells in western Kansas.
- Many short-duration spikes appear on the hydrograph and their frequency is increasing; we suspect the origin of these spikes is related to air expansion and contraction in the vent tube of the gauge pressure sensor (Cain et al., 2004), which is located by the telemetry box and exposed to sunlight. A second gauge transducer was placed in the well with its vent tube terminating just below the well top and did not exhibit spikes.

3.1.2 Scott County Index Well

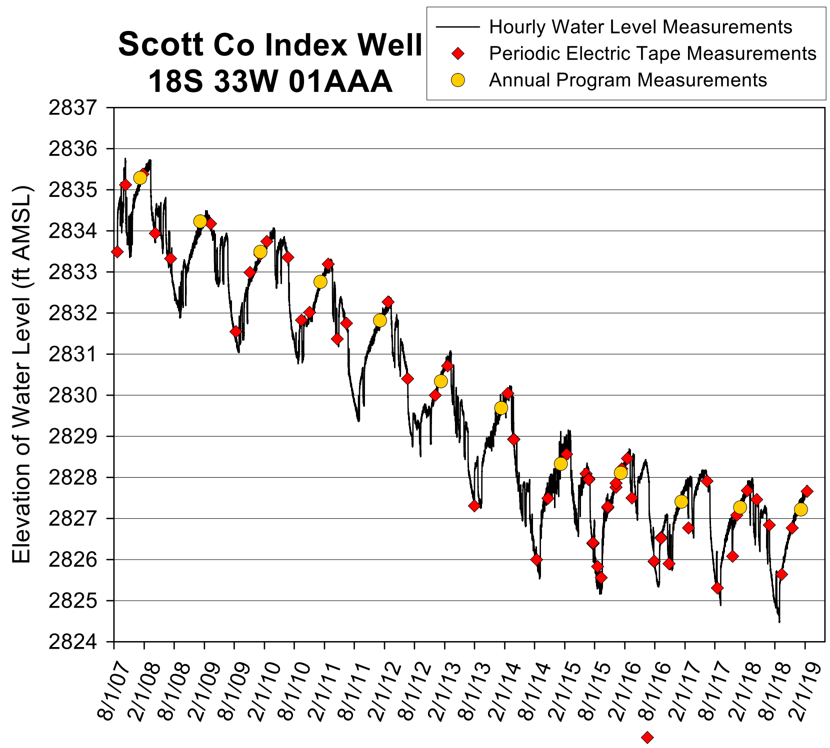

Figure 4—Scott County index well hydrograph—total data run to 2/13/19. A water-level elevation of 2,829 ft corresponds to a depth to water of 138.15 ft below lsf. The top of the screen is 215 ft below lsf (elevation of 2,752.15 ft), and the bottom of the aquifer is 223 ft below lsf (elevation of 2,744.15 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). Electric-tape measurement plotted below the graph appears to have been a transcription error.

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).
- Each year, the maximum water level is below that of the preceding year, creating a downward stair-stepping pattern.
- Transducer readings are in good agreement with manual measurements except for one anomalous electric-tape measurement.

3.1.3 Wallace County Index Well

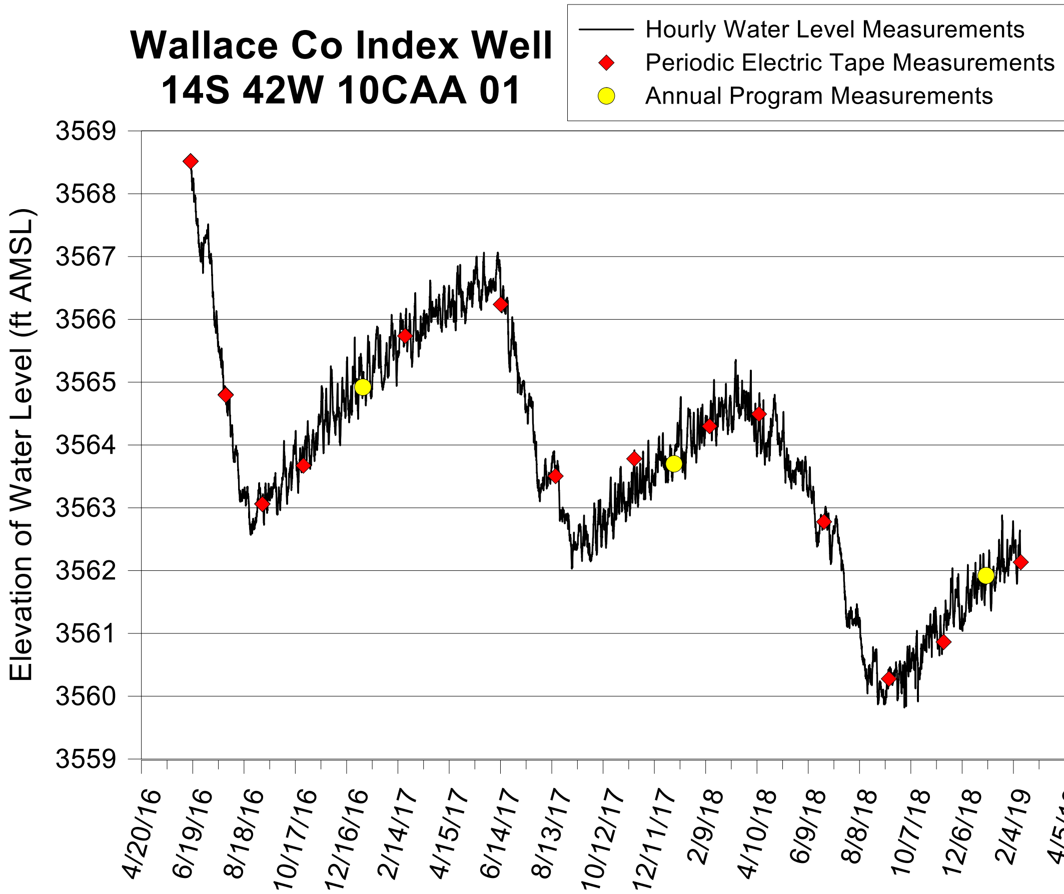

Figure 5—Wallace County index well hydrograph—total data run to 2/12/19. A water-level elevation of 3,565 ft corresponds to a depth to water of 263 ft below lsf. The top of the screen is 375 ft below lsf (elevation of 3,453 ft), and the bottom of the aquifer is 394 ft below lsf (elevation of 3,434 ft). 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 water level is below that of the preceding year, creating a downward stair-stepping pattern.
- Transducer readings are in good agreement with manual measurements.

3.1.4 Wichita County Index Well

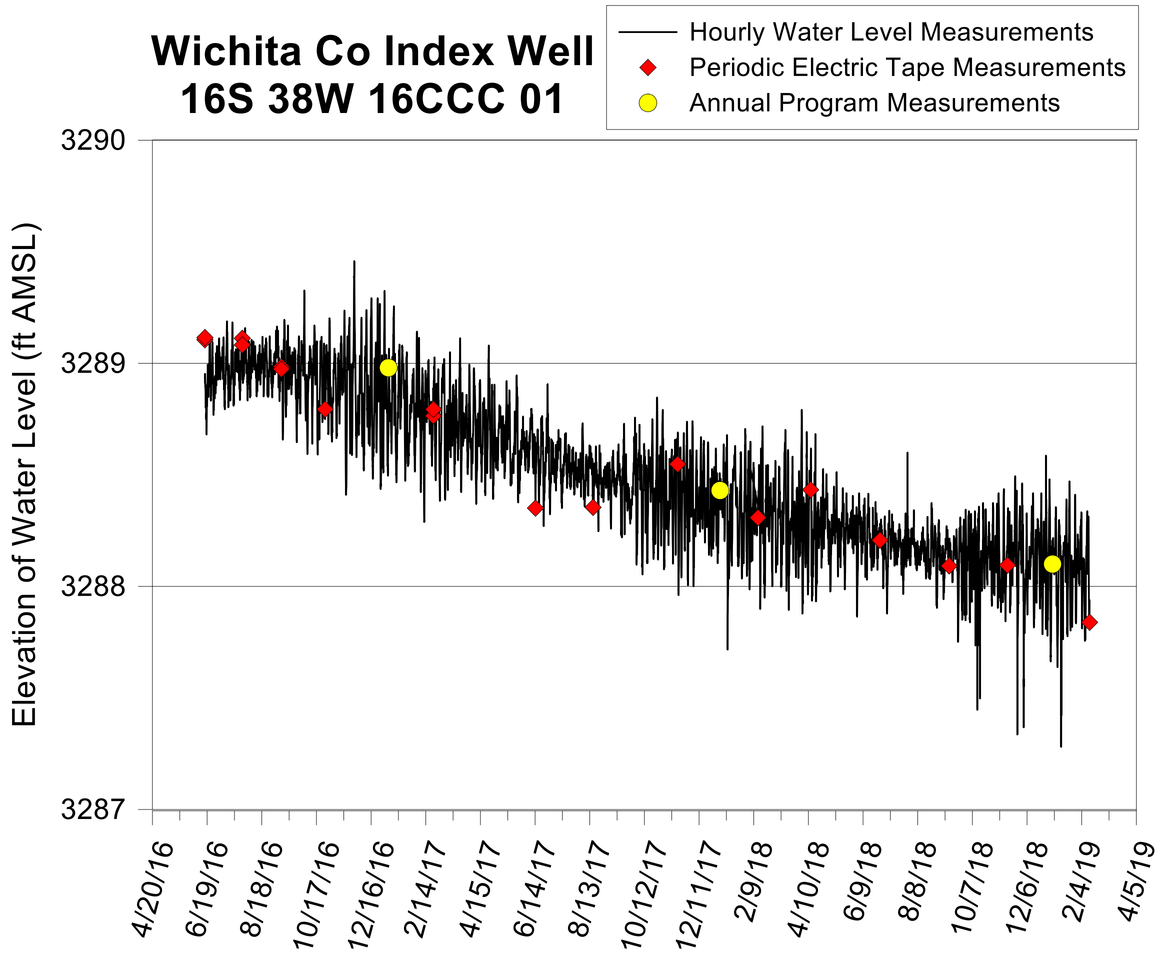

Figure 6—Wichita County index well hydrograph—total data run to 2/12/19. A water-level elevation of 3,289 ft corresponds to a depth to water of 159 ft below lsf. The top of the screen is 175 ft below lsf (elevation of 3,273 ft), and the bottom of the aquifer is 190 ft below lsf (elevation of 3,258 ft). 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).
- 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.

3.2 GMD3 Index Wells

Nine index wells are located in GMD3 (fig. 7). The Haskell index well was one of the original three index wells, while wells at the Cimarron, Hugoton, Liberal, and Rolla sites began monitoring in 2012–2013, the Willis Technology Farm index well began in the summer of 2016, and monitoring at the Kearny-Finney County index well began in the summer of 2017. Table 2 summarizes characteristics of these nine wells. Further details concerning these wells are given in the 2016 annual report (Butler et al., 2017) and the online appendices for this report (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

Table 2—Characteristics of the GMD3 index well sites.

Site	**2019 WL elev. (ft)[a]**	**2019 saturated thickness (ft)**	**Bedrock depth (estimated ft below land surface)[b]**	**Screened interval (ft below land surface)[b]**	**2017 water use (ac-ft)**		
					1 mi radius circle	**2 mi radius circle**	**5 mi radius circle**
Cimarron 210	2,474.17	290.2	345	200–210	47	47	8,909
Haskell	2,531.87	127.0	433	420–430	574	5,153	32,677
Hugoton 313[c,i]	2,916.77[c,d]	451.8	635	303–313	731	2,464	34,974[e]
Hugoton 495[i]	2,912.75	447.8	635	485–495			
Kearny-Finney	2,785.52	184.5[g]	360[g]	70–266[h]	859	3,024	24,341[j]
Liberal 160[c,i]	2,691.16[c,d]	445.2	576	140–160	0.10	1,892[e]	32,183[e,f]
Liberal 436[i]	2,657.00	411.0	576	426–436			
Rolla 366	3,187.61	211.6	399	356–366	252[k]	830[k]	6,791[k]
Willis Tech Farm	2,638.18	200.18	502	262–482	1,190	5,271	33,000[l]

[a] 2019 annual tape water-level measurements from WIZARD database.
[b] Measurements for the Cimarron, Hugoton, Liberal, and Rolla wells from table 2 in McMahon (2001).
[c] Not part of the annual water-level measurement network.
[d] 2019 water-level measurements from hand measurements taken 4/24–4/25/2019.
[e] Includes estimates of water use in Oklahoma based on "permitted" quantities (Liberal: 675 [2 mi circle] and 20,909 [5 mi circle] ac-ft; Hugoton: 17,989 [5 mi circle] ac-ft).
[f] Includes 8,034 ac-ft of non-irrigation water (primarily for industrial and municipal use) for city of Liberal.
[g] Based on logs of nearby wells to bedrock.
[h] Measurements estimated from borehole camera log.
[i] Wells originally on USGS telemetry systems; those systems were removed in 2017 because of a lack of funding. Hugoton 495 and Liberal 436 were added to the KGS telemetry system in spring and summer 2019.
[j] Includes 298 ac-ft of non-irrigation stock water, 199 ac-ft of municipal water, and 37 ac-ft of industrial water.
[k] Includes 34 [1 mi circle], 104 [2 mi circle], and 295 [5 mi circle] ac-ft of non-irrigation stock water and 100 ac-ft [5 mi circle] of municipal water.
[l] Includes 1,132 ac-ft of industrial use.

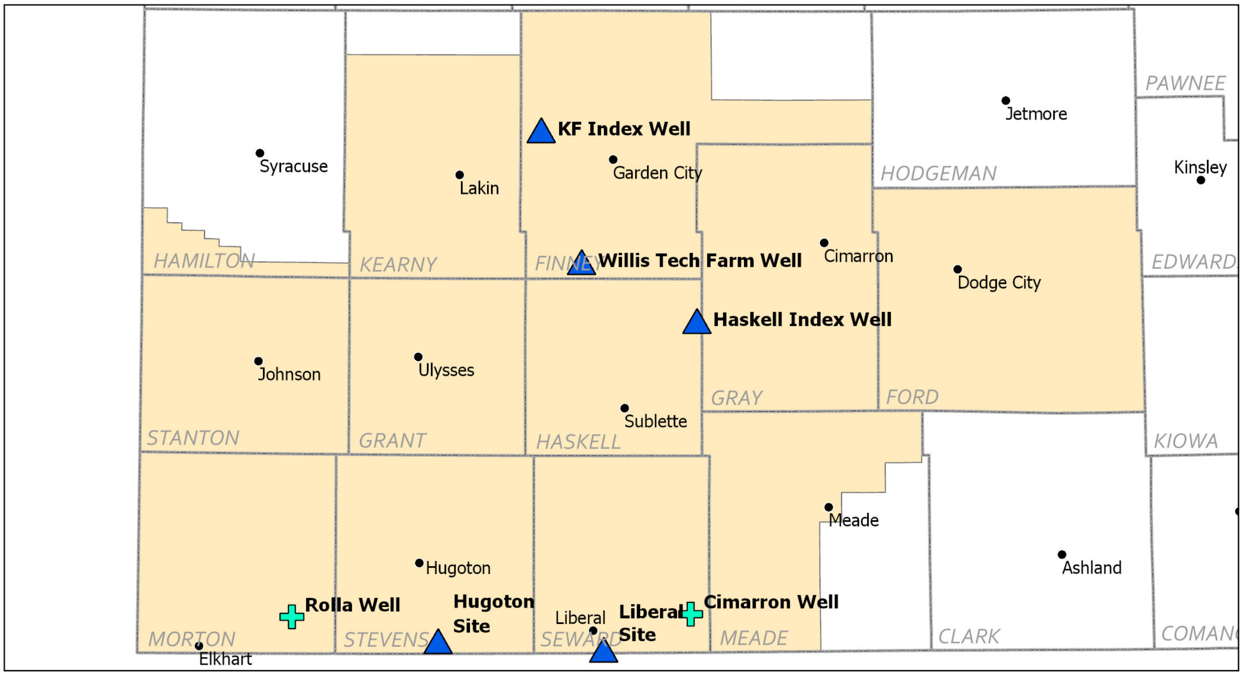

Figure 7—Map of index wells in GMD3. Triangles designate wells with telemetry equipment whereas plus signs designate wells without telemetry equipment. Data from wells with telemetry equipment can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml); data from wells without telemetry equipment are periodically downloaded (typically quarterly) and posted on the KGS website. The Hugoton and Liberal sites each have one well with telemetry equipment and one well without; the wells with telemetry equipment are located in the main body of the HPA. KF = Kearny-Finney.

