Kansas Geological Survey

High Plains Aquifer Index Well Program: 2016 Annual Report

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Willis Water Technology Farm Index Well

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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 (section to township) scale in the High Plains aquifer (HPA) in western and south-central Kansas. 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, the Kansas State University Northwest Research-Extension Center (KSU-NWREC), and the United States Geological Survey (USGS).

The project began with the installation of three monitoring ("index") wells in late summer 2007. Each well has a transducer that continuously monitors water levels and that is connected to telemetry equipment to allow real-time monitoring of well conditions on a publicly accessible website. An index 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 ongoing studies. A major focus of the program has been 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 impact of management strategies. At the time of this report, monitoring data (hourly frequency) from nine full recovery and pumping seasons and one continuing or completed, depending on location, recovery season have been obtained at the original three index wells. In late 2012, wells in four monitoring nests (one well from each nest) along the Kansas-Oklahoma state line in GMD3 were added to the network (border wells); additional wells were added from two of these nests (one well per nest) in August 2013 and, in cooperation with the USGS, telemetry equipment was installed in four of these wells in late 2013. In 2014, equipment for real-time monitoring of water levels was installed in an observation well at the KSU-NWREC facility in Colby and in a well just north of Belpre in GMD5. In addition, the Sheridan-6 Local Enhanced Management Area (SD-6 LEMA) monitoring wells were incorporated into the network. In the spring of 2016, three new index wells were drilled in GMD1; telemetry equipment was installed in those wells, a well in the SD-6 LEMA, and a well on the Willis Technology Farm in southern Finney County later in the year. In the late fall of 2016, a new index well was drilled southwest of Goodland in GMD4; telemetry equipment will be installed in that well in spring 2017.

This report provides a description of conditions as of late winter 2017. The report consists of (a) an update of the hydrographs for all of the index wells and for the expansion wells in the vicinity of the Scott and Thomas index wells (one well near the Scott index well and three wells in the vicinity of the Thomas index well); (b) an interpretation of the hydrographs from all of the index wells; (c) a discussion of the installation of the new index well in GMD4; (d) an update and interpretation of the hydrographs of the expansion wells in the vicinity of the Haskell index well; and (e) a discussion of climatic indices and radar precipitation data and their relationship to annual water-level changes at six of the wells and to water use in the vicinity of those wells.

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

(1) Water-level data collected using a pressure transducer and datalogger 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 during both pumping and recovery periods enables important practical insights to be drawn concerning the origin of the pumped water and the long-term viability of the aquifer in the vicinity of the index wells.
(3) Continuous monitoring has helped establish the hydrogeologic information conveyed by hydrographs of various forms.
(4) Because of uncertainties in both the effects of barometric pressure changes and the degree of well recovery at the time of the annual water-level measurement program, the data from the index wells provide the context needed for interpretation of the results of the annual measurement program.
(5) 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 subunit and larger scale using a new approach developed as part of this program.
(6) Radar precipitation data can be used to predict annual water-level changes and water use in the vicinity of the index wells.

The focus of project activities in 2017 will be on the continuation of monitoring at all project wells; continuation of the detailed analyses of hydrographs from all project wells; installation of telemetry equipment at the new index well in GMD4 and one additional well northwest of Garden City in GMD3; further assessment of the relationships among climatic indices, radar precipitation data, annual water-level change, and water use; and integration of 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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1. Introduction and Background

Groundwater withdrawals that have resulted in large water-level declines in the Ogallala–High Plains aquifer (henceforth, High Plains aquifer or HPA) in Kansas call into question the viability of the aquifer as a continuing resource for irrigated agriculture (Butler, Stotler, et al., 2013; Buchanan et al., 2015). The index well program (formerly, calibration monitoring well program) is directed at developing improved approaches for measuring and interpreting hydrologic responses in the HPA at the local (section to township—henceforth, 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, the Kansas State University Northwest Research-Extension Center (KSU-NWREC), and the United States Geological Survey (USGS).

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 valuable 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 nine full recovery and pumping seasons and one continuing 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 datalogger 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 during both pumping and recovery periods enables important practical insights to be drawn concerning the origin of the pumped water and the long-term viability of the aquifer in the vicinity of the index wells.

(3) Continuous monitoring has helped establish the hydrogeologic information conveyed by hydrographs of various forms.

(4) Because of uncertainties in both the effects of barometric pressure changes and the degree of well recovery at the time of the annual water-level measurement program, the data from the index wells provide the context needed for interpretation of the results of the annual measurement program.

(5) 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 as part of this program.
(6) Radar precipitation data can be used to predict annual water-level changes and water use in the vicinity of the index wells.

The index well network was expanded in 2016 by the drilling of three new wells in Lane, Wichita, and Wallace counties in GMD1 and one new well in Sherman County in GMD4 and the installation of monitoring equipment in an existing well on the Willis Technology Farm in southern Finney County. Note that the term "index well" is used here to designate a well at which continuous 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) or logistical issues; these expansion wells are mostly in the vicinity of the original three index wells. Both types of wells are considered in this report.

This report provides a description of conditions as of late winter 2017. The report consists of (a) an update of the hydrographs for all of the index wells and for the expansion wells in the vicinity of the Scott and Thomas index wells (one well near the Scott index well and three wells in the vicinity of the Thomas index well); (b) an interpretation of the hydrographs from all of the index wells; (c) a discussion of the installation of the new index well in GMD4; (d) an update and interpretation of the hydrographs of the expansion wells in the vicinity of the Haskell index well; and (e) a discussion of climatic indices and radar precipitation data and their relationship to annual water-level changes at six of the wells and to water use in the vicinity of those wells. Unlike in previous reports, the wells discussed in this report will be grouped according to the GMD in which they are located.

2. Program History

The index well program began with the installation of three transducer-equipped wells, designed and sited to function as HPA monitoring wells, in late summer 2007 (henceforth, 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 (green boxes 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 spring 2012, we started to explore adding a group of wells to the network. These wells were in four well nests that were 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 (filled black circles with green plus signs 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. Those data can be viewed on the KGS (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml) and USGS (waterdata.usgs.gov/ks/nwis/current/?type=gw) websites. Data from the Cimarron and Rolla sites can be viewed up to the latest download on the KGS website. 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 are operated cooperatively by the KGS and USGS.

In February 2014, the KGS and staff at the KSU-NWREC facility in Colby began to discuss adding the long-time monitoring 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, we are using the facility's wi-fi system to communicate with the transducer-datalogger unit. 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 could not be transferred to the KGS website because of limitations of the telemetry system vendor's website. After considerable efforts to resolve problems with the vendor, the decision was made to switch vendors. In late summer 2015, the transducer-datalogger unit and telemetry equipment were replaced by those of another vendor. The data have been accessible from the KGS and GMD5 websites since September 18, 2015.

In 2012, we began to collaborate with GMD4 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 appeared to be induced by high temperatures in the datalogger housings. After the decision was made to incorporate these wells into the index well program, we replaced the existing monitoring equipment 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, telemetery 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 spring 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 summer 2016, we converted an existing well on the Willis Technology Farm in southern Finney County in GMD3 to an index well (see cover photo). 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 2016, we further expanded the network by installing a new well in Sherman County southwest of Goodland. An integrated pressure transducer-datalogger unit and telemetry equipment will be installed in the well in early spring 2017.

Figure 1 shows the current state of the index well network. There are now 14 wells in the network with telemetry equipment and real-time data access from the KGS website, six wells without telemetry equipment (data downloaded approximately quarterly and displayed on the KGS website), and one well awaiting the installation of monitoring equipment. We anticipate at least one well will be added to the network in 2017.

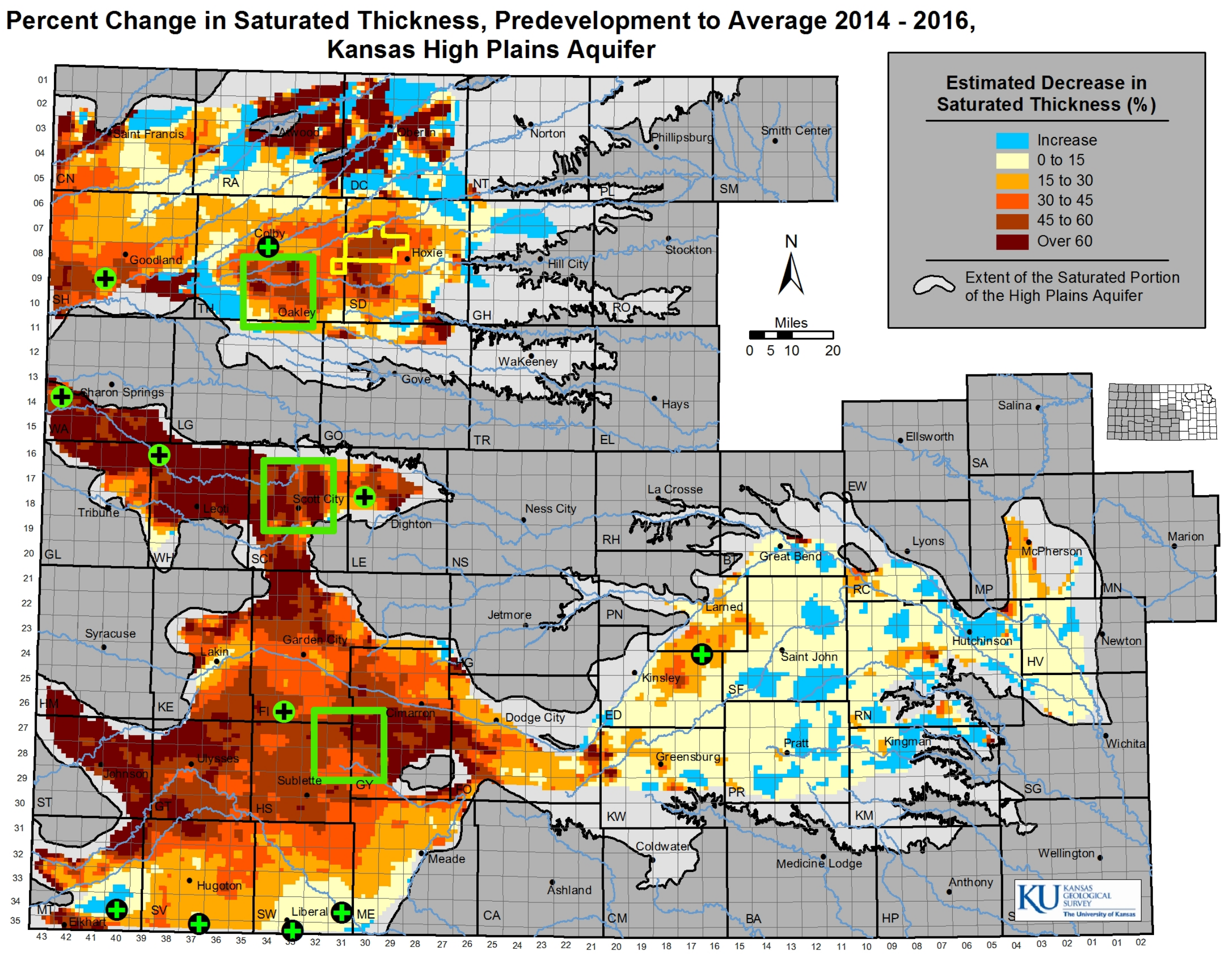

Figure 1—The Kansas portion of the High Plains aquifer, with aquifer and county boundaries shown. Each colored pixel represents one section (1 mi^2), coded for the degree of groundwater depletion from the beginning of large-scale development to the average of conditions in 2014–2016. The green boxes are approximately centered on the original index well sites; the black circles with green plus signs indicate the locations of the border wells, the Colby well, and the Belpre well; the yellow outlined area indicates the location of the SD-6 LEMA, where there are five index wells; the green circles with black plus signs indicate the locations of the GMD1 index wells drilled in spring 2016, the Willis Technology Farm index well installed in summer 2016, and the Sherman County index well drilled in late 2016. Additional wells (expansion wells) are monitored within each of the green boxes.

3. Overview of Index Well Sites and Monitoring Data

This section provides a brief overview of the hydrographs from the 20 index wells currently in operation. The duration of the monitoring ranges from more than nine and a half years of hourly measurements at the three original index wells to less than nine months at the most recently added wells. Although pumping occurs sporadically throughout the year, the major drawdown in water level in all of the index wells occurs during the irrigation pumping season in the summer 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 virtually all 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, such as the duration of recovery at the time of the measurement, that are unrelated to aquifer trends. 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). The vast majority of the index wells were added to the annual water-level measurement network and have been measured as part of the annual program ever since.