3.2.1 Cimarron Index Well

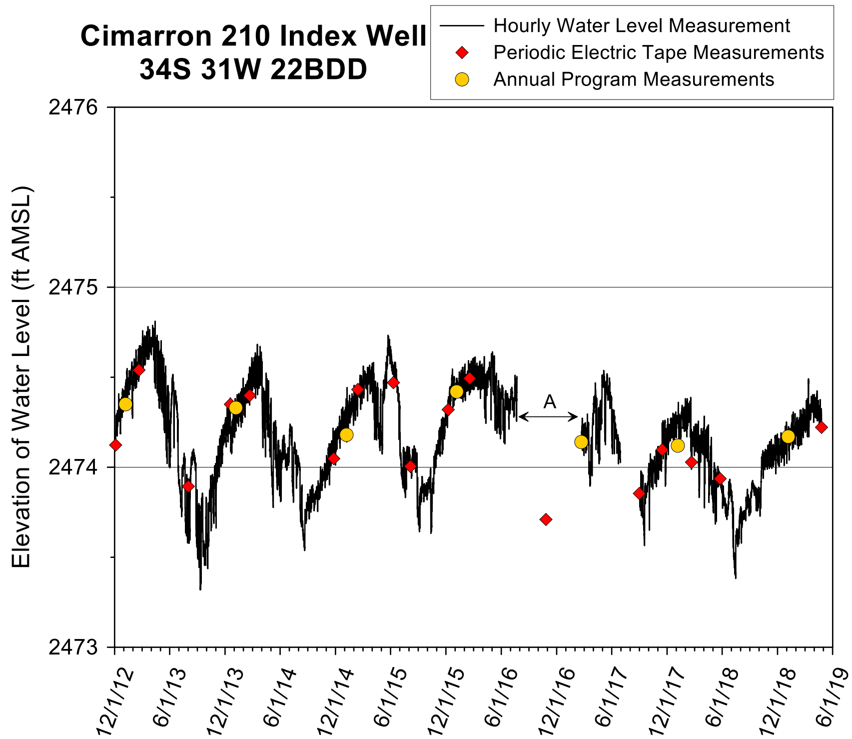

Figure 8—Cimarron 210 index well hydrograph—total data run to 4/25/19. A water-level elevation of 2,474 ft corresponds to a depth to water of 55.0 ft below lsf. The top of the 10 ft screen is 200 ft below lsf (elevation of 2,329 ft), and the bottom of the aquifer is 345 ft below lsf (elevation of 2,184 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.
- Water use within a 2 mi radius of the well is the lowest of any of the index wells.
- Water level has declined 1.8 ft since January 2000 (decline rate of 0.10 ft/yr).
- Transducer readings are in good agreement with manual measurements.

3.2.2 Haskell County Index Well

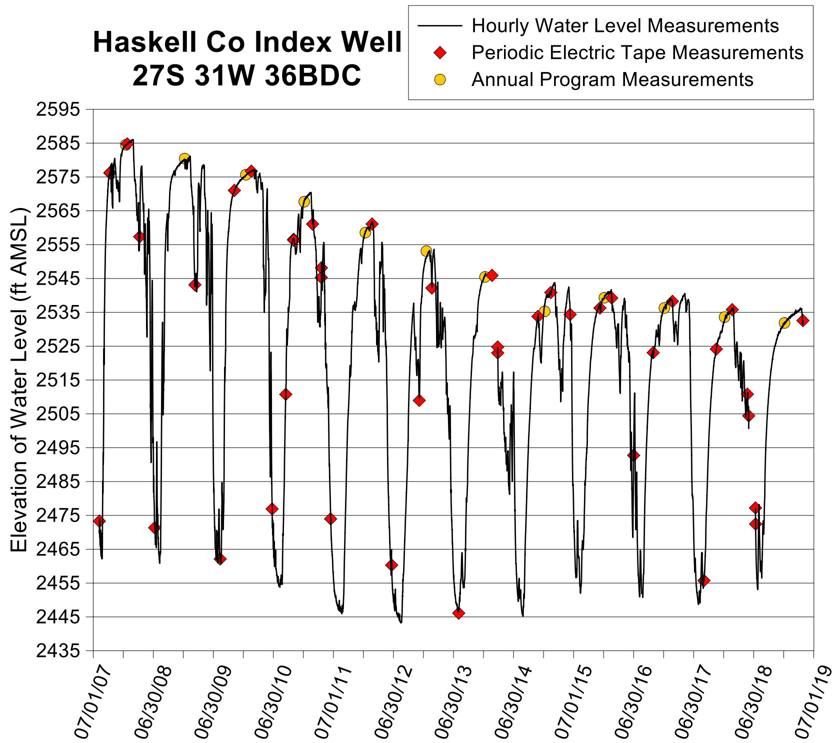

Figure 9—Haskell County index well hydrograph—total data run to 4/26/19. A water-level elevation of 2,445 ft corresponds to a depth to water of 392.85 ft below lsf. The top of the screen is 420 ft below lsf (elevation of 2,417.85 ft), and the bottom of the aquifer is 433 ft below lsf (elevation of 2,404.85 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.

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 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) and complete (after 2014) cessation of pumping at two nearby irrigation wells (Butler et al., 2017) and complete (after 2014) cessation of pumping at three additional nearby irrigation wells.
- The minimum water-level elevation in 2018 was the highest since 2010 and the maximum recovered water level in the spring of 2019 was within 0.03 ft of that in 2018, the smallest difference observed since the start of monitoring.
- Transducer readings are in reasonable agreement with manual measurements.

3.2.3 Hugoton Site

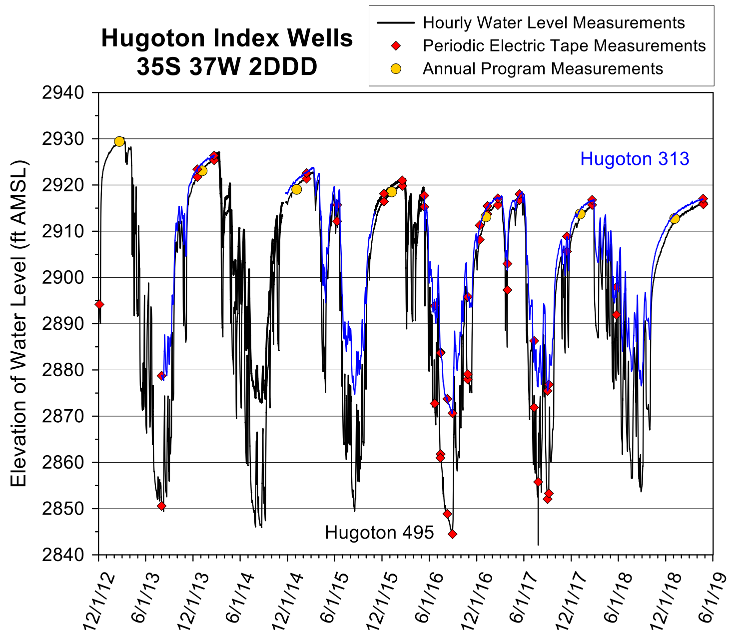

Figure 10—Hydrographs of Hugoton index wells—total data run to 4/24/19. A water-level elevation of 2,930.0 ft corresponds to a depth to water of 170.0 ft below lsf. For the Hugoton 495 well, the top of the 10 ft screen is 485 ft below lsf (elevation of 2,615 ft). For the Hugoton 313 well, the top of 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 is associated with movement of the transducer in the well and is considered spurious.

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 57.2 ft since January 2000 (decline rate of 3.0 ft/yr).
- The minimum water-level elevation in 2018 was the highest since the start of monitoring, and the maximum recovered water level in the spring of 2019 was 0.4 ft higher than that in 2018, the only increase since the start of monitoring.
- Transducer readings are in good agreement with manual measurements.

3.2.4 Kearny-Finney Index Well

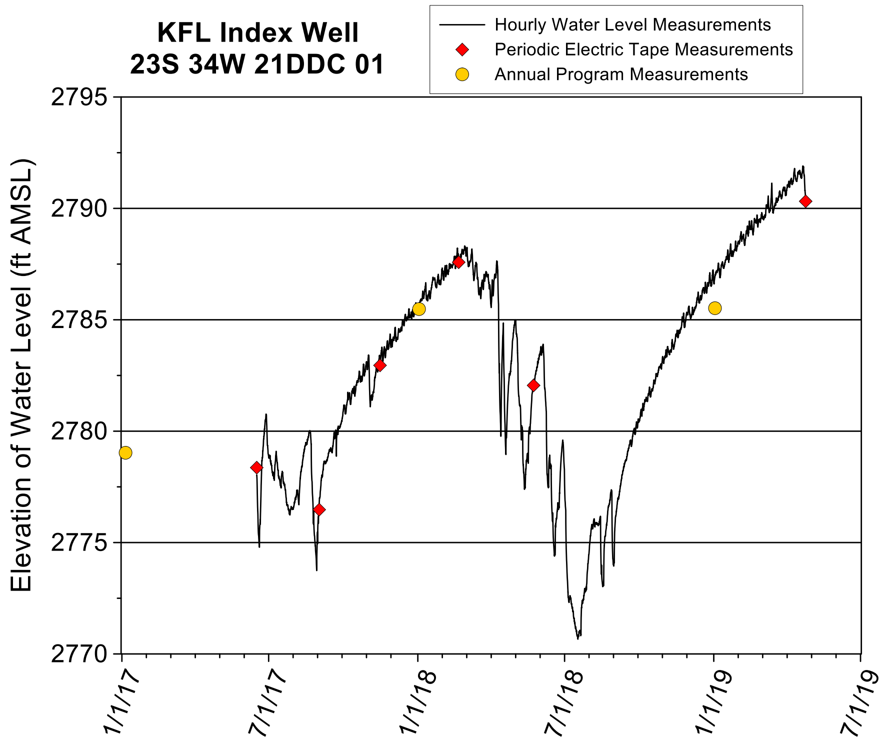

Figure 11—Kearny-Finney index well (KFL) hydrograph—total data run to 4/24/19. A water-level elevation of 2,788 ft corresponds to a depth to water of 173 ft below lsf. Nominal bottom of well is 300 ft below lsf (elevation of 2,661 ft), but the well is currently filled with sediments to 266 ft below lsf (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 approximately 53 ft since January 2008 (half of that total decline occurred in 2011 and 2012).
- Minimum water-level elevation for 2018 was 3.1 ft lower than that of 2017 but the maximum recovered water level in the spring of 2019 was 3.6 ft higher than that of 2018.
- Transducer readings are in good agreement with electric-tape measurements; 2019 annual measurement appears to be in error.

3.2.5 Liberal Site

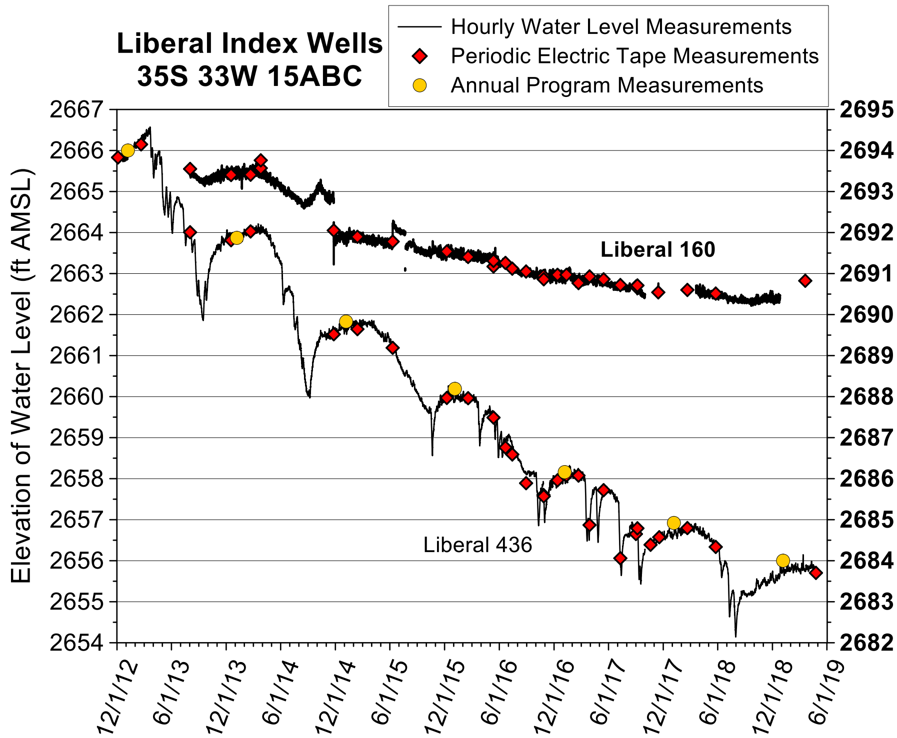

Figure 12—Hydrographs of Liberal index wells—total data run to 4/25/19. The Liberal 436 plot corresponds to the left y-axis. A water-level elevation of 2,664 ft corresponds to a depth to water of 157 ft below lsf. The top of the 10 ft screen is 426 ft below lsf (elevation of 2,395 ft). The Liberal 160 plot corresponds to the right y-axis. A water-level elevation of 2,692 ft corresponds to a depth to water of 129 ft below lsf. The top of the 20 ft screen is 140 ft below lsf (elevation of 2,681 ft). Bottom of the aquifer is 576 ft below lsf (elevation of 2,245 ft). A sensor failed at Liberal 160 well on November 16, 2017, and on December 26, 2018. Pre-2017 gaps in hydrograph for Liberal 160 were discussed in a previous report (Butler et al., 2017).

Major Points

- Two wells are monitored in a four-well nest.
- Liberal 436: The hydrograph form and the relatively small (< 0.35 ft) amplitude fluctuations superimposed on water levels indicate confined conditions.
- Liberal 160: The amplitude of the water-level fluctuations in Liberal 160 indicates unconfined conditions.
- The pumping response observed in Liberal 436 is difficult to discern in Liberal 160, indicating little hydraulic connection between the monitoring intervals for the two wells.
- After the end of the irrigation season, water levels in Liberal 436 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.
- The water level in Liberal 436 has declined 27.2 ft since January 2000 (decline rate of 1.43 ft/yr).
- Transducer readings are in reasonable agreement with manual measurements.

3.2.6 Rolla Index Well

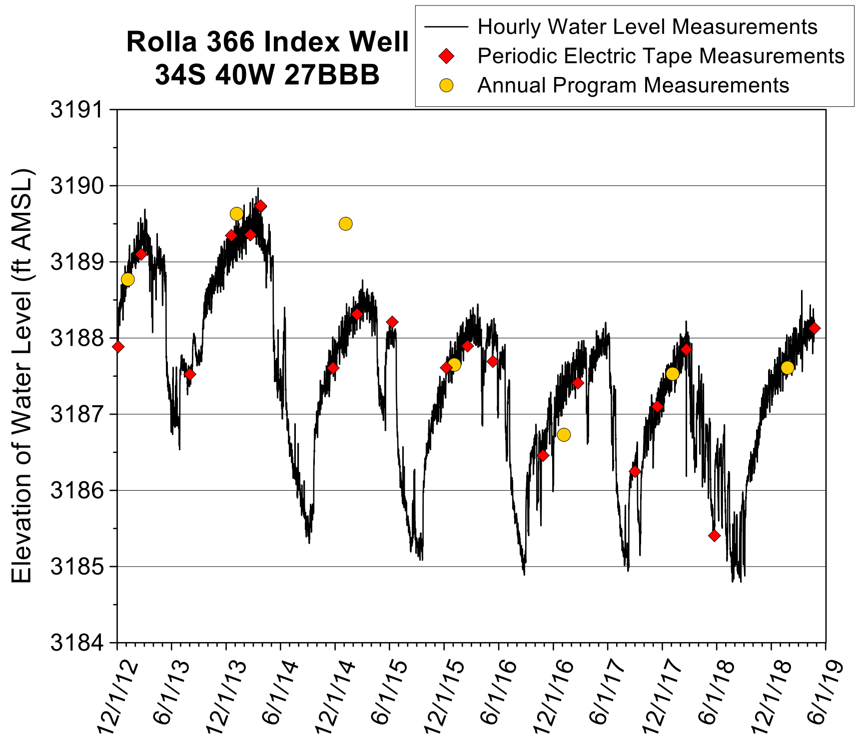

Figure 13—Rolla 366 index well hydrograph—total data run to 4/24/19. A water-level elevation of 3,188 ft corresponds to a depth to water of 187 ft below lsf. The top of the 10 ft screen is 356 ft below lsf (elevation of 3,019 ft), and the bottom of the aquifer is 399 ft below lsf (elevation of 2,976 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 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). Water-level elevations in the spring of 2019 surpassed those of the previous two years.
- There has been a very small change in minimum water-level elevation over the last four irrigation seasons.
- The water level has declined 9.4 ft since January 2000 (decline rate of 0.49 ft/yr).
- Transducer readings are in good agreement with electric-tape measurements but poorer agreement with annual measurements.

3.2.7 Willis Water Technology Farm Index Well

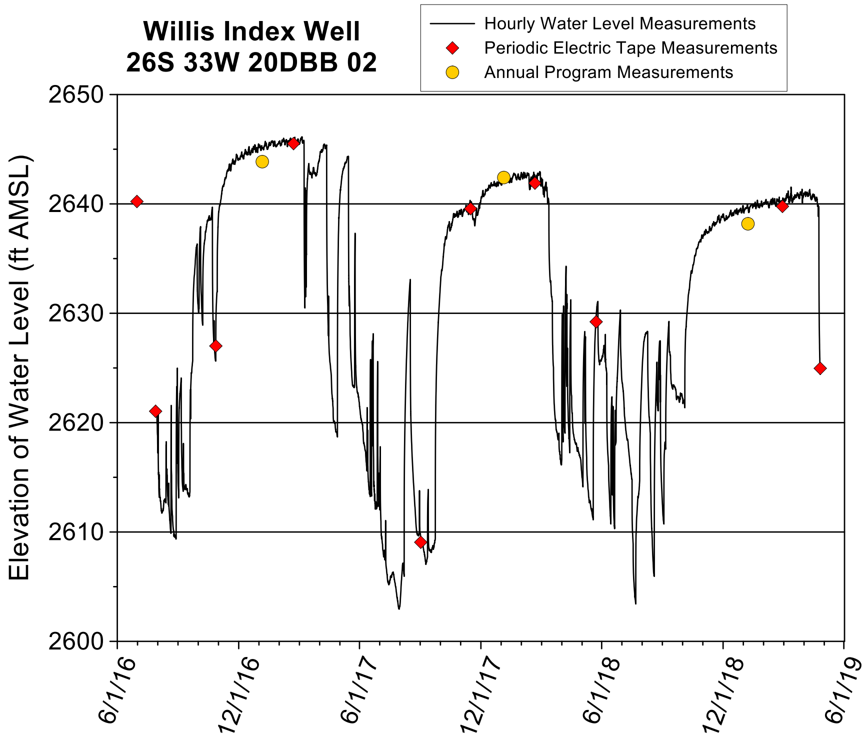

Figure 14—Willis Water Technology Farm index well hydrograph—total data run to 4/26/19. A water-level elevation of 2,640 ft corresponds to a depth to water of 300 ft below lsf. The top of the 220 ft screen is 262 ft below lsf (elevation of 2,678 ft), and the bottom of the aquifer is 502 ft below lsf (elevation of 2,438 ft). The first electric-tape measurement was taken before continuous monitoring began.