In the following sections, the hydrograph and characteristics of each well are discussed. The wells are organized by the GMD in which they are located. In addition to the hydrograph, two tables are presented for most wells: one provides information about the well hydrograph and the local water use (henceforth, hydrograph and use table), and the other provides comparisons between the annual water-level measurements and the transducer measurements (henceforth, comparison table). If the monitoring period exceeds five years, the hydrograph-use tables included in the report present data from the first year of operation of the index well and the last four years plus the range over the monitoring period. In that case, the comparison table presents the last five years of measurement comparisons. Tables providing data from all years of index well operation are available online at www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml.

3.1. GMD1 Index Wells

Four index wells are located in GMD1. The Scott County index well is one of the original index wells, and the Lane, Wallace, and Wichita counties index wells were installed in the spring of 2016. Table 1 summarizes the characteristics of these four wells.

Table 1—Characteristics of the GMD1 index well sites.

Site	2017 WL elev. (ft)[a]	2017 Saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2015 Water Use (ac-ft)		
					1-mi circle	2-mi circle	5-mi circle
Lane	2,768.8[b]	34.8[b]	118	105–115	544	1,668	3,298
Scott	2,827.4	83.3	223	215–225	814	2,796	13,972
Wallace	3,564.9	130.9	394	375–385	605	3,226	13,387
Wichita	3,289.0	31.0	190	175–185	267	3,005	10,250

[a] 2017 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html)
[b] Suspect measurement.

3.1.1. Lane County Index Well

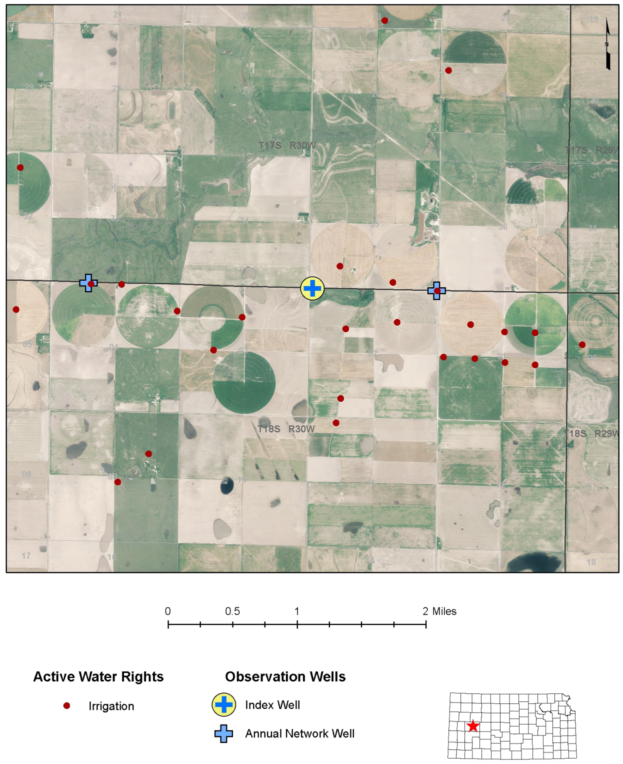

Figure 2—Aerial view of the Lane County index well site, additional annual program wells, and nearby points of diversion.

Figure 2 is an aerial view of the Lane County site (T. 18 S., R. 30 W., 2 BBB) at a scale that shows the index well, the nearby annual program wells, and the nearby wells with active water rights. The index well was drilled in the early spring of 2016; installation was completed on March 30, 2016. The well was equipped with a transducer-datalogger unit and monitoring began on June 17, 2016. Telemetry equipment was installed on September 8, 2016.

3.1.1.1. *Hydrograph and General Observations*

Figure 3 shows the complete hydrograph for the Lane index well, and table 2 summarizes its general characteristics. The very small amplitude fluctuations superimposed on the water levels are likely an indication of an unconfined aquifer overlain by a vadose zone with high air permeability; this interpretation was supported by an analysis using the BRF software developed earlier in this program (Bohling et al., 2011). The impact of individual pumping wells is not discernible; the water-level response to pumping appears more integrated in nature than at most of the index wells.

The monitoring period has been short so further interpretation of the hydrograph will be deferred to subsequent reports. The 2016–2017 recovery began on September 19, 2016, and continued at the time of this report (March 9, 2017). There appears to have been no pumping during the recovery period.

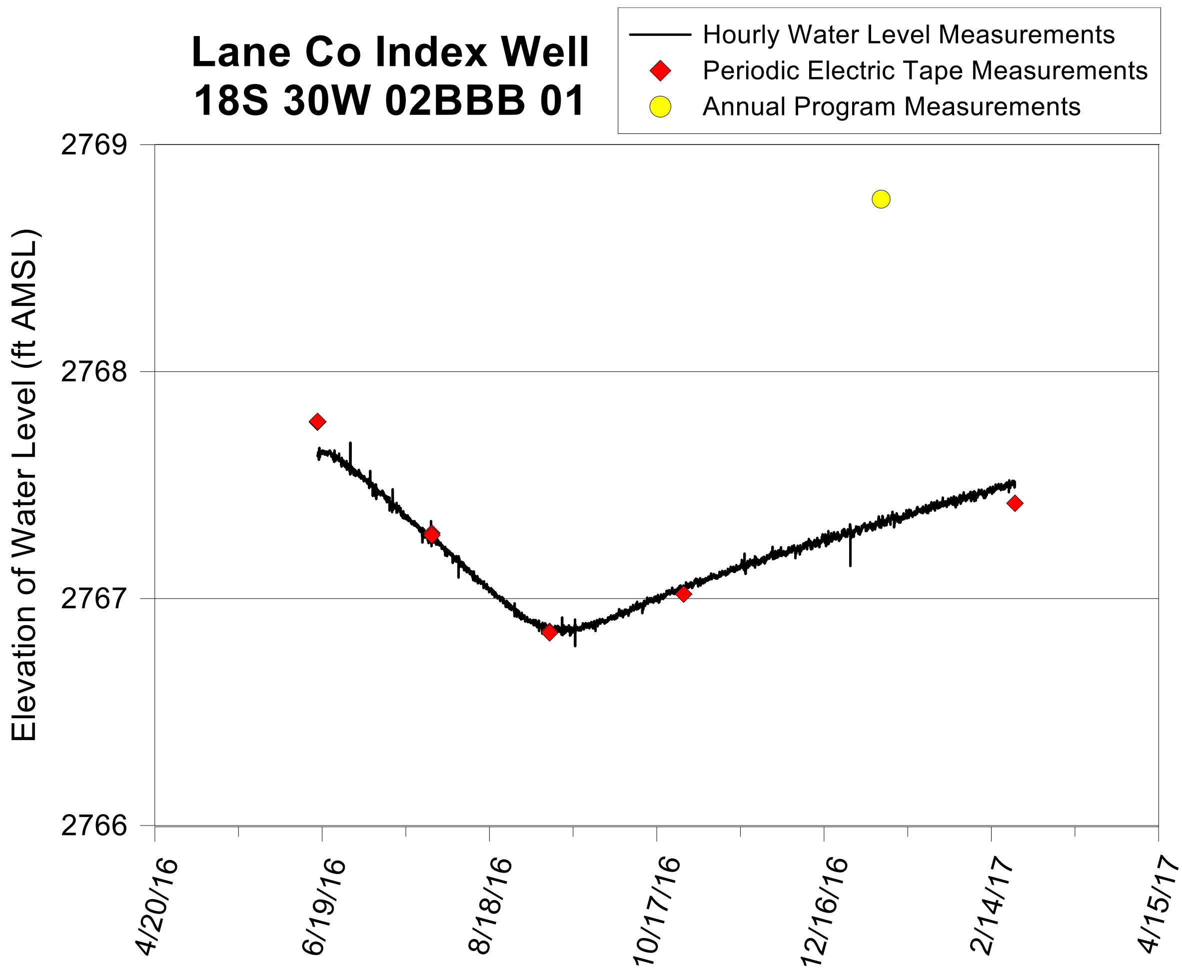

Figure 3—Lane County index well hydrograph—total data run to 2/22/17. A water-level elevation of 2,767 ft corresponds to a depth to water of 85 ft below land surface (lsf); the top of the screen is 105 ft below lsf (elevation of 2,747 ft); and the bottom of the aquifer is 118 ft below lsf (elevation of 2,734 ft). The screen terminates 3 ft above the bottom of the aquifer. The 2017 annual water-level measurement appears to be in error.

Table 2—General characteristics of the Lane County index well hydrograph and local water-use data.

		2016
Minimum Water-Level Elevation	Feet	2,766.8
	Date	9/17/16
Maximum Observed Recovery Elevation	Feet	NA
	Date	NA
Apparent Recovery	Feet	NA
Annual Change in Maximum Observed Recovery	Feet	NA
Recovery Season	Start	9/19/16
	End	NA
	Length (Days)	NA
Pumping During Recovery Season	Length (Days)	NA
Length of Pumping Season	Days	NA
2-mi Radius Water Use[a]	Irrigated Acres	NA
	Total Use (ac-ft)	NA
	Use per Irrigated Acre (ft)	NA

[a]2015 Irrigated Acres—2,237, Total use—1,668.0 ac-ft, Use per Irrigated Acre—0.75 ft

3.1.2. Scott County Index Well

Figure 4—Scott County index well site, an additional annual program well, and nearby points of diversion.

Figure 4 is an aerial view of the Scott County site (T. 18 S., R. 33 W., 1 AAA) at a scale that shows the index well, an additional nearby annual program well, and the location of wells with active water rights. The SC-8 GMD1 expansion well, which is discussed in Section 3.5.1, is located 6.5 miles due south of the Scott County index well.

3.1.2.1. *Hydrograph and General Observations*

Figure 5 shows the complete hydrograph for the Scott index well, table 3 summarizes its general characteristics, and table 4 compares the manual and transducer measurements from the well. The unconfined nature of the aquifer zone in which the index well is screened is indicated by the hydrograph form (see Butler et al. [2014]—Section 4.3) and by the relatively small change (difference between maximum and minimum observed water levels within a year; average of 3.8 ft over the monitoring period) 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.

The 2015–2016 recovery started on September 16, 2015. There was little pumping during the recovery period; pumping for the 2016 irrigation season started on March 4, 2016. The season began with a 12-day pumping period that ended on March 16 and a second 21-day pumping period from March 28 to April 18, 2016. Pumping then ceased until June 27. This break in pumping was likely due to planting of summer crops and late spring and early summer rains. After a sudden drop in water level of more than 0.7 ft within 24 hours on June 27–28, pumping appeared to continue at all wells in the vicinity until August 29. During the 2016-17 recovery, there were extended periods of pumping from October 17 to November 17, 2016, and a five-day period of pumping beginning on February 17, 2017. Recovery continued at the time of the preparation of this report (March 9, 2017).

As a result of the sensor failure at the Haskell County index well on January 12, 2014, the original transducer was replaced at the Scott County index well on March 27, 2014. However, as described in the previous annual report (Butler, Whittemore, Reboulet, et al., 2016), transducer measurements during the 2014 recovery period and much of 2015 were noisier than previous years. After an extended period of testing, we replaced both the transducer-datalogger unit and the cable. On October 20, 2015, a new 30 psig sensor and cable were installed in the well. Data acquired after the installation show that the transducer noise has been greatly reduced.

Every year from 2008 to 2015, the minimum recorded water-level elevation declined from the previous year at the Scott County index well. However, the minimum 2016 water-level elevation was 0.1 ft higher than that in 2015 (6.6 ft lower than in 2008, the first year for which a value was recorded). The maximum recovered water level has declined every year since the onset of monitoring. The lowest maximum recovered water level was in 2016 and was 0.5 ft below that of 2015 and 7.0 ft below that of 2008 (average annual decline of 0.78 ft/yr). Given that the 2017 maximum water-level elevation will likely be about 0.7 ft less than that in 2016, the expectation is that the minimum water-level elevation in 2017 will be considerably lower than that of 2016. Water-use data for 2016 will be available later in 2017. Water use within the 2 mi radius surrounding the index well in 2015 (2,796 ac-ft) was the smallest during the monitoring period and 552 ac-ft below the average for the monitoring period (3,348 ac-ft).