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.
- 2017 water use (2 mi radius circle centered on well) was the highest of any of the index wells.
- Transducer readings are in good agreement with manual measurements except for the 2017 and 2019 annual measurement.

3.3 GMD4 Index Wells

Eight index wells are located in GMD4, four of which have telemetry equipment that allows real-time viewing of data (fig. 15). The Thomas index well was one of the original three index wells, whereas monitoring at the Colby, the Sheridan-6 (SD-6) LEMA, and Sherman index wells was initiated in 2012, 2014, and 2017, respectively. Table 3 summarizes characteristics of these eight wells. Further details concerning these wells are given in the 2016 annual report (Butler 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 GMD4 index well sites.

Site	2019 WL elev. (ft)[a]	2019 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2017 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Colby	3,026.1	99.1[c]	250–300	156–175	574[h]	2,043[i]	9,241[j]
SD-6 Baalman	2,710.7[k]	75.7	262	260–270	529	2,068	11,663[d]
SD-6 Beckman[b,l]	NA[b]				514	2,002[g]	10,168[e]
SD-6 Moss[b]	2,625.7[b]	52.7	243	205–245	155	1,621	10,924[f]
SD-6 Seegmiller	2,739.6	71.6	265	225–265	530	2,196	12,107[e]
SD-6 Steiger[b]	2,851.1[b]	63.1	177	145–185	127	887	7,661
Sherman	3,618.2	147.2	323	310–320	1,250	2,375	8,677
Thomas	2,970.3	66.9	284	274–284	723	1,943	9,312

[a] 2019 annual tape water-level measurements from WIZARD database.

[b] Not an annually measured index well; 2019 water-level measurements from hand measurements taken 02/11/2019 at Moss and 02/13/2019 at Steiger. Beckman well could not be accessed because of damage to the well site.

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

[d] Includes 605 ac-ft of non-irrigation stock water.

[e] Includes 592 ac-ft of non-irrigation stock water.

[f] Includes 458 ac-ft of non-irrigation stock water and 303 ac-ft of municipal water.

[g] Includes 290 ac-ft of non-irrigation stock water.

[h] Includes 324 ac-ft of municipal water.

[i] Includes 1,074 ac-ft of municipal water and 272 ac-ft of contamination remediation water.

[j] Includes 1,197 ac-ft of municipal water and 272 ac-ft of contamination remediation water.

[k] Annual measurement on 01/04/2019, clearly in error by about 1.2 ft so used average of transducer measurements from 8 a.m. to 4 p.m. on that day.

[l] Well construction information not available.

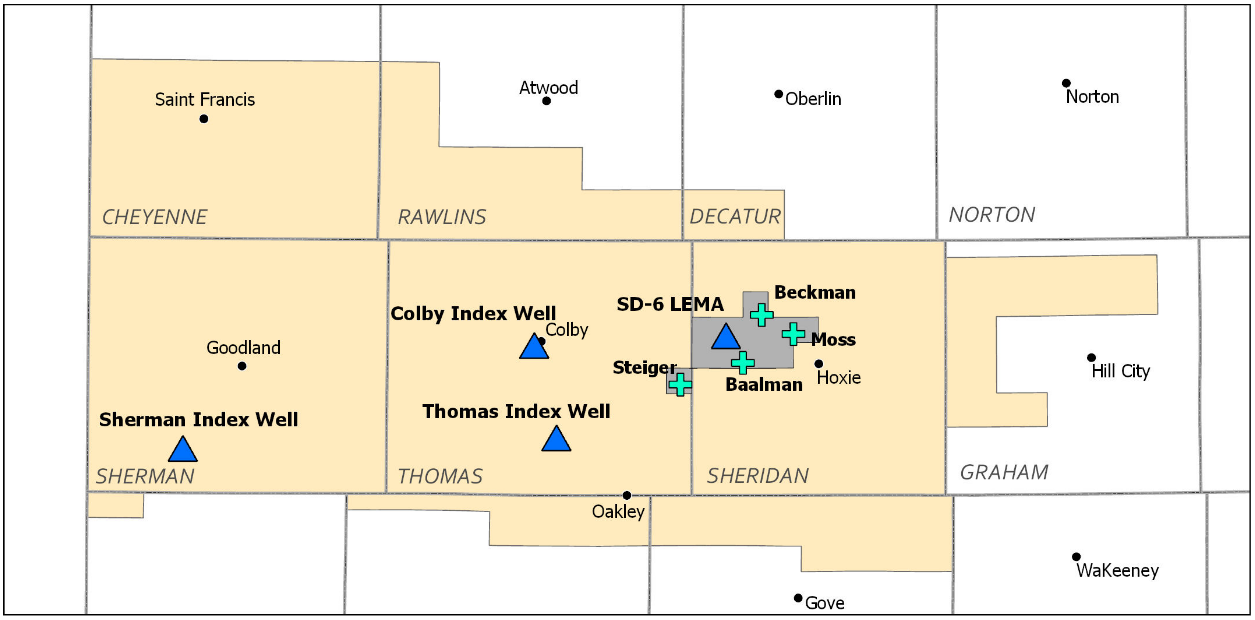

Figure 15—Map of index wells in GMD4. Triangles designate wells with telemetry equipment whereas plus signs designate wells without telemetry equipment. Data from wells with telemetry equipment can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml); data from wells without telemetry equipment are periodically downloaded (typically quarterly) and posted on the KGS website. Shaded area is the Sheridan-6 LEMA. The SD-6 Seegmiller well is the triangle within the SD-6 LEMA area.

3.3.1 Colby Index Well

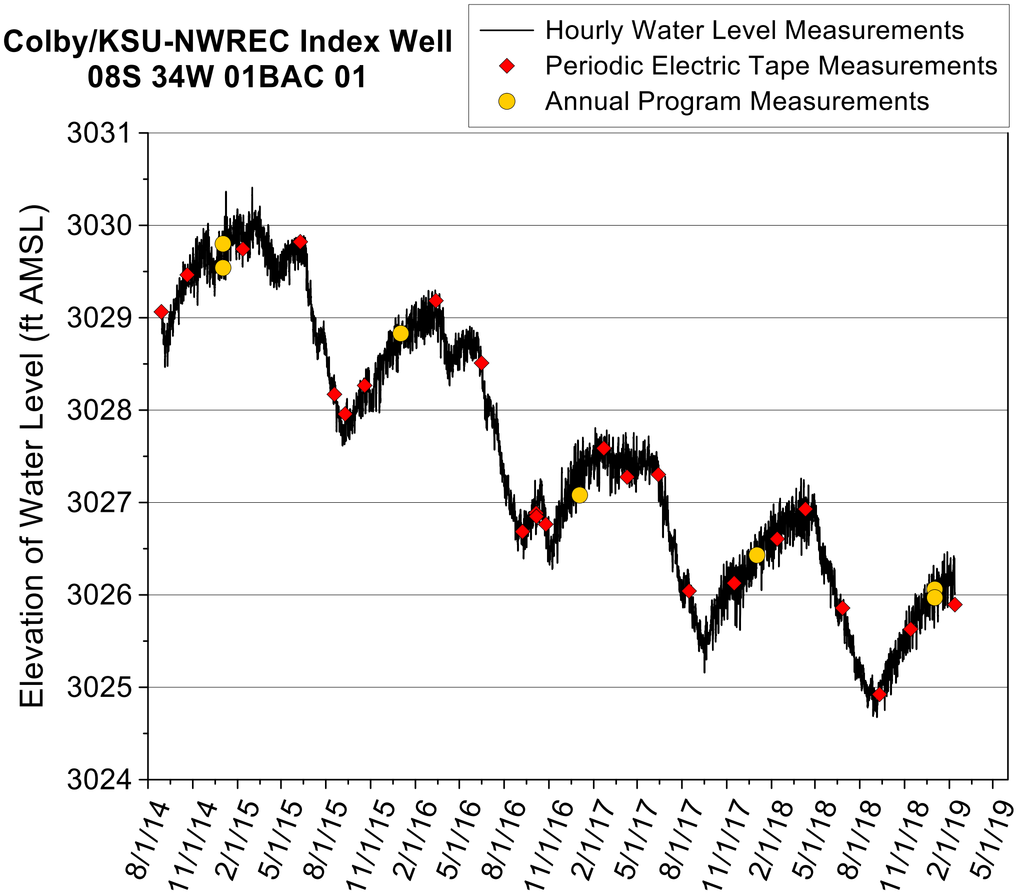

Figure 16—Colby index well hydrograph—total data run to 2/12/19. A water-level elevation of 3,029 ft corresponds to a depth to water of 148 ft below lsf. Total depth of the well is 175 ft below lsf (elevation of 3,002 ft). The screened interval extends from 156 to 175 ft below lsf. The base of the aquifer is estimated to be 250–300 ft below lsf (Butler et al., 2017).

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 in most years continue to recover until the start of the next season; apparent stabilization of water levels in late winter and early spring of 2017 is likely 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 0.91 ft/yr over the monitoring period and a total of 36.8 ft since January 1948.
- Transducer readings are in good agreement with manual measurements.

3.3.2 SD-6 Baalman Index Well

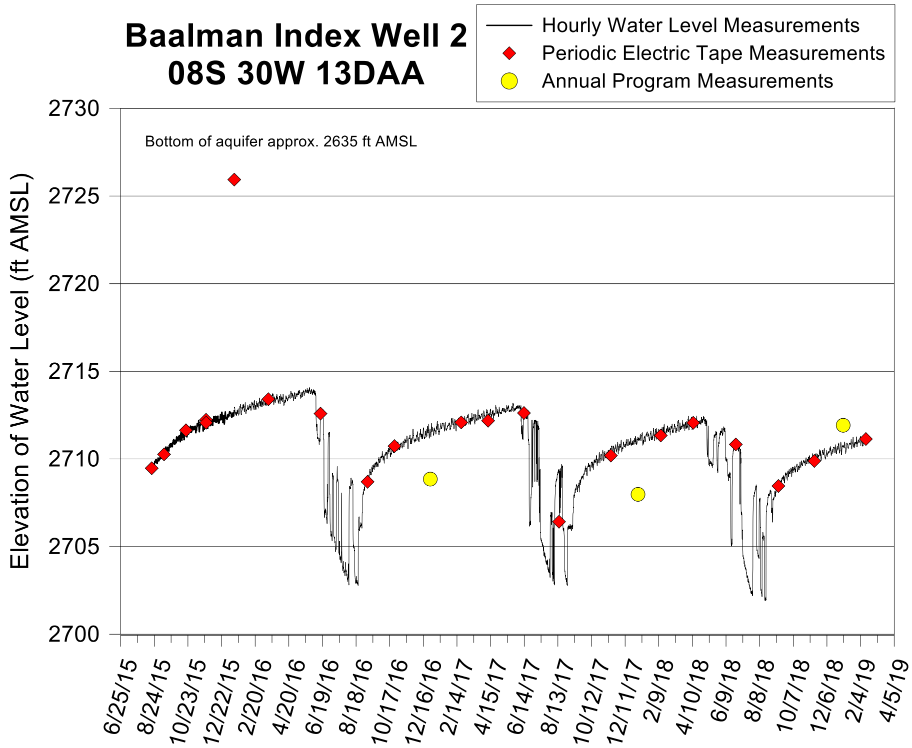

Figure 17—Baalman index well hydrograph—total data run to 2/13/19. A water-level elevation of 2,712 ft corresponds to a depth to water of 185 ft below lsf. The top of the 10 ft screen is 260 ft below lsf (elevation of 2,637 ft), and the bottom of the aquifer is 262 ft below lsf (elevation of 2,635 ft). 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.
- Near the end of the recovery period, water levels appear to be converging on a value that is below the water level at the start of the pumping season; this pattern is often an indication that lateral flow to the well is constrained, which could either be a result of nearby low-permeability units or substantial pumping in the surrounding area that decreased lateral flow to the index well location.
- Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.77 ft (9.2 inches)/acre in the vicinity of the Baalman index well (2 mi radius).
- Transducer readings are in good agreement with periodic electric-tape measurements except for the January 2016 measurement but poor agreement with annual program measurements.

3.3.3 SD-6 Beckman Index Well

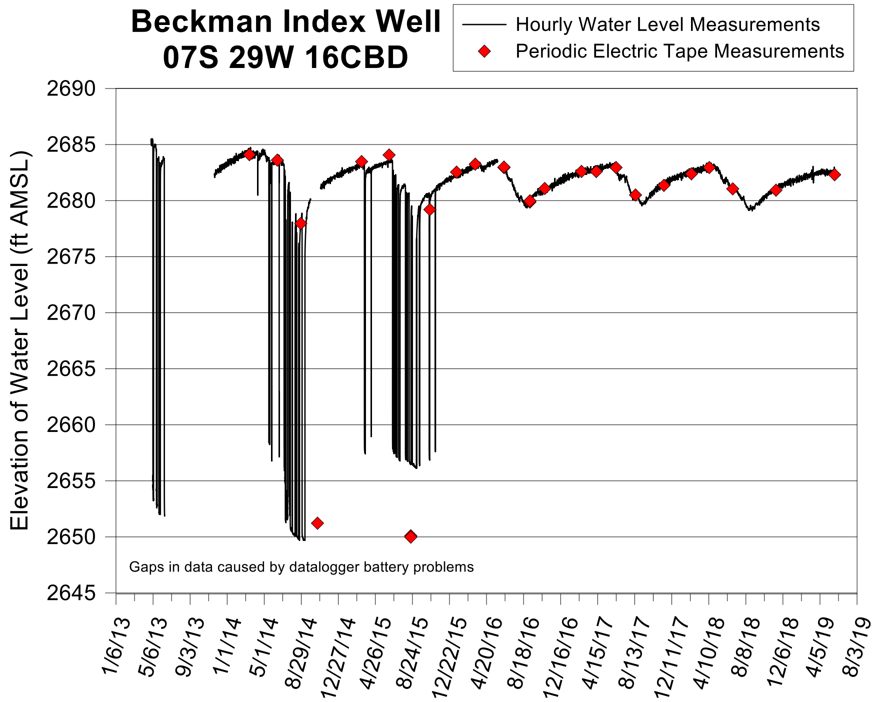

Figure 18—Beckman index well hydrograph—total data run to 5/22/19 (damage to well site prevented downloading of data in February 2019—repaired in late spring of 2019). A water-level elevation of 2,680 ft corresponds to a depth to water of 200.15 ft below lsf. The difference between the electric-tape 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 does not appear to have been pumped for the last three irrigation seasons; pumping at nearby wells, however, did continue throughout the monitoring period.
- The relatively large amplitude fluctuations superimposed on the water levels, particularly evident during the recovery period, are an indication of unconfined conditions.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.73 ft (8.7 in)/acre in the vicinity of the Beckman index well (2 mi radius).
- Transducer readings are in good agreement with manual measurements in the latter half of the monitoring period.

3.3.4 SD-6 Moss Index Well

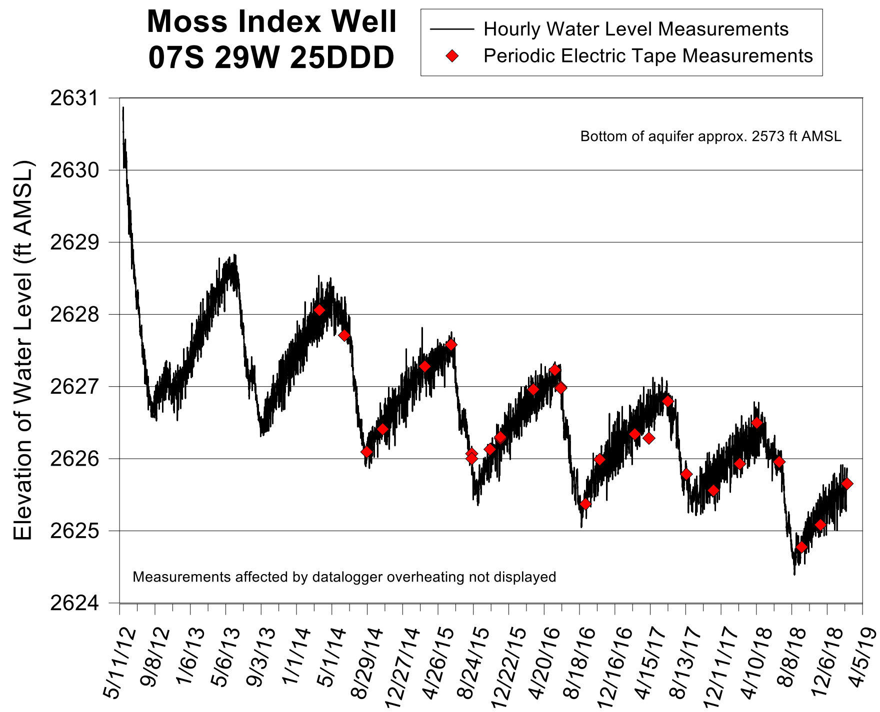

Figure 19—Moss index well hydrograph—total data run to 2/13/19. A water-level elevation of 2,627 ft corresponds to a depth to water of 189.0 ft below lsf. The top of the 40 ft screen is 205 ft below lsf (elevation of 2,611.0 ft), and the bottom of the aquifer is 243 ft below lsf (elevation of 2,573.0 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 has been above that of the preceding year once (2017). 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 0.84 ft (10.0 in)/acre in the vicinity of the Moss index well (2 mi radius).
- Transducer readings are in good agreement with manual measurements.