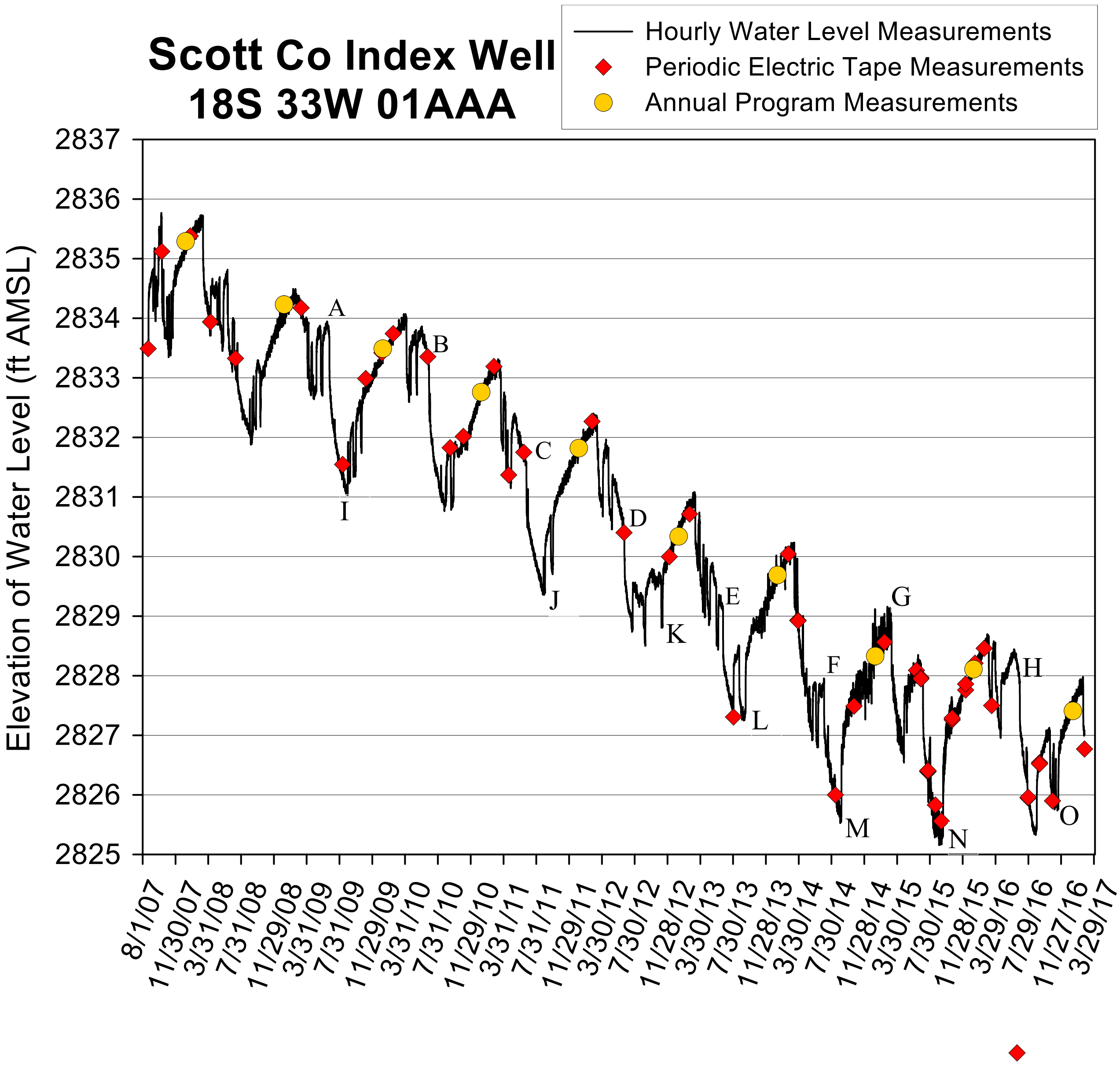

Figure 5—Scott County index well hydrograph—total data run to 2/22/17. A water-level elevation of 2,829 ft corresponds to a depth to water of 138.15 ft below land surface (lsf); the top of the screen is 215 ft below lsf (elevation of 2,752.15 ft); and the bottom of the aquifer is 223 ft below lsf (elevation of 2,744.15 ft). The screen terminates 2 ft below the bottom of the aquifer. A–O defined in text (Section 4.1). Transducer data adjusted for change in position as described in previous annual report (Butler, Whittemore, Reboulet, et al., 2016). Electric tape measurement plotted below the plot area (just above this caption) appears to have been a transcription error.

Table 3—General characteristics of the Scott County index well hydrograph and local water-use data.

		2007	2013	2014	2015	2016	Min	Max
Minimum Water-Level Elevation	Feet	< 2,833.4	2,827.3	2,825.5	2,825.2	2,825.3	2,825.2	<2,833.4
	Date	11/5/07	9/7/13	8/31/14	9/2/15	8/25/16	(2015)	(2007)
Maximum Recovery Elevation	Feet	NA	2,831.1	2,830.2	2,829.2	2,828.7	2,828.7	2,835.7
	Date	NA	3/9/13	3/13/14	2/22/15	2/27/16	(2016)	(2008)
Apparent Recovery	Feet	NA	2.6	2.9	3.7	3.5	>2.3 (2008)	3.7 (2015)
Annual Change in Max. Recovery	Feet	NA	-1.3	-0.9	-1.0	-0.5	-0.5 (2016)	-1.2 (2009)
Recovery Season	Start	NA	9/7/12	9/14/13	9/4/14	9/16/15		
	End	NA	3/11/13	3/13/14	3/9/15	3/4/16		
	Length (Days)	NA	185.2	180.3	185.3	169.8	169.8 (2016)	217.8 (2010)
Pumping in Recovery Season	Length (Days)	NA	5	8.6	0[a]	0[a]	0 (2015, 2016)	>48.2 (2008)
Length of Pumping Season	Days	NA	186.7	175.1	191.2	177.8	145.7 (2010)	191.2 (2015)
2 mi Radius Water Use	Irrigated Acres	4,132	3,857	3,649	3,309	NA	3,309 (2015)	4,132 (2007)
	Total (ac-ft)	3,175.1	3,228.2	3,460.7	2,795.7	NA	2,795.7 (2015)	4,059.0 (2008)
	Irrigation Use (ac-ft)	3,095.8	3,212.0	3,443.2	2,788.9	NA	2,788.9 (2015)	4,014.3 (2008)
	Use per Irrigated Acre (ft)	0.75	0.83	0.94	0.84	NA	0.75 (2007, 2009)	1.02 (2008)

[a] Could not confidently identify any pumping periods during recovery.

Table 4—Annual water-level measurement[a,b] comparison with transducer measurements, Scott County index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[c]	Method
1/9/2013	2,830.34	-1.48 (-1.32)	Steel tape
	2,830.40[d]	-1.36	Transducer
1/10/2014	2,829.69	-0.65 (-0.84)	Steel tape
	2,829.59[d]	-0.81	Transducer
1/8/2015	2,828.33	-1.36 (-1.08)	Steel tape
	2,828.35[d]	-1.24	Transducer
1/7/2016	2,828.11	-0.22 (-0.46)	Steel tape
	2,828.13[d]	-0.22	Transducer
1/10/2017	2,827.41	-0.70 (NA)	Steel tape
	2,827.45[d]	-0.68	Transducer

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=391404101010701).
[b] Only last five years shown.
[c] Value in ( ) is the decline in the maximum recovered water level measured by the index well transducer.
[d] Average of values over time interval 0800–1600.

3.1.3. Wallace County Index Well

Figure 6—Aerial view of Wallace County index well site, additional annual program wells, and nearby points of diversion.

Figure 6 is an aerial view of the Wallace County site (T. 14 S., R. 42 W., 10 CAA) at a scale that shows the index well, two additional annual program wells, and nearby wells with active water rights. The well was drilled in the early spring of 2016; installation was completed on April 8, 2016. The well was equipped with a transducer-datalogger unit and monitoring began on June 16, 2016. Telemetry equipment was installed on July 27, 2016.

3.1.3.1. *Hydrograph and General Observations*

Figure 7 shows the complete hydrograph for the Wallace index well, and table 5 summarizes its general characteristics. The large amplitude fluctuations superimposed on the water levels, particularly during the recovery period, are an indication of an unconfined aquifer, an interpretation that was supported by an analysis using the BRF software developed earlier in this program (Bohling et al., 2011).

The monitoring period has been short, so further interpretation of the hydrograph will be deferred to subsequent reports. The 2016–2017 recovery began on August 26, 2016, and continued at the time of the preparation for this report (March 9, 2017). There appears to have been no pumping of nearby wells during the recovery period.

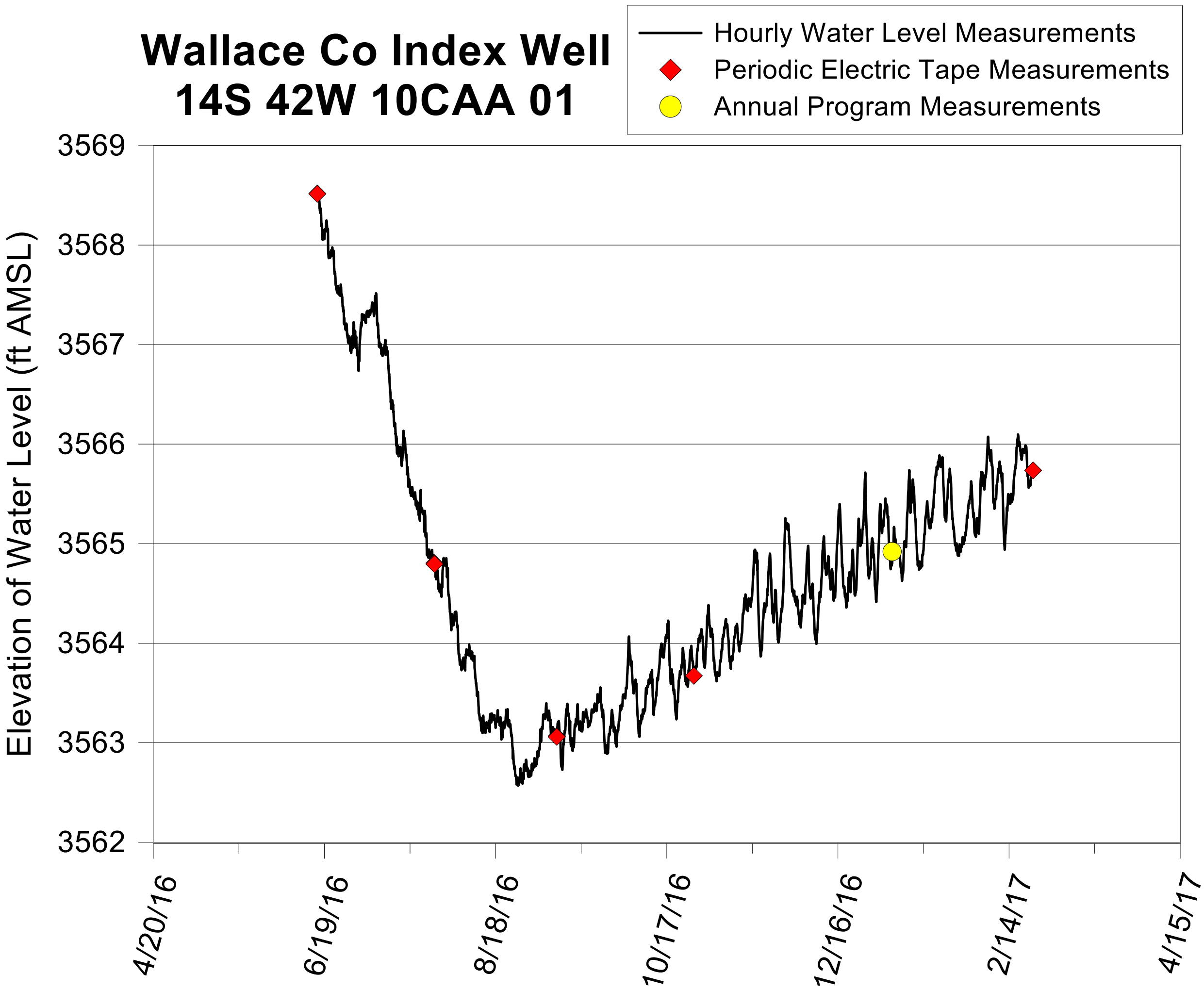

Figure 7—Wallace County index well hydrograph—total data run to 2/22/17. A water-level elevation of 3,565 ft corresponds to a depth to water of 263 ft below land surface (lsf); the top of the screen is 375 ft below lsf (elevation of 3,453 ft); and the bottom of the aquifer is 394 ft below lsf (elevation of 3,434 ft). The screen terminates 9 ft above the bottom of the aquifer.

Table 5—General characteristics of the Wallace County index well hydrograph and local water-use data.