3.3.5 SD-6 Seegmiller Index Well

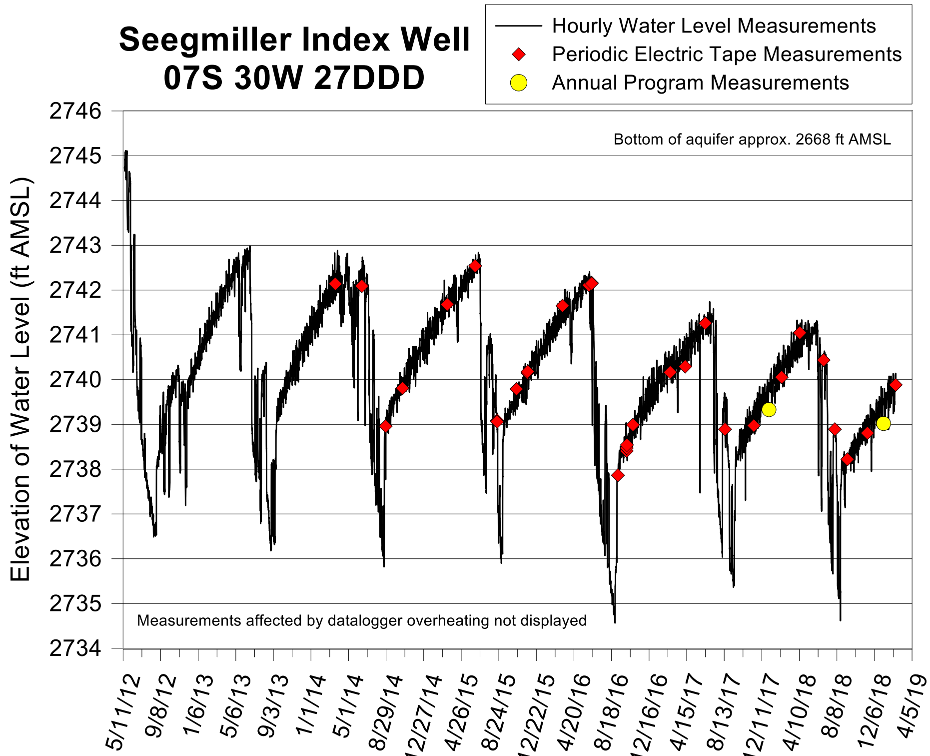

Figure 20—Seegmiller index well hydrograph—total data run to 2/13/19. A water-level elevation of 2,740 ft corresponds to a depth to water of 193.0 ft below lsf. The top of the 40 ft screen is 225 ft below lsf (elevation of 2,708.0 ft), and the bottom of the aquifer is 265 ft below lsf (elevation of 2,668.0 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 for 2017 was 0.8 ft above that of 2016, the largest increase observed during the monitoring period. The minimum level for 2018 was the same as that of 2016.
- Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.77 ft (9.2 in)/acre in the vicinity of the Seegmiller index well (2 mi radius).
- Transducer readings are in good agreement with manual measurements.

3.3.6 SD-6 Steiger Index Well

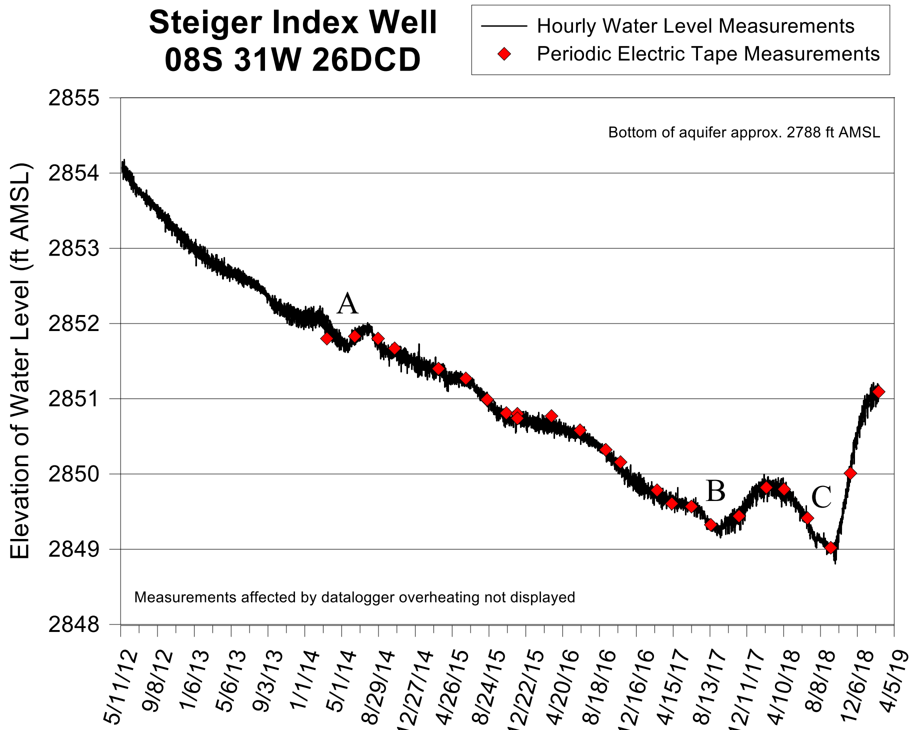

Figure 21—Steiger index well hydrograph—total data run to 2/13/19. A water-level elevation of 2,851 ft corresponds to a depth to water of 114.0 ft below lsf. The top of the 40 ft screen is 145 ft below lsf (elevation of 2,820.0 ft), and the bottom of the aquifer is 177 ft below lsf (elevation of 2,788.0 ft). A, B, and C 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 beyond those marked A, B, and C.
- The effect of individual wells cutting on and off cannot be discerned.
- It is difficult to ascertain a consistent picture of behavior during non-pumping periods; water levels have been rising continuously since the end of the 2018 pumping season.
- Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.85 ft (10.2 in)/acre in the vicinity of the Steiger index well (2 mi radius).
- Transducer readings are in good agreement with manual measurements.

3.3.7 Sherman County Index Well

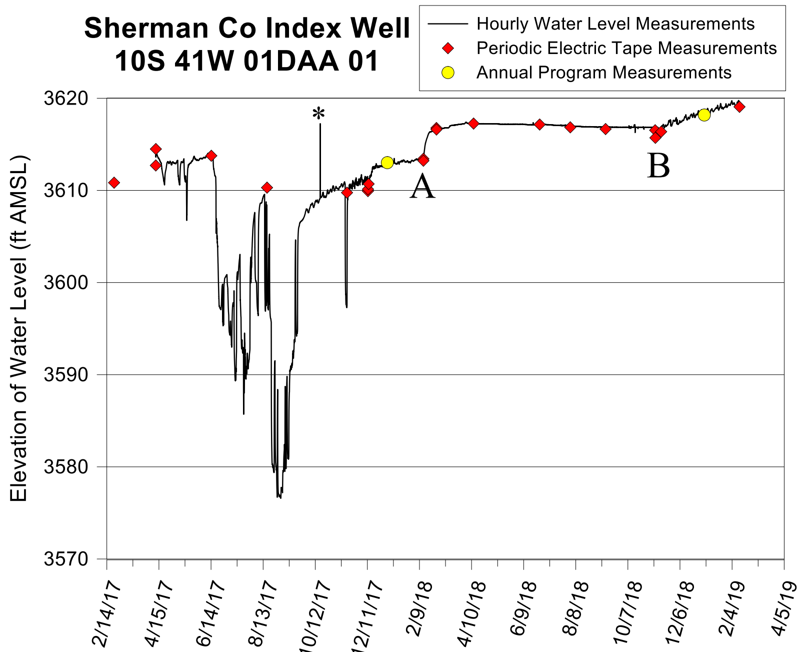

Figure 22—Sherman County index well hydrograph—total data run to 2/12/19. A water-level elevation of 3,617 ft corresponds to a depth to water of 177 ft below lsf. The top of the 10 ft screen is 310 ft below lsf (elevation of 3,484 ft), and the bottom of the aquifer is 323 ft below lsf (elevation of 3,471 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 sensor was originally placed 3.2 ft below the top of the sump. The sump, however, completely filled with fine-grained sediments during the monitoring period. Thus, hydrograph responses are not considered reliable until a new sensor was placed in the well 8.6 ft above the top of the screen (301.4 ft below lsf) on 2/13/18 (A on plot). The record acquired with the new sensor shows that the effect of barometric pressure fluctuations is negligible, an indicator of a screened interval that is in very poor hydraulic connection with the aquifer. In addition, there is no indication of pumping during the 2018 irrigation season. Well development on 11/7/18 (B on plot) reestablished the hydraulic connections between the well and the aquifer; this is reflected by the sizable response to barometric pressure fluctuations and the recovering water levels.
- 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 with the new sensor after 2/13/18.
- The sensor removed from the well was thoroughly cleaned and then tested in the laboratory. The sensor performed well, indicating that the responses obtained early in the monitoring period (before the sump filled with fines) were likely reliable measures of the position of the water level in the well.

3.3.8 Thomas County Index Well

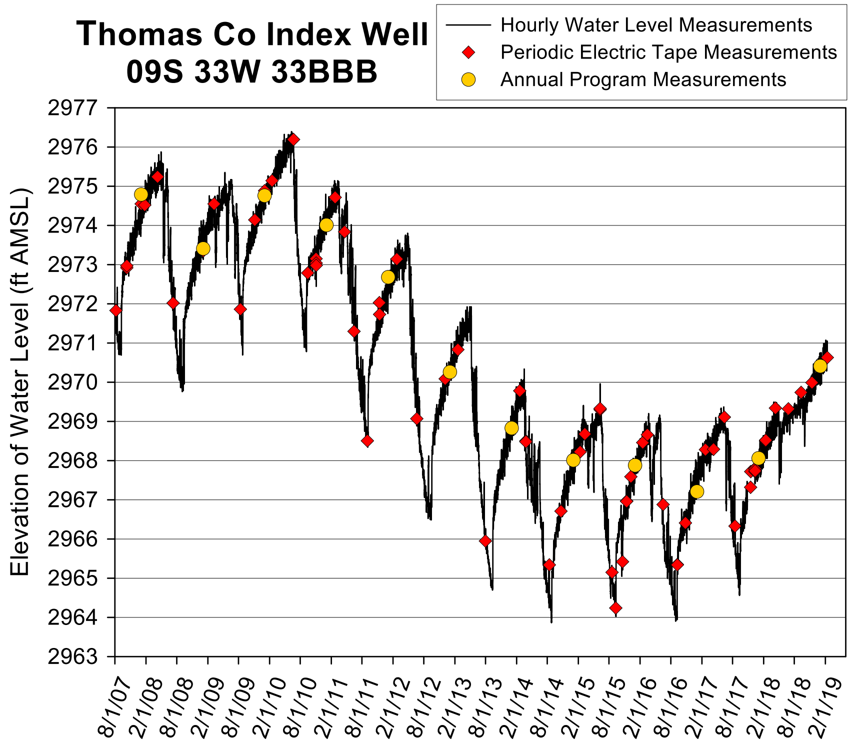

Figure 23—Thomas County index well hydrograph—total data run to 2/12/19. A water-level elevation of 2,968 ft corresponds to a depth to water of 219.56 ft below lsf. The top of the screen is 274 ft below lsf (elevation of 2,913.6 ft), and the bottom of the aquifer is 284 ft below lsf (elevation of 2,903.6 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 failure of both sensor and backup sensor.

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 annual water-level measurement in 2019 was 2.35 ft above that of 2018, only the third time in the monitoring period that there has been a year-on-year increase in water level at this well; such increases indicate years in which the net inflow to the area around the well exceeded the pumping.
- 2018 water use was likely 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.
- Transducer readings are in good agreement with manual measurements.

3.4 GMD5 Index Wells

Two index wells are located in GMD5, both of which have telemetry equipment that allows real-time viewing of data (fig. 24). Table 4 summarizes characteristics of these two wells. Further details concerning the Belpre well are given in the 2016 annual report (Butler 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 4—Characteristics of the GMD5 index well sites.

Site	2019 WL elev. (ft)[a]	2019 saturated thickness (ft)	Bedrock depth (ft below land surface)	Screened interval (ft below land surface)	2017 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
Belpre	2,040.92	135.2–160.9[b]	175–200[b]	89–109	496	2,336	18,378
Larned	1,943.72	59.4	71	66–71	279	3,283	18,707

[a] 2019 annual tape water-level measurements from WIZARD database.
[b] Well not drilled to bedrock; depth to bedrock estimated from nearby well logs.

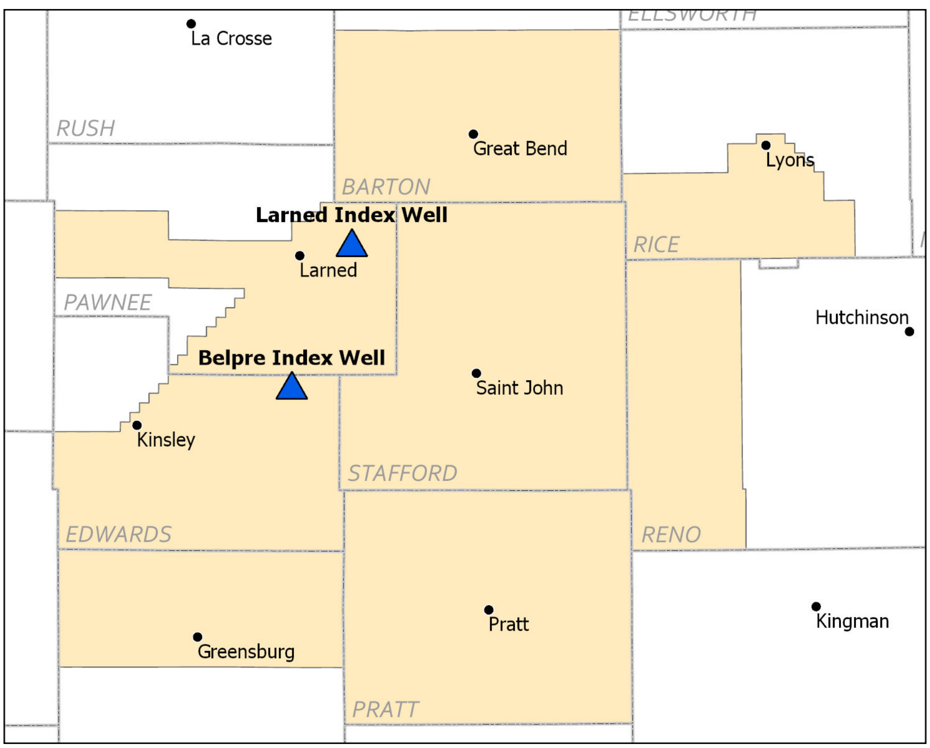

Figure 24—Map of GMD5 with Belpre and Larned index wells (blue triangles). Data from both wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml).

3.4.1 Belpre Index Well

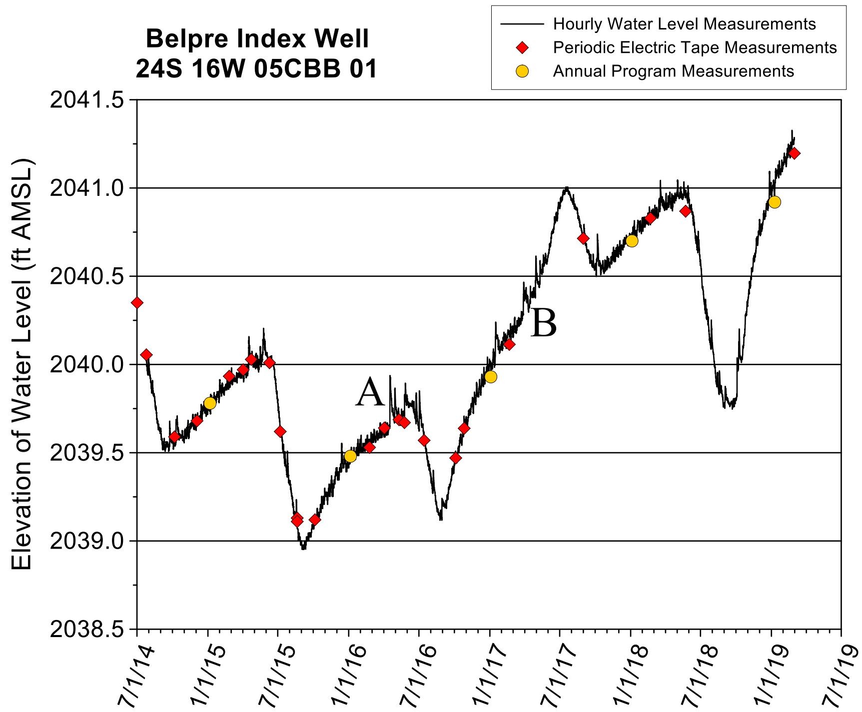

Figure 25—Belpre index well hydrograph—total data run to 3/1/19. A water-level elevation of 2,040 ft corresponds to a depth to water of 40 ft below lsf. The top of the 20 ft screen is 89 ft below lsf (elevation of 1,991 ft), and the bottom of the screen is 109 ft below lsf (elevation of 1,971 ft). The 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 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.
- 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 flow (Butler et al., 2017). The kink in the plot at B was produced by regional recharge events from widespread precipitation, which led to an increase of water level over previous years and a late start to the 2017 pumping season.
- At the time of this report, the water level is the highest since the start of continuous monitoring.
- The water level has declined 9.60 ft since January 1988 (decline rate of 0.31 ft/yr).
- Transducer readings are in good agreement with manual measurements.