		2016
Minimum Water-Level Elevation	Feet	3,562.6
	Date	8/25/16
Maximum Observed Recovery Elevation	Feet	NA
	Date	NA
Apparent Recovery	Feet	NA
Annual Change in Maximum Observed Recovery	Feet	NA
Recovery Season	Start	8/26/16
	End	NA
	Length (Days)	NA
Pumping During Recovery Season	Length (Days)	NA
Length of Pumping Season	Days	NA
2 mi Radius Water Use[a]	Irrigated Acres	NA
	Total Use (ac-ft)	NA
	Irrigation Use Only (ac-ft)	NA
	Use per Irrigated Acre (ft)	NA

[a]2015 Irrigated Acres—4,590, Total use—3,226 ac-ft, Irrigation use—3,174.7 ac-ft, Use per Irrigated Acre—0.69 ft.

3.1.4. Wichita County Index Well

Figure 8—Aerial view of Wichita County index well site, an additional annual program well, and nearby points of diversion.

Figure 8 is an aerial view of the Wichita County site (T. 16 S., R. 38 W., 16 CCC) at a scale that shows the index well, an additional annual program well, and nearby wells with active water rights. The index well was drilled in early spring of 2016; installation was completed on April 1, 2016. The well was equipped with a transducer-datalogger unit and monitoring began on June 16, 2016. Telemetry equipment was installed on July 27, 2016.

3.1.4.1. *Hydrograph and General Observations*

Figure 9 shows the complete hydrograph for the Wichita index well, and table 6 summarizes its general characteristics. The amplitude of the fluctuations superimposed on the water levels is an indication of an unconfined aquifer, an interpretation that was supported by an analysis using the BRF software developed earlier in this program (Bohling et al., 2011).

The monitoring period has been short, so further interpretation of the hydrograph will be deferred to subsequent reports. The very small pumping-induced changes in water level during the monitoring period make it difficult to describe features of the hydrograph at this time.

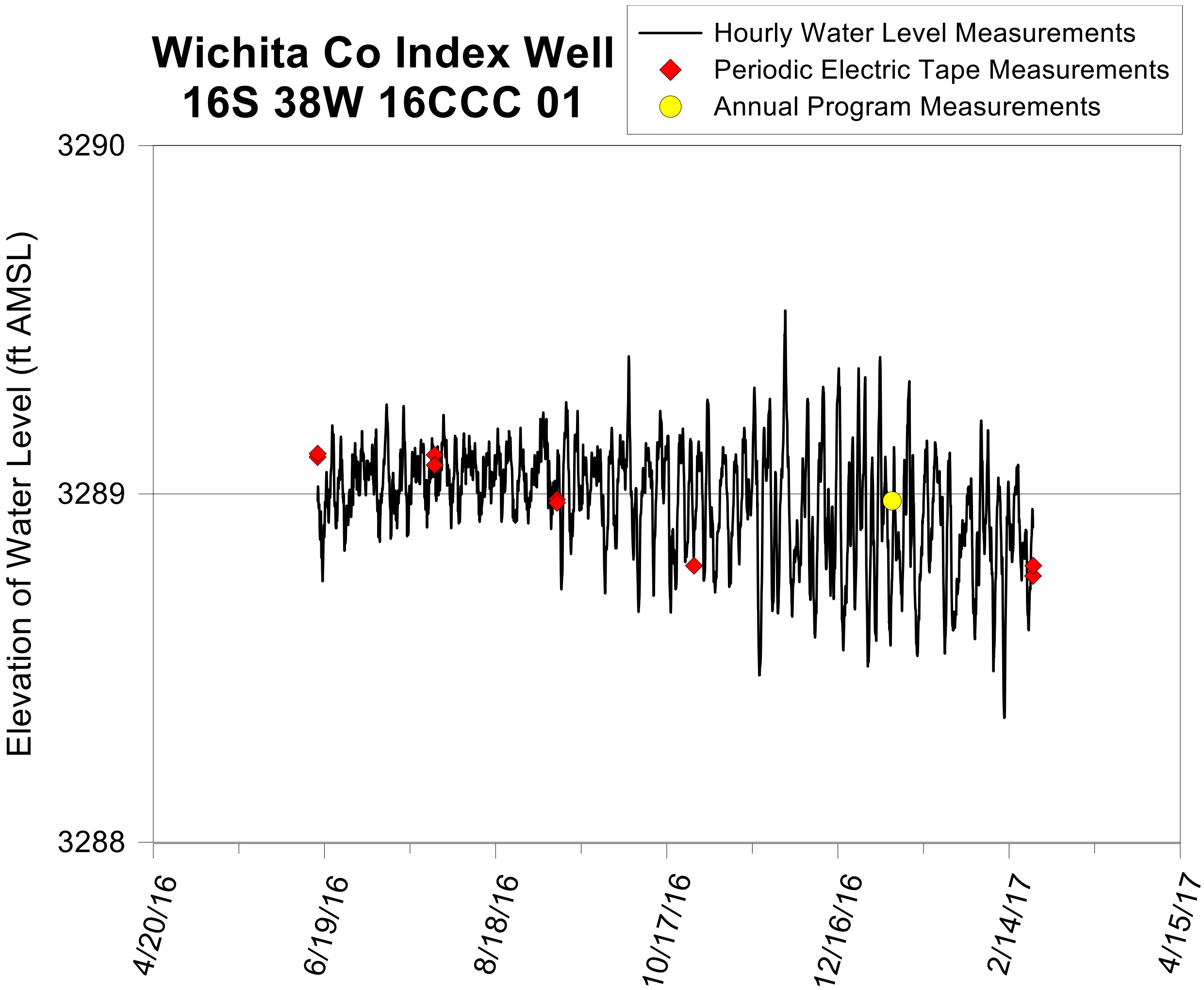

Figure 9—Wichita County index well hydrograph—total data run to 2/22/17. A water-level elevation of 3,289 ft corresponds to a depth to water of 159 ft below land surface (lsf); the top of the screen is 175 ft below lsf (elevation of 3,273 ft); and the bottom of the aquifer is 190 ft below lsf (elevation of 3,258 ft). The screen terminates 5 ft above the bottom of the aquifer.

Table 6—General characteristics of the Wichita County index well hydrograph and local water-use data.