3.4.2 Larned Index Well

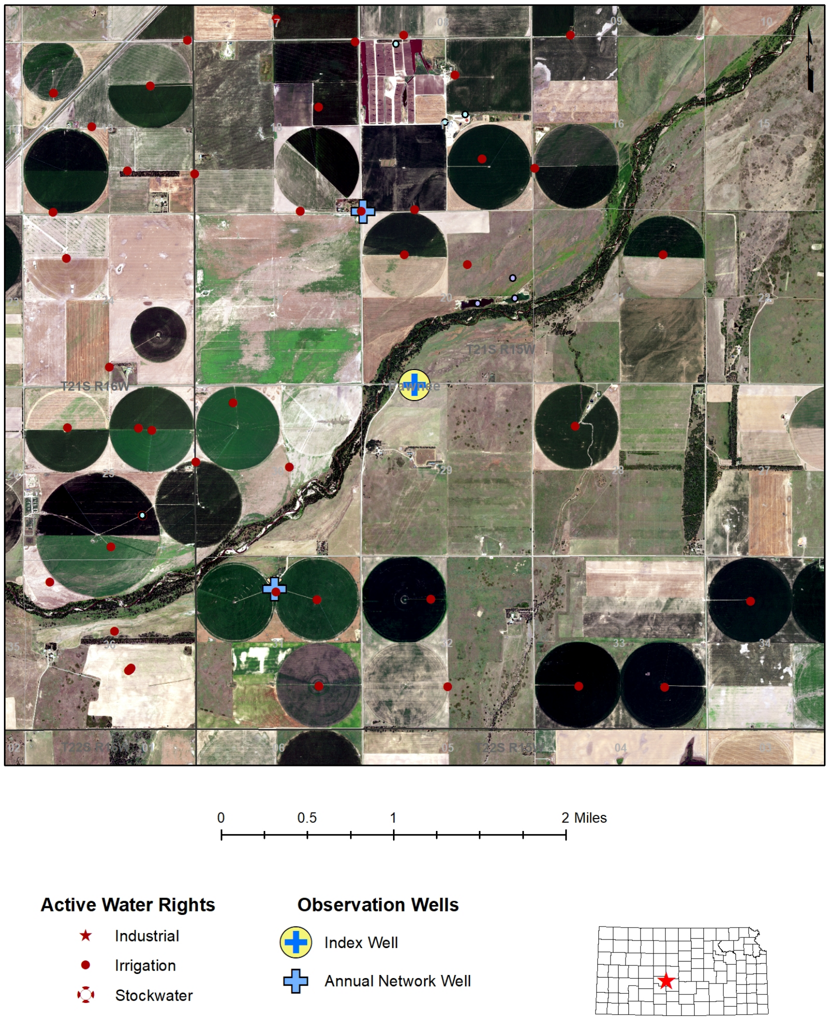

Figure 26—Aerial view of the Larned index well and nearby annual wells and points of diversion.

Figure 26 is an aerial view of the Larned index well site (T. 21 S., R. 15 W., 29 BAB 01) at a scale that shows the site of the index well, two additional annual program wells, and the nearby wells with active water rights. The site includes two wells in the overlying Arkansas River alluvial aquifer and one well in the HPA. The HPA well has been monitored off and on since 2002 but was only equipped with telemetry equipment in late May 2018. The HPA acts as a semiconfined aquifer in the vicinity of the Larned index well (Butler et al., 2011).

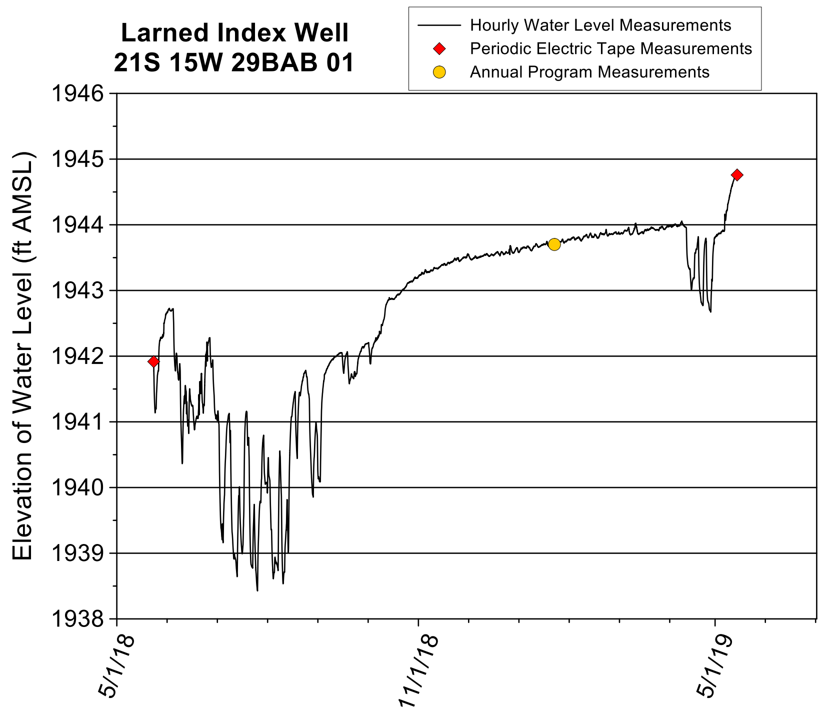

Figure 27—Larned index well hydrograph—total data run to 5/14/19. A water-level elevation of 1,944 ft corresponds to a depth to water of 11.3 ft below lsf. The top of the 5 ft screen is 66 ft below lsf (elevation of 1,889.3 ft), and the bottom of the screen, which is at the base of the aquifer, is 71 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.
- After the end of the irrigation season, water levels continue to recover until the start of the next season.
- The sharp increase in water-level in May 2019 was produced by a large flow event in the Arkansas River (maximum discharge reached 2,020 ft^3/s with a stage change greater than 6.25 ft).
- Transducer readings are in good agreement with manual measurements.

3.5 Expansion Wells

3.5.1 GMD1 Expansion Wells

Seven expansion wells (SC-8 and wells 1 through 6) are now operating in GMD1 (table 5 and fig. 28). 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 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).

Table 5—Characteristics of the GMD1 expansion well sites.

Site	2019 WL elev. (ft)	2019 saturated thickness (ft)[d]	Bedrock depth (estimated ft below land surface)[d]	Screened interval (ft below land surface)	2017 water use (ac-ft)		
					1 mi radius circle	2 mi radius circle	5 mi radius circle
SC-8	2,848.2[a]	85.2	174	NA	207	1,294	8,185[l]
Site 1	2,929.6[a]	26.6	195	NA	231[e]	852[e]	3,386[e]
Site 2	3,053.4[a]	42.4	160	NA	0	241	3,223[f]
Site 3	3,425.5[a]	22.5	220	NA	55	872	9,023[g]
Site 4	3,535.4[b]	[m]	[m]	NA	518	2,003	5,745[h]
Site 5	NA[c]	NA[c]	158	NA	367[i]	1,969[j]	8,341[k]
Site 6	3,300.6[a]	79.6	184	NA	0	220	1,055

[a] 2019 annual tape water-level measurements from WIZARD database.
[b] Not an annually measured index well; 2019 water-level measurements from average of transducer measurements from 8 a.m. to 4 p.m. on the date of the annual measurements for this area (1/4/19).
[c] Transducer stopped recording before the date of the annual water-level measurements for this area (1/4/19).
[d] Wells do not have WWC5 forms so values are estimated from nearby wells with WWC5 forms.
[e] Includes 89 ac-ft, 240 ac-ft, and 324 ac-ft of non-irrigation stock water for 1 mi, 2 mi, and 5 mi circles, respectively.
[f] Includes 81 ac-ft of non-irrigation stock water.
[g] Includes 20 ac-ft of municipal water and 92 ac-ft of non-irrigation stock water.
[h] Includes 255 ac-ft of industrial water and 259 ac-ft of non-irrigation stock water.
[i] Includes 21 ac-ft of non-irrigation stock water.
[j] Includes 351 ac-ft of municipal water and 21 ac-ft of non-irrigation stock water.
[k] Includes 697 ac-ft of municipal water and 173 ac-ft of non-irrigation stock water.
[l] Includes 697 ac-ft of municipal water and 193 ac-ft of non-irrigation stock water.
[m] Lack of agreement among nearby WWC5 forms prevented estimation.

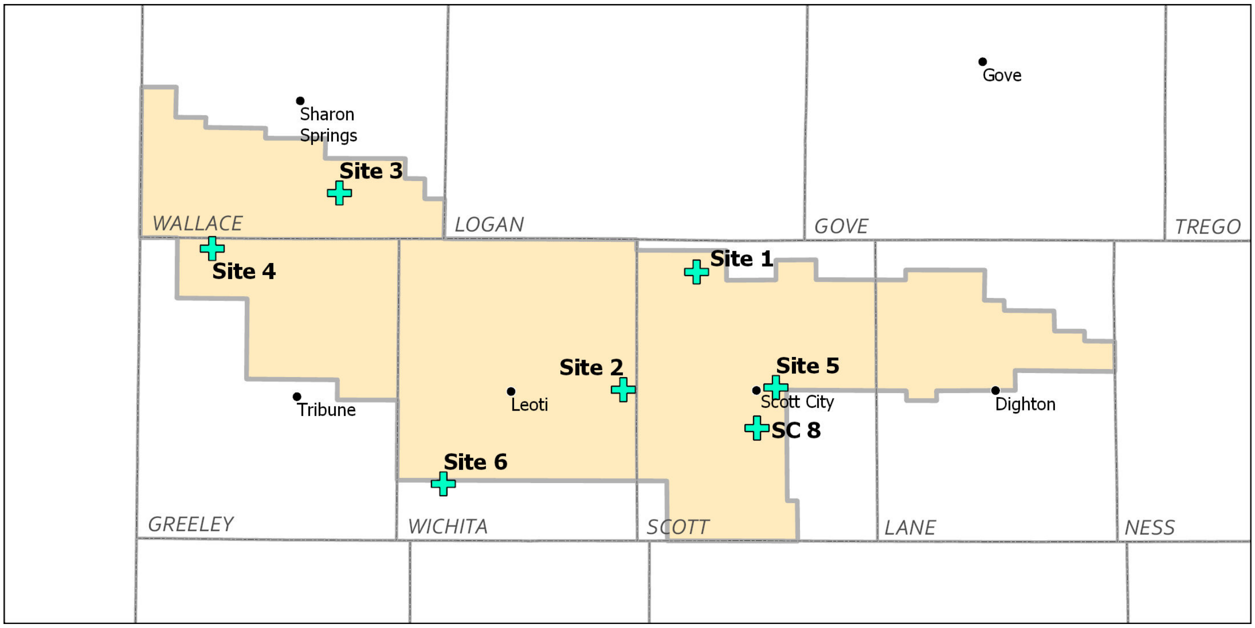

Figure 28—Map of the GMD1 expansion wells.

3.5.1.1 SC-8 Site – Scott County

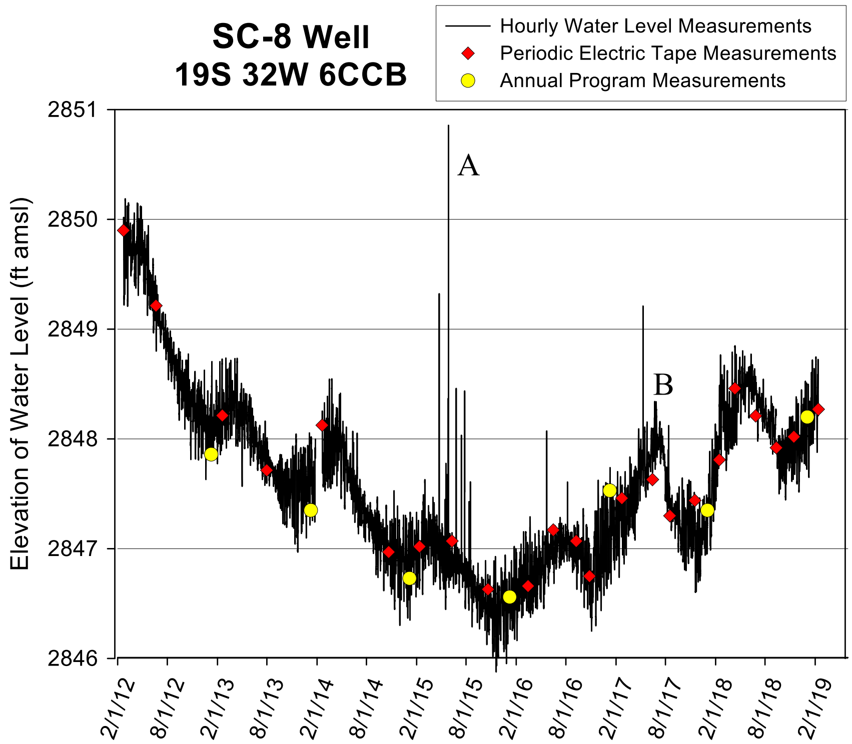

Figure 29—SC-8 well hydrograph—total data run to 2/12/19. A water-level elevation of 2,847 ft corresponds to a depth to water of 89 ft below lsf. Bottom of well is approximately 102 ft below lsf (elevation of 2,835 ft). Transducer measurements have been corrected from earlier reports for an incorrect offset parameter (Butler et al., 2017). A and B 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 et al., 2017). On August 15, 2017 (B), openings in the side of the casing at the land surface were sealed by GMD1 staff; large spikes have not been recorded since that time.
- The rise in the hydrograph after the 2018 annual measurement is the largest during the monitoring period; the reason for the rise has yet to be determined.
- Transducer readings are in good agreement with manual measurements.

3.5.1.2 Expansion Site 1 – Scott County

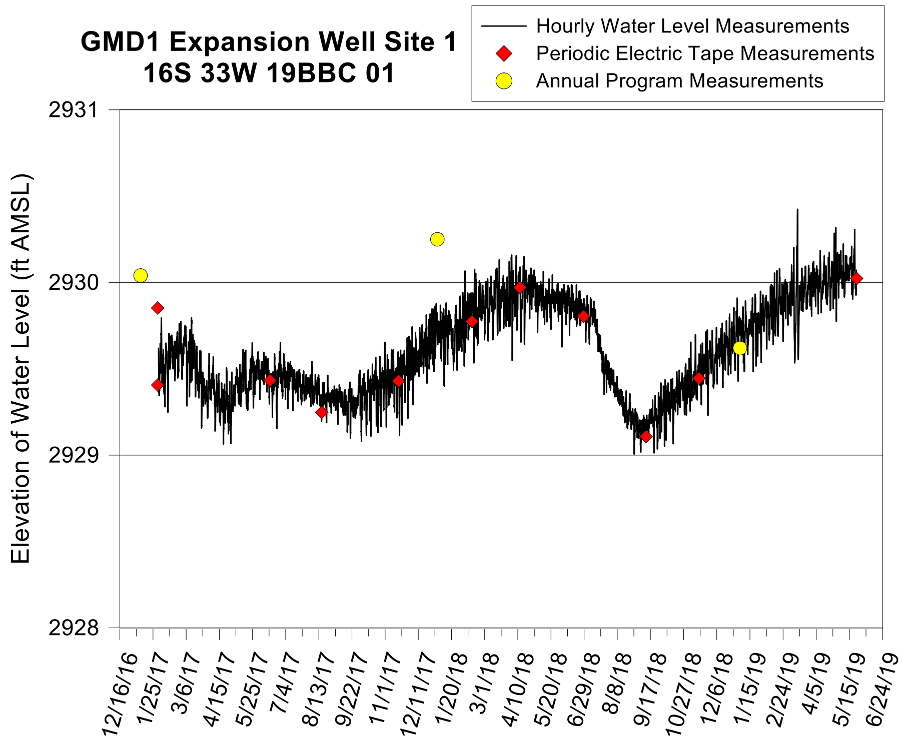

Figure 30—GMD1 Expansion Site 1 well hydrograph—total data run to 5/23/19. A water-level elevation of 2,930 ft corresponds to a depth to water of 168 ft below lsf. Bottom of well is 193.2 ft below lsf (elevation of 2,904.8 ft).

Major Points

- Moderate amplitude fluctuations superimposed on the water levels, which are particularly prominent during the recovery period, are an indication of unconfined conditions.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels never stabilize).
- Maximum water level for 2019 will be above that of 2017 and 2018.
- Transducer readings are in good agreement with electric-tape measurements after commencement of monitoring but not with 2018 annual program measurement.

3.5.1.3 Expansion Site 2 – Wichita County

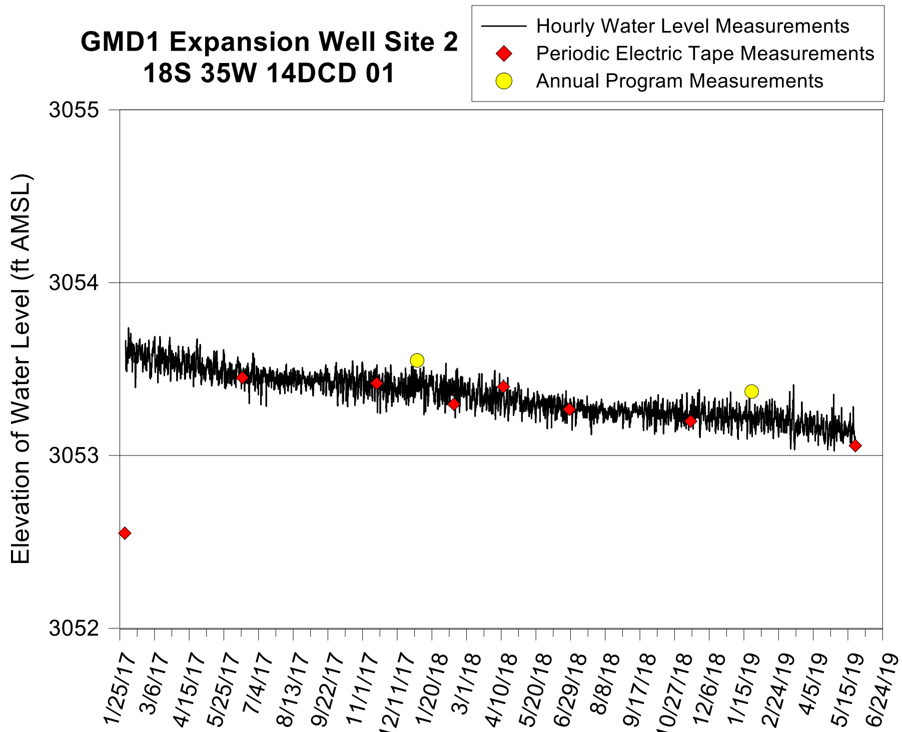

Figure 31—GMD1 Expansion Site 2 well hydrograph—total data run to 5/23/19. A water-level elevation of 3,053 ft corresponds to a depth to water of 118 ft below lsf. Bottom of well is 130.9 ft below lsf (elevation of 3,040.1 ft). First electric-tape measurement may be a transcription error.

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 (smaller range during the summer).
- It is difficult to discern pumping and recovery seasons; cannot discern effect of individual wells cutting on and off.
- Water level has changed little (1.44 ft) since January 1988.
- Transducer readings are in good agreement with manual measurements after the first electric-tape measurement.

3.5.1.4 Expansion Site 3 – Wallace County

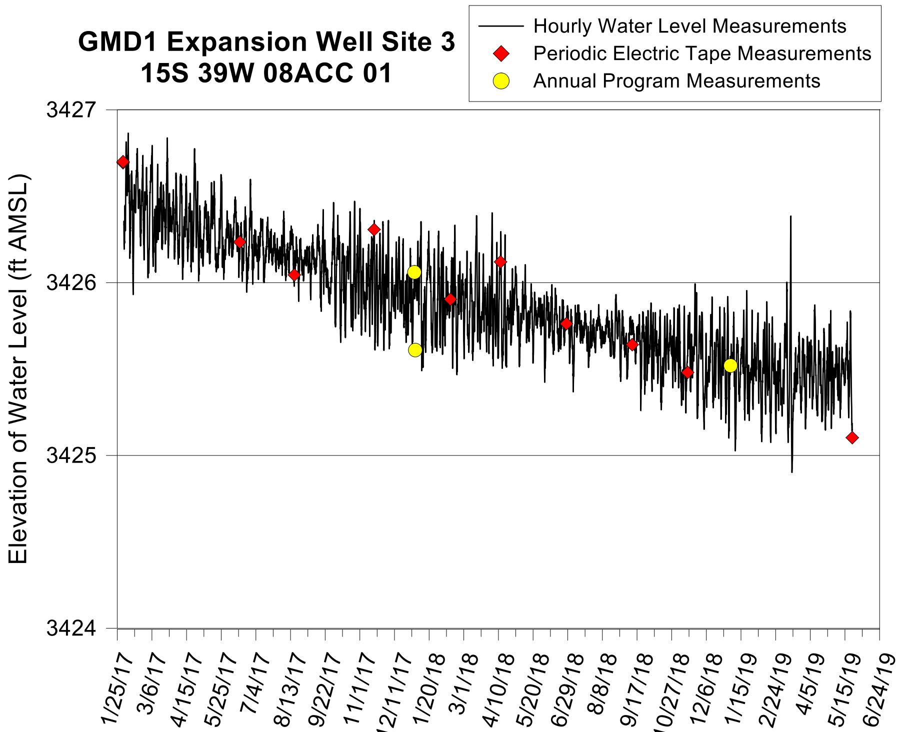

Figure 32—GMD1 Expansion Site 3 well hydrograph—total data run to 5/23/19. A water-level elevation of 3,426 ft corresponds to a depth to water of 197 ft below lsf. Bottom of well is 219.9 ft below lsf (elevation of 3,403.1 ft).

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 (smaller range during the summer).
- It is difficult to discern pumping and recovery seasons; cannot discern the effect of individual wells cutting on and off.
- Water level has declined 4.1 ft since 2008 (0.37 ft/yr) and 34.4 ft since 1988 (1.11 ft/yr).
- Transducer readings are in good agreement with manual measurements.

3.5.1.5 Expansion Site 4 – Greeley County

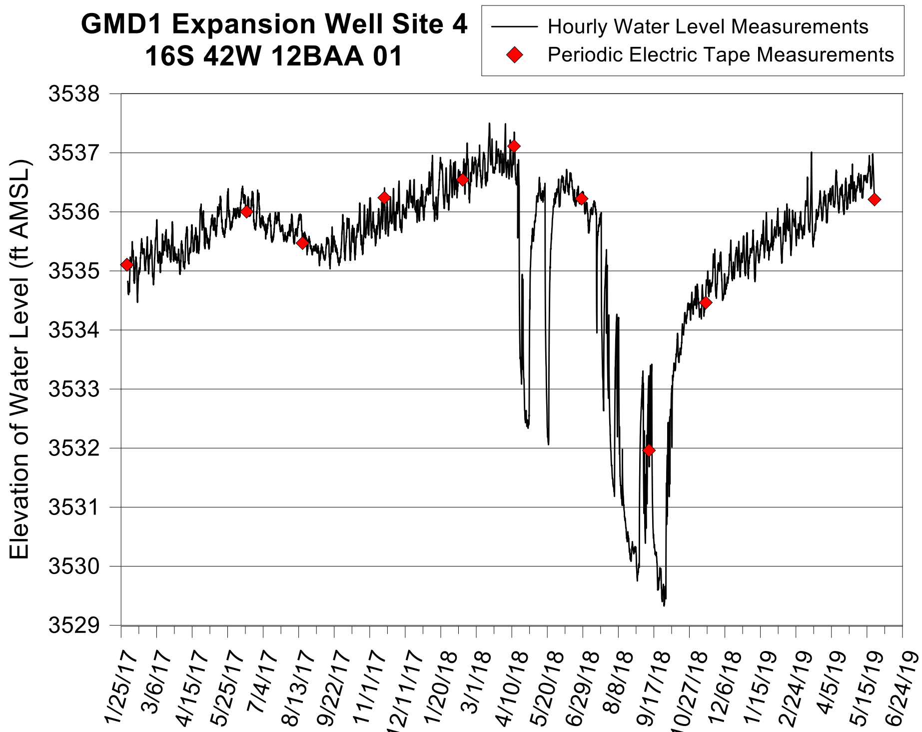

Figure 33—GMD1 Expansion Site 4 well hydrograph—total data run to 5/23/19. A water-level elevation of 3,537 ft corresponds to a depth to water of 236 ft below lsf. Bottom of well is 264.5 ft below lsf (elevation of 3,508.5 ft).

Major Points

- Relatively large amplitude fluctuations superimposed on the water levels are an indication of an unconfined aquifer.
- Little nearby pumping in 2017 irrigation season but much more in 2018. Effect of one or more nearby individual wells cutting on and off is clearly seen in the 2018 irrigation season.
- After the end of the irrigation season, water levels continue to recover until the start of the next season (water levels do not stabilize).
- Transducer readings are in good agreement with manual measurements.

3.5.1.6 Expansion Site 5 – Scott County

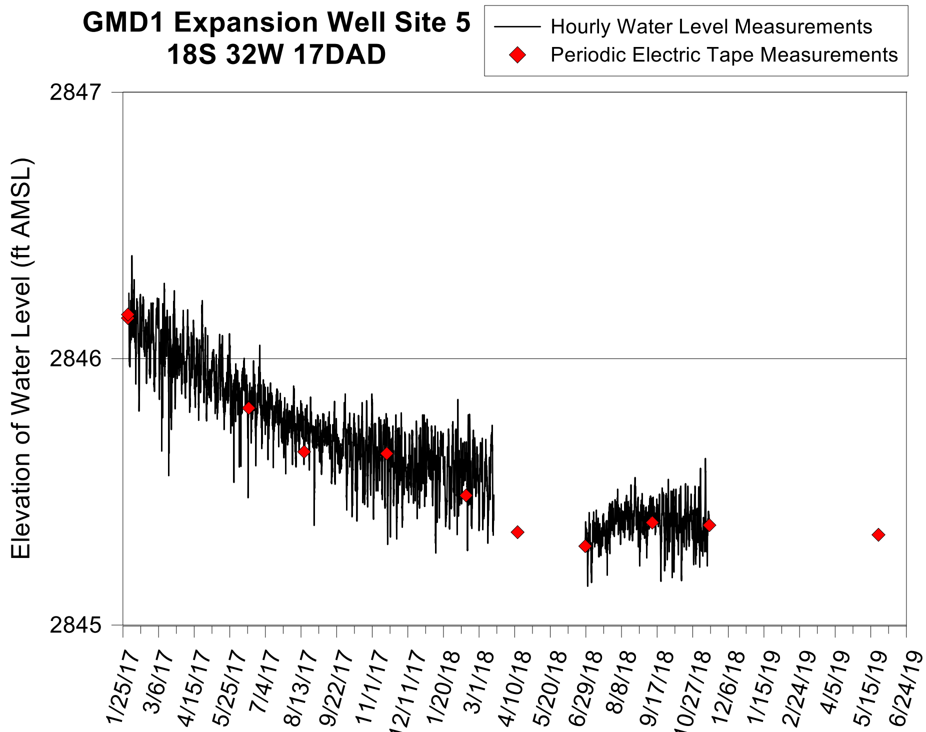

Figure 34—GMD1 Expansion Site 5 well hydrograph—total data run to 11/14/18, sometime after which the battery died. A water-level elevation of 2,846 ft corresponds to a depth to water of 130 ft below lsf. Elevation of well bottom is not known.

Major Points

- Moderate amplitude fluctuations superimposed on the water levels are an indication of an unconfined aquifer.
- It is difficult to discern the effect of individual wells cutting on and off.
- The battery died on 3/17/18 and then again sometime between 11/14/18 and 5/23/19. Transducer-datalogger unit removed from well on 5/23/19. Unit will likely be replaced.
- The water level at a nearby annual well (18S 32W 17ABA 02) has fallen 11.9 ft since 2008 (1.1 ft/yr) and 29.2 ft since 1988 (0.9 ft/yr).
- Transducer readings are in good agreement with manual measurements.

3.5.1.7 Expansion Site 6 – Wichita County

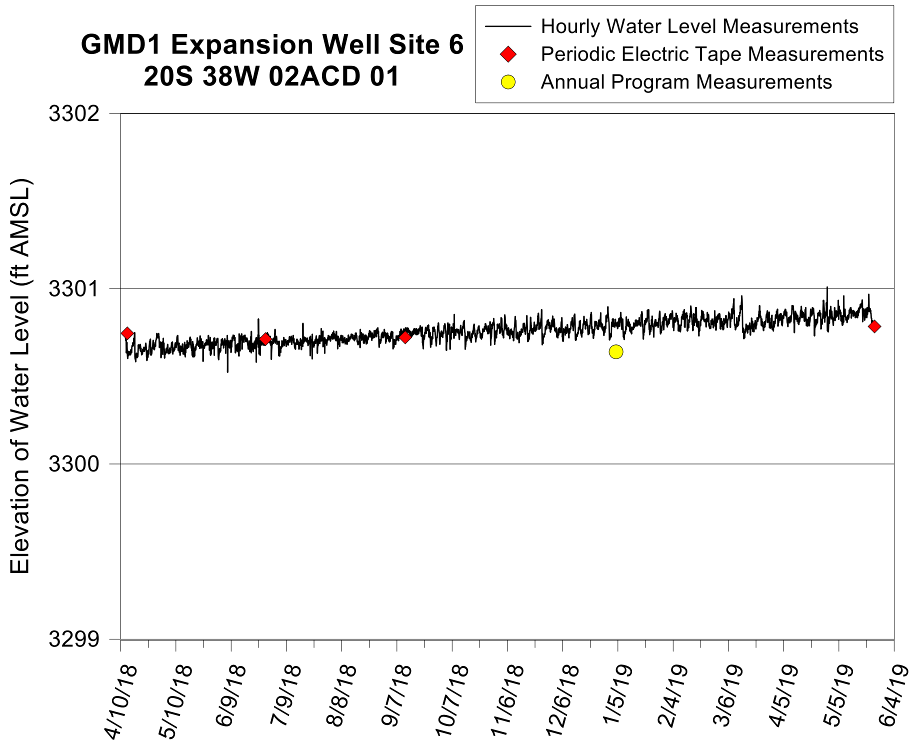

Figure 35—GMD1 Expansion Site 6 well hydrograph—total data run to 5/24/19. A water-level elevation of 3,301 ft corresponds to a depth to water of 104 ft below lsf. Elevation of well bottom is not known. Bottom of aquifer is at an elevation of 3,221 ft (184 ft below lsf).

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; the small seasonal variations in the amplitude are produced by seasonal changes in the range over which barometric pressure can vary (smaller range during the summer).
- It is difficult to discern the effect of any nearby or regional pumping.
- The water table has been slowly rising over the monitoring period in comparison with a slowly declining water level during 2005 to 2016 for a former annual measurement well about 0.25 mi distant.
- No reported 2017 water use in 1 mi radius circle centered on well; smallest 2017 water use for 5 mi radius circle of any index or expansion well.
- Transducer readings are in relatively good agreement with manual measurements.

3.5.2 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 et al. (2017) and earlier reports for a discussion of the hydrographs from those wells.

3.5.3 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 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 pumping volume is determined by the number of operating irrigation wells and the amount of water pumped from each well. The major drivers for the per-well amount 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 transmissivity is not near the lower limit for an irrigation well, then the main factor controlling the annual pumping is the meteorological conditions for a given year.

Since 1997, the number of water-right permitted wells (mainly irrigation wells) in the three western GMDs has remained nearly constant. The large increase in the number of points of diversion (wells) occurred during the 1950s through the early 1980s; the increase from 1997 to 2017 ranged from less than a percent to several percent of the current total, depending on the county. For example, the number of unique points of groundwater diversion, which were active/non-dismissed, authorized through appropriated and vested groundwater rights in Thomas, Scott, and Haskell counties in 2018 were 854, 906, and 1,071, respectively. The number of points of diversion active in 2018 that were added after 1997 are 26 (3.1% increase), 16 (1.8% 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 include lateral groundwater flow, precipitation recharge (including focused recharge over intermittent stream valleys and playas, and enhanced precipitation recharge over irrigated fields due to higher soil moisture), irrigation return flow, decreased groundwater discharge to streams due to declining groundwater levels, drainage through fine-grained sediment in newly created unsaturated zones, flow down the gravel pack in the annular space of well boreholes, and any vertical groundwater flow across the interface of the HPA and underlying bedrock.

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 six years, relative to practices for similar climatic conditions before the establishment of the LEMA, to achieve true water savings.

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 the cooperative measurements made by the USGS, with DWR continuing its measurements. The KGS then developed additional procedures 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 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 36 shows an image of the percent of normal annual precipitation during 2018 from the NWS website. The data are stored as gridded cells (up to 2017 data) and now in raster format with 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.

Just as in 2017, 2018 annual precipitation exceeded normal precipitation over most of the western third of the state (the Ogallala region of the HPA – GMDs 1, 3, and 4). However, the percentage exceedance was generally greater in 2018 than in 2017. In the Quaternary region of the HPA in south-central Kansas (GMDs 2 and 5), the 2018 annual precipitation also exceeded normal precipitation, in contrast to near normal in 2017. In addition, the map reveals the substantial spatial variation in precipitation within regions such as climatic divisions or GMDs.

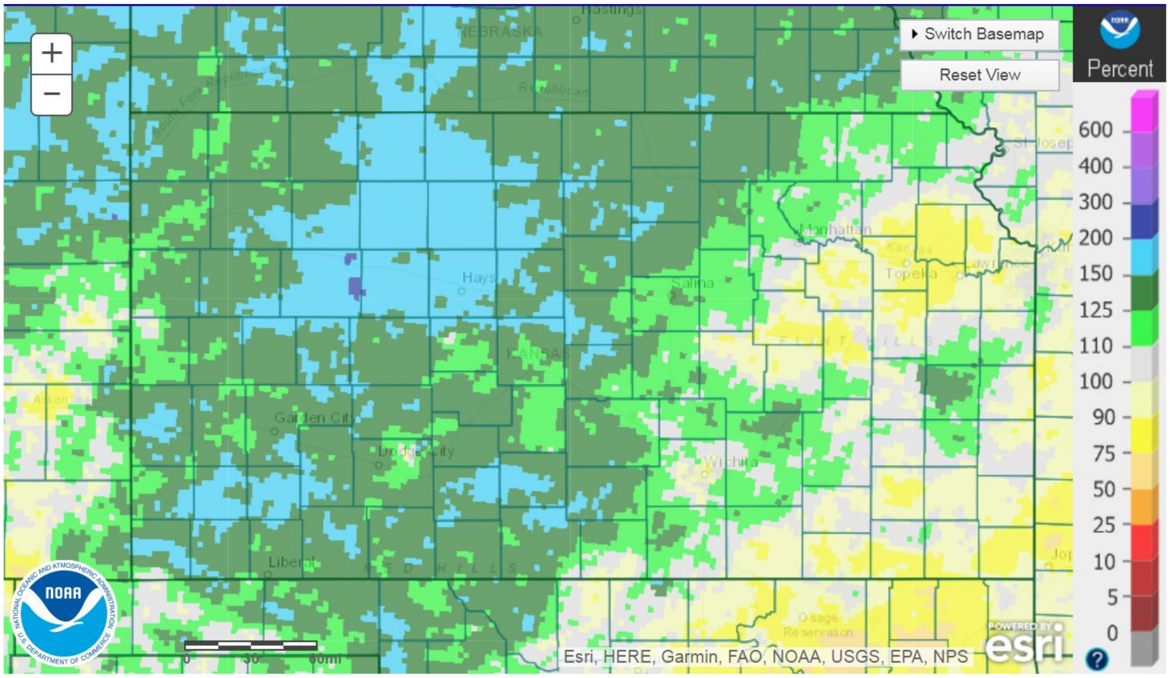

Figure 36—Percent of normal radar precipitation for Kansas in 2018. County lines and the state boundary (bolded) are displayed.

4.4 Water-Level Change in the Groundwater Management Districts

Figure 37 displays the mean annual year-to-year changes in winter water levels during 2005–2018 for the GMDs currently involved in the index well program; these values are based on wells for which measurements were made every winter from 2005 to 2019. 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 the four GMDs currently involved in the index well program generally mimic the variations in radar precipitation (March–October sum), which are also displayed on fig. 37. The annual water-level changes in the three western GMDs in 2017 were either the smallest annual decline (GMD1) or the only (GMD3) or largest rise above zero (GMD4) during the 2005–2018 monitoring period. These 2017 changes were consistent with the relatively large 2017 radar precipitation values. The water-level changes in 2018 also were not far from zero; the change for GMD1 was essentially zero and the changes for GMDs 3 and 4 were within ±0.4 ft of zero, reflecting the generally wetter than normal precipitation. In contrast, the annual water-level changes in GMD5 in 2017 and 2018 were positive but not close to the maximum value observed in 2007 for the period. The 2017 March–October precipitation in GMD5 was above average but below that for 2007 and three other years; however, the 2018 precipitation was the greatest observed during 2005–2018.

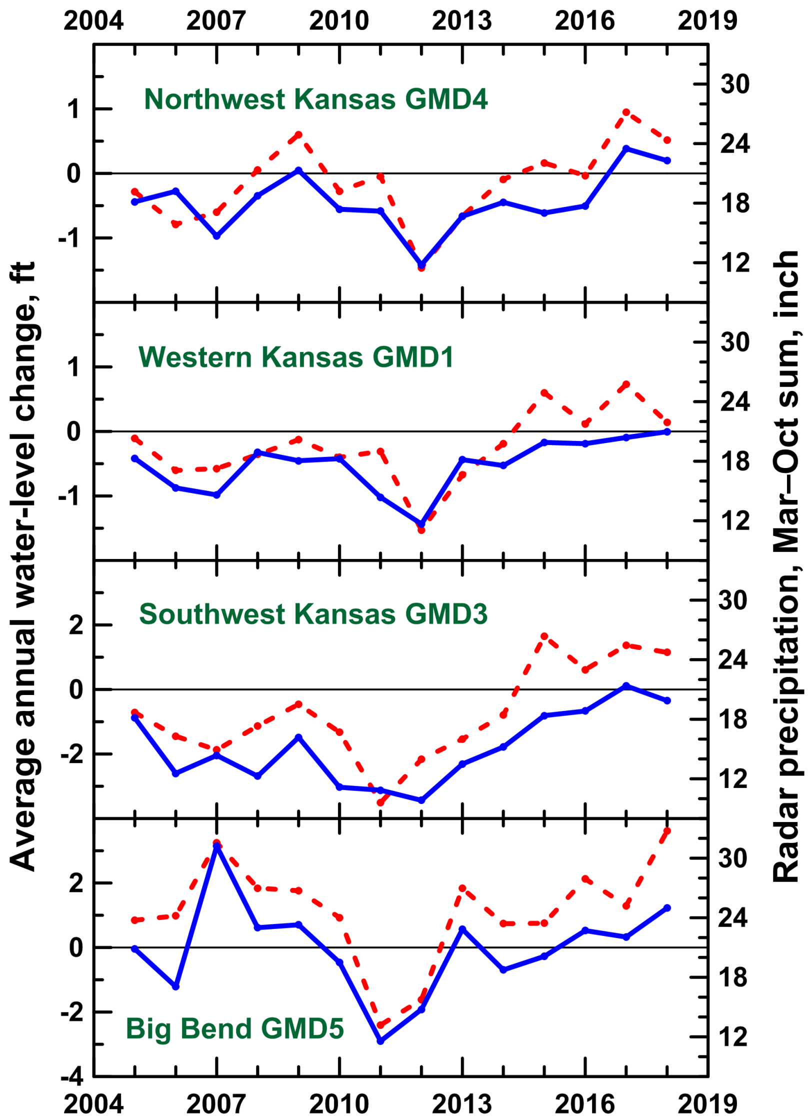

Figure 37—Mean annual water-level change and radar precipitation (sum of March–October precipitation) for GMDs 4, 1, 3, and 5 during 2005–2018. The water-level change for a particular year is the water-level difference between the following year and that year for continuously measured wells for 2005–2019. 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 by steel tape in the original three index wells since January 2008. Figure 38 shows the annual water-level changes for both the tape and transducer values for 2008–2018 (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. 37) . 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 2008–2018 (fig. 38). 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 2015 and 2018, the directions of change in the annual water-level changes for the Thomas and Scott index wells are 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.

Although the changes in the 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 2018 are 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) and variations in pumping related to the court-ordered shutdown of nearby irrigation wells (see section 3.2.2).

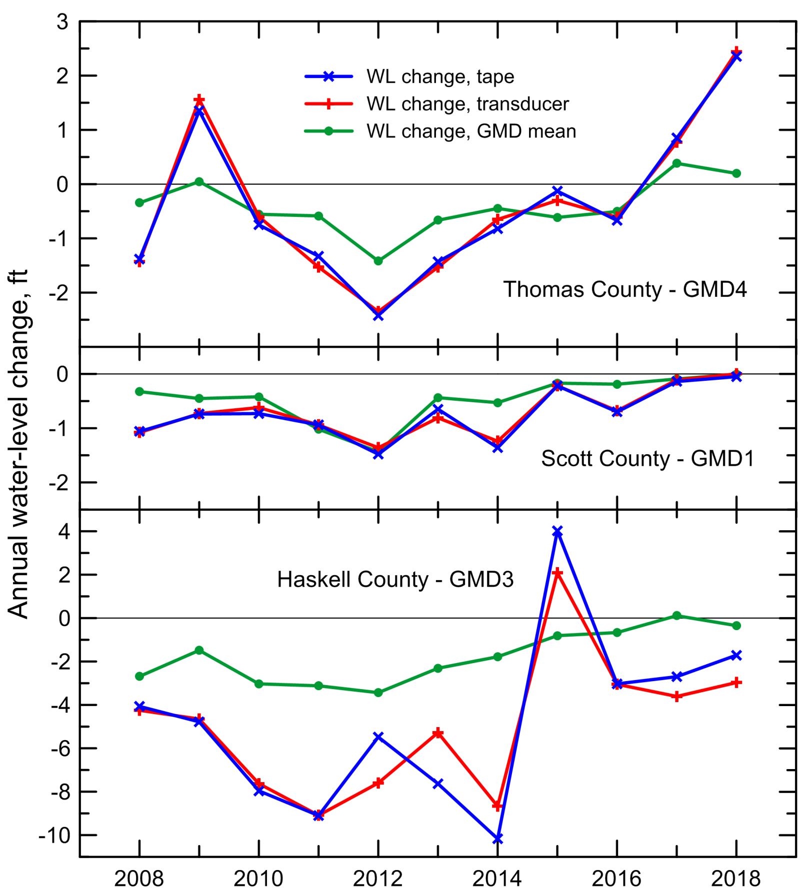

Figure 38—Annual winter water-level changes in the original three index wells and the mean annual changes in the three GMDs in western Kansas in which they are located. Note the different y-axis range for Haskell County versus that for Thomas and Scott counties; suspect 2013 tape measurement at the Haskell index well caused the 2012 and 2013 tape water-level change values to be markedly different from those based on the transducer measurements.

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

One of the major accomplishments of the index well program has been the discovery of the strong linear relationship between annual water use and annual water-level change in the Kansas HPA and the development of the theoretical support for that relationship. As shown in previous project reports and peer-reviewed publications (e.g., Butler et al., 2015; Butler, Whittemore, Wilson, and Bohling, 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 sustainability (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 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 et al. [2017] and associated discussion). In this section, we update those correlations using 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 often greater for larger areas around the index wells, the area around which water-level changes are significantly affected by pumping during one year are not expected to exceed 2 miles. For example, the cone of depression for a well in the HPA probably does not extend significantly beyond a mile radius but could potentially be affected by overlapping cones of depression of wells as distant as 2 miles.

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

Figure 39 displays the correlation between annual water-level change and annual water use in the vicinity of the Thomas index well for 2008–2017. The pumping reduction for sustainability is 14%, which is considerably smaller than the 22% for all of GMD4 for 2005–2017. The average annual water use was 4.1 in/yr for the 2 mi radius area centered on the well, which is substantially greater than the 1.5 in/yr for all of GMD4. The water use at stable water levels (net inflow) was 3.5 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.

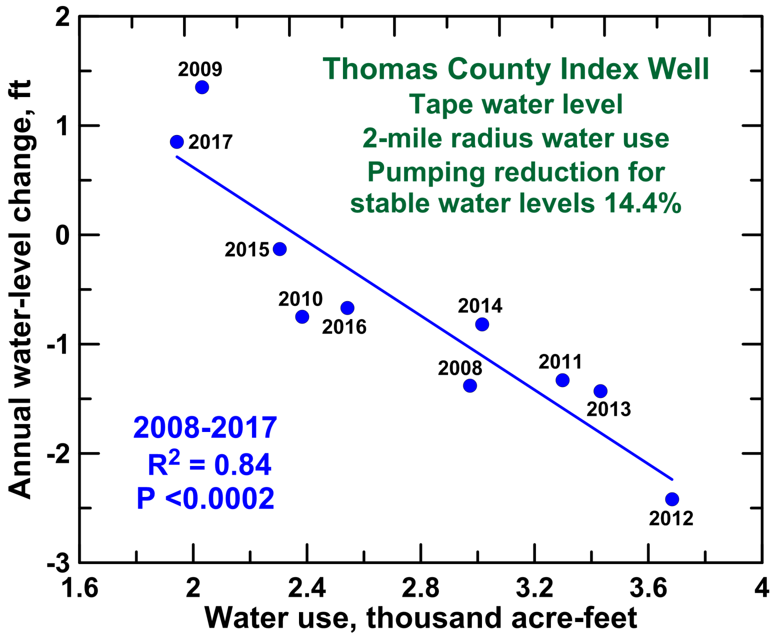

Figure 39—Correlation of annual water-level change based on manual measurements in the Thomas County index well with annual water use within a 2 mi radius around the well during 2008–2017.

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

Figure 40 displays the correlation between annual water-level change and annual water use in the vicinity of the Scott index well for 2008–2017. The pumping reduction for sustainability is 41%, which is appreciably larger than the 30% for all of GMD1 for 2005–2017. The average annual water use was 4.7 in/yr for the 2 mi radius area centered on the well, which is substantially greater than the 1.9 in/yr for all of GMD1. The water use at stable water levels (net inflow) was 2.8 in/yr for the 2 mi radius area, which again is substantially greater than the 1.3 in/yr for GMD1. 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.

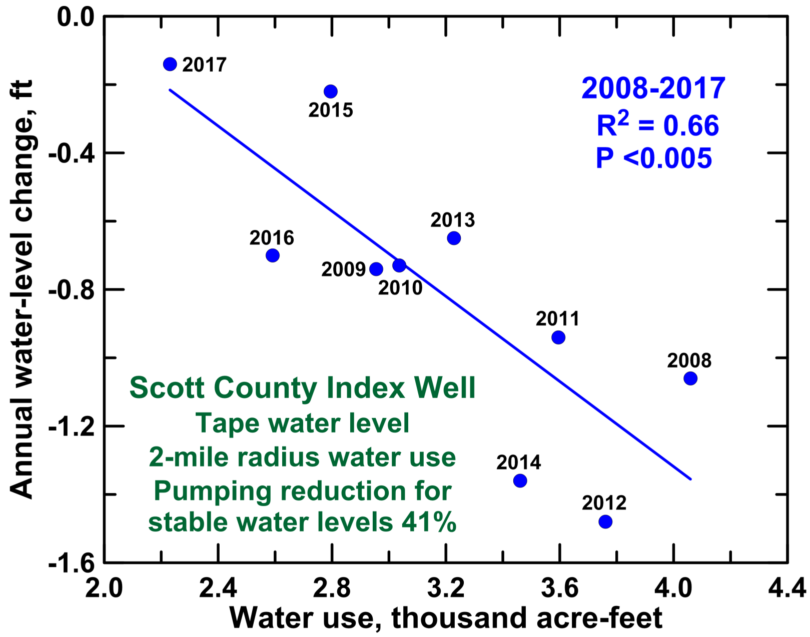

Figure 40—Correlation of annual water-level change based on manual measurements in the Scott County index well with annual water use within a 2 mi radius around the well during 2008–2017.

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

Figure 41 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 2008–2017. 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 2013–2017 (especially during 2015–2017) 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 3.2.2 as well as to the greater than average precipitation in 2013–2017 than during 2008–2012 in GMD3 (see fig. 37). The pumping reduction for stable water levels for the average annual water use before the court-ordered pumping shutdowns (2008–2012) is 69%, which is much larger than the 26% for all of GMD3 for 2005–2017. The pumping reduction for stable water levels for the average annual water use after the shutdowns (2013–2017) is 54%, 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 9.6 in/yr for the 2 mi radius area centered on the well during 2008–2012 and 2013–2017, respectively, which are considerably greater than the 4.1 in/yr for all of GMD3. The water use at stable water levels (net inflow) was 4.4 in/yr for the 2 mi radius area, which again is substantially greater than the 3.1 in/yr for 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 much greater net inflow. In this case, the greater density of water use may have induced upward vertical flow from the underlying Dakota aquifer. In addition, the heavy pumping undoubtedly induced leakage from the thick clay interval overlying the sand unit at the bottom of the HPA in the vicinity of the Haskell well.

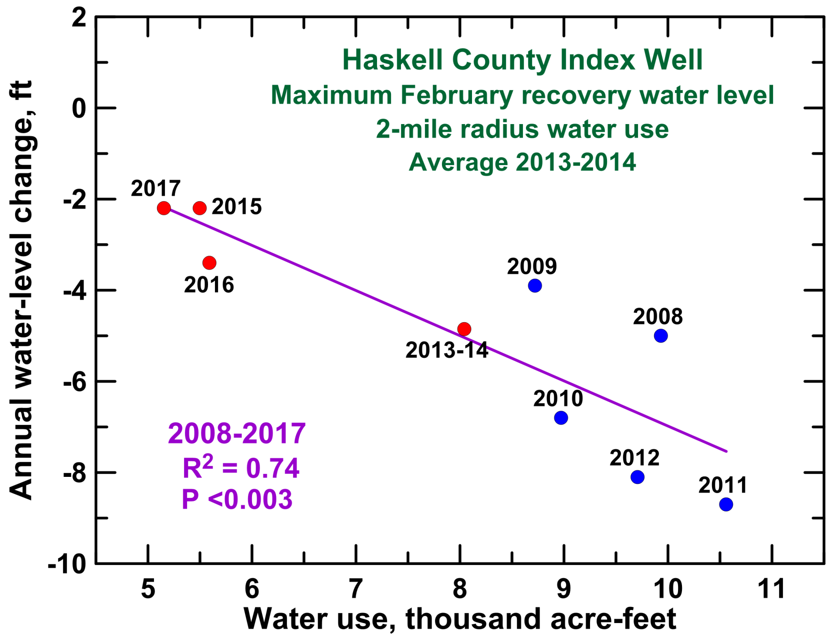

Figure 41—Correlation of change in maximum recovery water level during February based on transducer measurements in the Haskell County index well with annual water use within a 2 mi radius around the well during 2008–2017. Red points designate values after the court-ordered shutdowns (see section 3.2.2); 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. 42). 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 (56%) 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 (4.1 in/yr for 2 mi radius) but substantially greater than the 1.5 in/yr for all of GMD4. The water use at 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 (3.5 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. 42). The percent pumping reduction required to attain stable water levels (32%) is considerably less than that required in the vicinity of the Scott County index well (41% for 2 mi radius) but close to that required for all of GMD1 (30%). The average annual water use was 4.3 in/yr for the 1 mi radius area, which is somewhat less than that in the vicinity of the Scott index well (4.7 in/yr for 2 mi radius) but substantially greater than the 1.9 in/yr for all of GMD1.

The water use at stable water levels (net inflow), however, was 3.0 in/yr for the 1 mi radius area, which is similar to that in the vicinity of the Scott index well (2.8 in/yr for 2 mi radius) but much greater than the 1.3 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. 42). The percent pumping reduction required to attain stable water levels (2.7%) is the smallest reduction required at any of the index wells for which relationships have been developed but larger than the 1.5% required for all of GMD5 for the same period (2005–2017). 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 3.4 in/yr for the 2 mi radius area, which is considerably greater than the 2.4 in/yr for all of GMD5. The water use at stable water levels (net inflow) was 3.3 in/yr for the 2 mi radius area, which again is considerably larger than the 2.4 in/yr for all of GMD5.

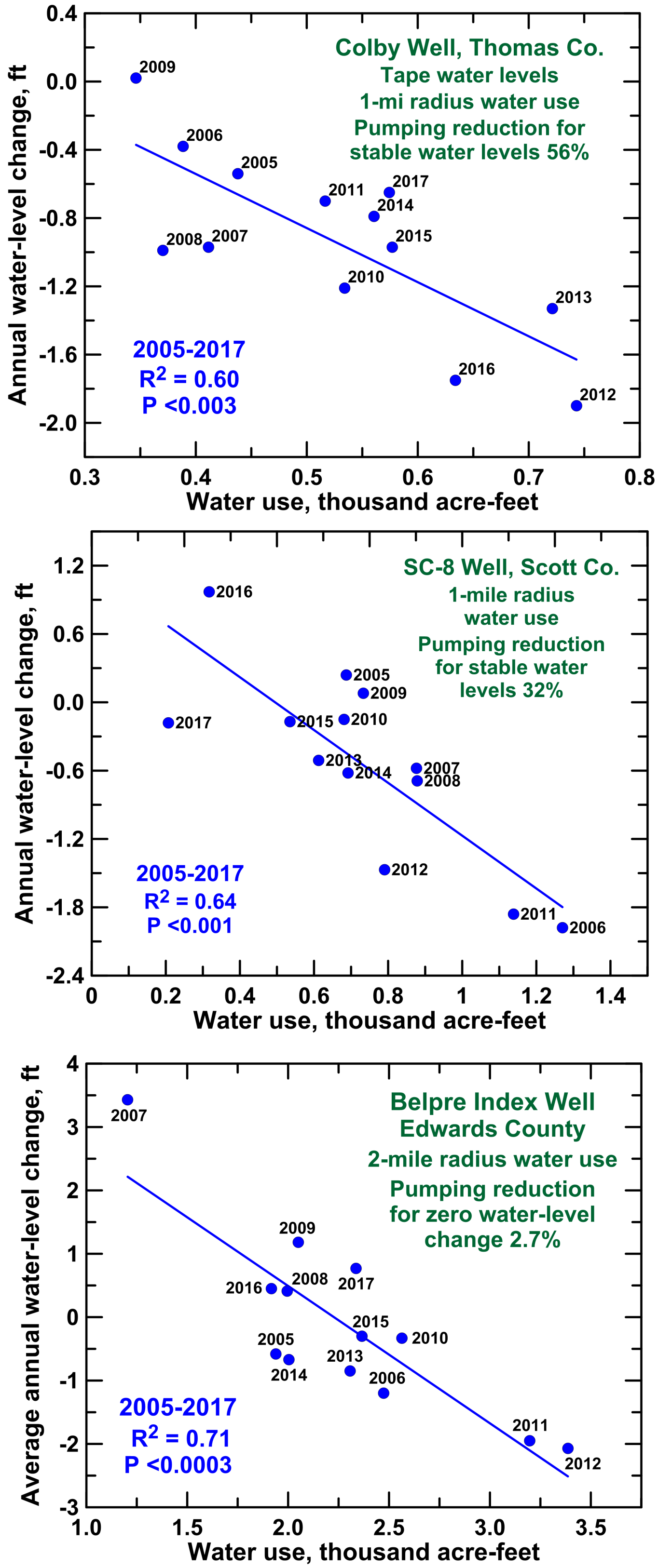

Figure 42—Correlation of annual water-level change in the Colby, SC-8, and Belpre wells with annual water use within a 1 or 2 mi radius circle around the wells during 2005–2017.

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 March to October radar precipitation 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 37 includes the variation in radar precipitation versus time since 2005 for the GMDs currently involved in the index well program. 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 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 precipitation was summed; results were presented for both the nearest point (representing a 6.6 mi^2 area) and the spatial mean of the 9-point block (representing a 60 mi^2 area) of radar precipitation values centered around the well (see table 40 of Butler 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 the 1 mi radius for water use and the 6.6 mi^2 area for radar precipitation were used. The generally high statistical correlations found for the relationships show that annual water use can be predicted relatively well by radar precipitation around the index wells nearly a year before reported water use data are available for a year.

The monthly precipitation sums that give optimum correlations for the Thomas and Scott counties index wells are April–August or March–September (fig. 43), which essentially span the main part of the irrigation season. The 2017 precipitation was the greatest during the 2008–2017 period for the index well data and was also the year of the least water use.

Two plots are shown for the water use and radar precipitation relationship for the Haskell index well (fig. 44). 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 3.2.2); 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 after the well shutdowns compared to before. A similar break in the relationship is seen for the correlation between annual water use and radar precipitation in the Sheridan-6 LEMA (Butler, Whittemore, Wilson, and Bohling, 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.

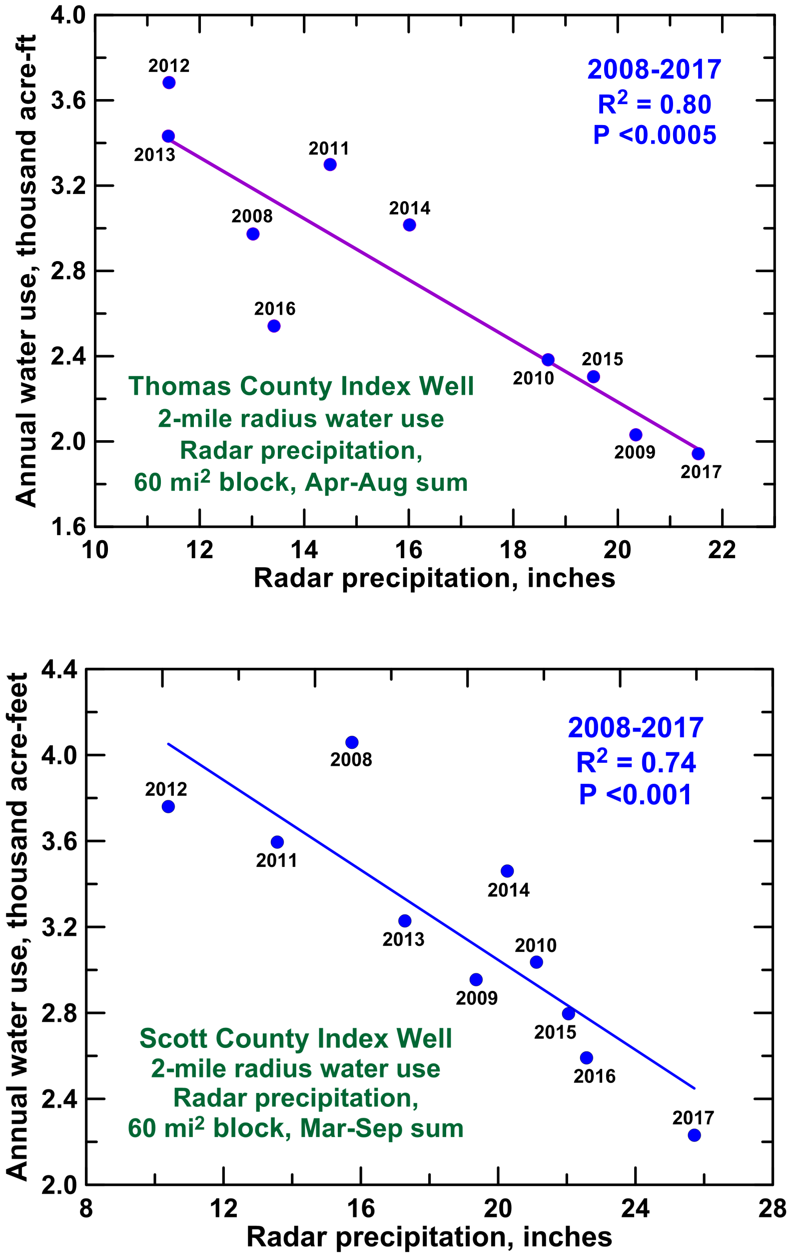

Figure 43—Correlation of annual total groundwater use with radar precipitation at the Thomas and Scott index wells for 2008–2017.

Figure 45 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 2008–2017 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 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 2008–2017 data. The month range for the SC-8 well optimum correlation starts a month earlier (February) than for the Scott County index well, although the range for both ends in

September. The water use data for 2005–2007 fall within the band of variation of the 2008–2017 data for the Belpre well; thus, the longer time span was used in the plot in fig. 45. Just as for the SC-8 well, the optimum month range for the Belpre well started in February. This earlier 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.

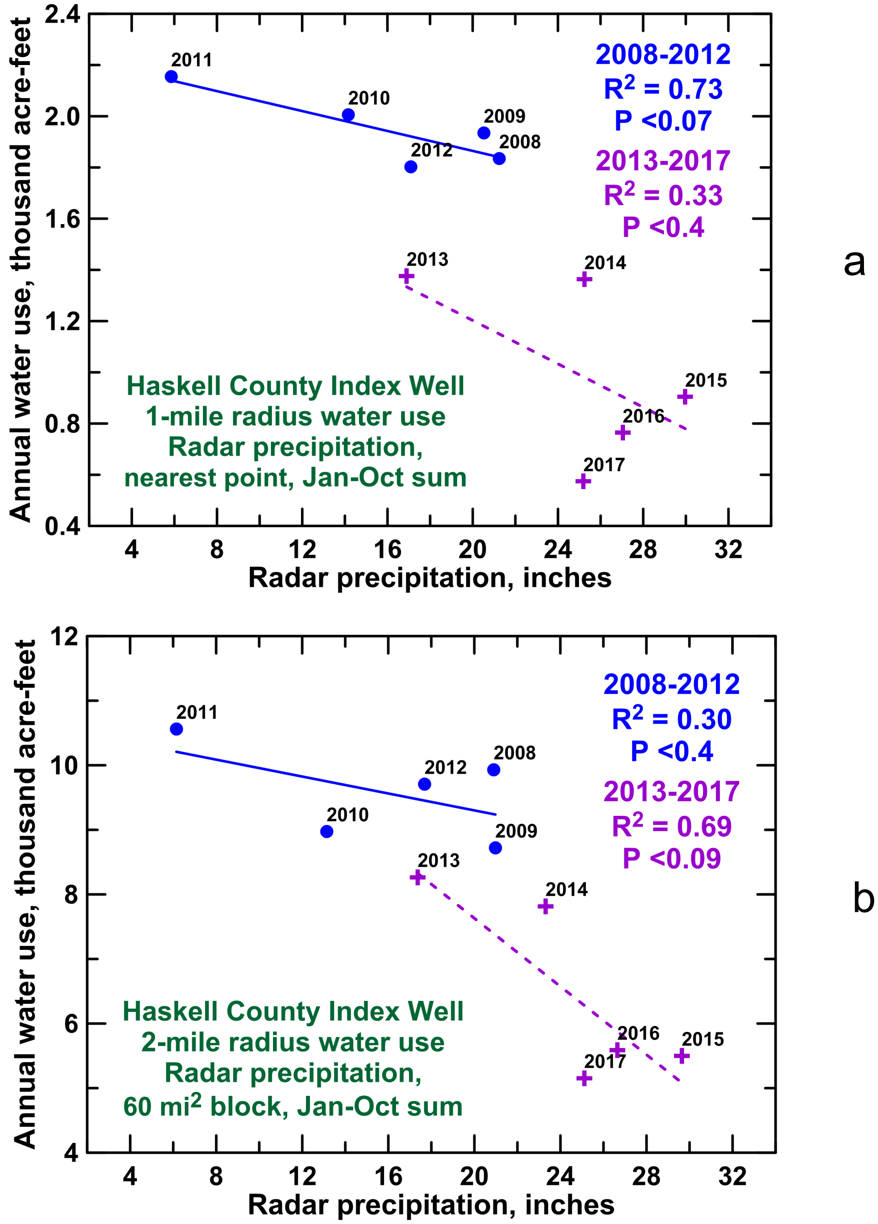

Figure 44—Correlation of annual total groundwater use with radar precipitation at the Haskell index well for 2008–2017 for a) a 1 mi radius and b) a 2 mi radius of water use. The 2008–2012 and 2013–2017 periods represent years before and after a court-ordered shutdown of nearby irrigation well pumping.

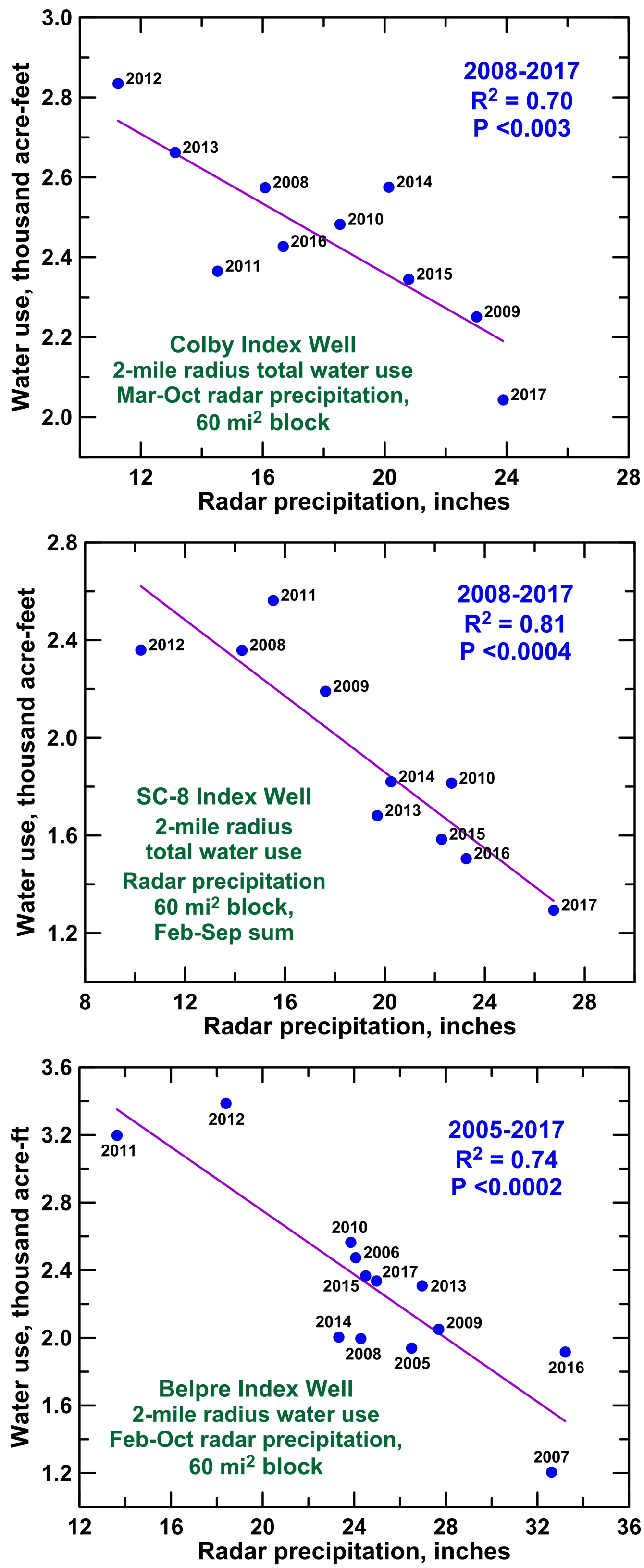

Figure 45—Correlation of annual total groundwater use with radar precipitation at the Colby, SC-8, and Belpre wells for 2008–2017 (Colby and SC-8) and 2005–2017 (Belpre).

5 Summary of 2018 Accomplishments and Plans for 2019

5.1 2018 Accomplishments

- Collected and processed data from the 30 wells currently involved in the index well program. Telemetered data from 14 wells are served on the web. Each well was visited approximately quarterly and downloads from all wells have been used for analysis and presentations.
- Installed telemetry equipment and initiated monitoring at an existing well east of Larned in GMD5.
- Installed sensor and initiated monitoring at the sixth GMD1 expansion well.
- 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 relationship between precipitation, annual water-level change, and annual water use at the index wells and the GMDs currently involved in the index well program.
- Continued integration of program data into the digital Kansas High Plains Aquifer Atlas (Fross et al., 2012).
- Gave presentations about the index well program to KWO, DWR, and GMD personnel, among others.

5.2 Planned Activities, 2019

- Continue monitoring and processing water-level data from the 30 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 four existing wells in GMD2.
- Continue to seek new wells to add to the network. Areas of particular interest are northern Sherman/southern Cheyenne counties in GMD4, Grant and Gray counties in GMD3, and Stafford and Pawnee counties in GMD5.
- Continue assessment of the information that can be acquired from hydrograph inspection.
- Continue assessment of the relationships among climatic indices, radar precipitation data, annual water-level change, and annual water use in the HPA.
- Explore the possibility of establishing well nests in GMD3 with one well in the HPA and one well in the Dakota aquifer.
- Integrate information from drillers' logs in the vicinity of the Thomas and Scott index wells into interpretation of water-level responses in those areas.

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