		2016
Minimum Water-Level Elevation	Feet	3,288.5
	Date	11/8/16
Maximum Observed Recovery Elevation	Feet	NA
	Date	NA
Apparent Recovery	Feet	NA
Annual Change in Maximum Observed Recovery	Feet	NA
Recovery Season	Start	NA
	End	NA
	Length (Days)	NA
Pumping During Recovery Season	Length (Days)	NA
Length of Pumping Season	Days	NA
2 mi Radius Water Use[a]	Irrigated Acres	NA
	Total Use (ac-ft)	NA
	Use per Irrigated Acre (ft)	NA

[a]2015 Irrigated Acres—2,850, Total use—3,005.4 ac-ft, Use per Irrigated Acre—1.05 ft

3.2. *GMD3 Index Wells*

Eight index wells are located in GMD3. The Haskell index well is one of the original three index wells, whereas the Cimarron, Hugoton, Liberal, and Rolla index wells were installed in 2012–2013, and the Willis Technology Farm index well was installed in summer 2016. Table 7 summarizes characteristics of these eight wells.

Table 7—Characteristics of the GMD3 index wells.

Site	2017 WL elev. (ft)[a]	2017 Saturated thickness (ft)[b]	Bedrock depth (estimated ft below land surface)[b]	Screened interval (ft below land surface)[b]	2015 Water Use (ac-ft)		
					1-mi circle	2-mi circle	5-mi circle
Cimarron 210	2,474.14[d]	290.1	345	200–210	53	53	8,364
Haskell	2,536.3	131.5	433	420–430	904	5,498	30,914
Hugoton 313[c]	2,917.13[d]	452.1	635	303–313	875	3,190	37,053[e]
Hugoton 495	2,913.11	448.1	635	485–495			
Liberal 160[c]	2,690.77[d]	445.8	576	140–160	0.02	1,654[e]	32,083[e,f]
Liberal 436	2,658.16	413.2	576	426–436			
Rolla 366	3,186.73	210.7	399	356–366	341	1,148	8,160
Willis Tech Farm	2,643.86	205.9	502	262–482	1,062	5,321	36,927

[a] 2017 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 an annually measured index well but an additional sensor and telemetry equipped well.
[d] 2017 water-level measurements from hand measurements taken 2/10/2017.
[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 7,304 ac-ft of non-irrigation water for city of Liberal.

3.2.1. Cimarron Index Well

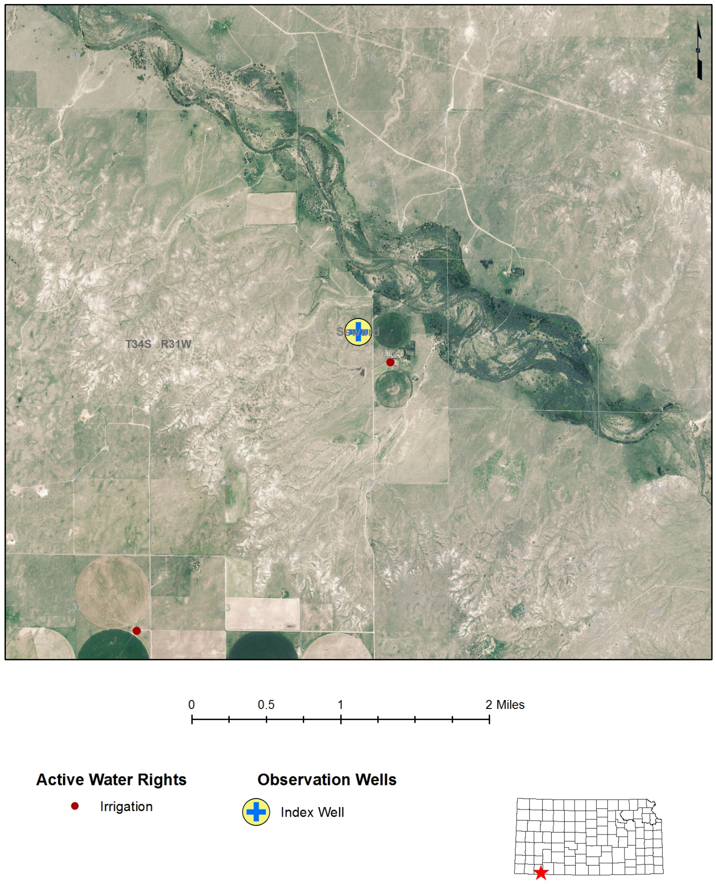

Figure 10—Aerial view of Cimarron index well site and nearby points of diversion.

Figure 10 is an aerial view of the Cimarron site (T. 34 S., R. 31 W., 22 BDD) at a scale that shows the index well and the nearby wells with active water rights; there was no additional annual network well in the area. The site includes three wells in the HPA and one in the Permian bedrock; the middle well in the HPA, screened 200–210 ft below land surface, has been equipped with a transducer-datalogger unit (henceforth, Cimarron 210 or Cimarron index well).

3.2.1.1. *Hydrograph and General Observations*

Figure 11 shows the complete hydrograph for the Cimarron index well, table 8 summarizes its general characteristics, and table 9 compares the manual and transducer measurements from the well. The unconfined nature of the aquifer zone in which the index well is screened is indicated by the hydrograph form and by the small change in water level during the pumping season, despite the nearby (within 0.3 mi) irrigation well. The fluctuations superimposed on the water levels, particularly evident during the recovery periods, are produced by variations in barometric pressure. The small magnitude of these fluctuations (< 0.2 ft) is due to the relatively shallow depth to water (55 ft) at the site.

The 2015–2016 recovery began on September 5, 2015, and ended on May 9, 2016. Other than a five-day period of pumping in mid-October, there was only sporadic pumping during the recovery period. The 2016 pumping season began on May 9. There was off-and-on pumping until June 14, after which there appears to have been little pumping until the transducer began to produce spurious data on July 22. The transducer-datalogger unit was removed from the well on October 26, 2016, and a new unit was installed on February 22, 2017. Water-use data for 2016 will be available later in 2017. In 2015, water use within the 2 mi radius surrounding the index well was 53 ac-ft, the lowest water use at any of the index wells. The 2015 water use was applied on 70 acres, resulting in water use per acre irrigated of 0.8 ft (table 8).

Previous water-level data were collected at this well by the USGS in 1999 and 2000; estimates of the water-level depths were obtained from McMahon (2001, fig. 8) after adjusting land surface elevations using recent elevation measurements (85 ft added to McMahon [2001, table 2] elevations). After the 1999 pumping season, the water level at Cimarron 210 recovered to an elevation of approximately 2,476 ft. In February 2017, the water level was at 2,474.1 ft, a loss of about 1.9 ft in 16 years.

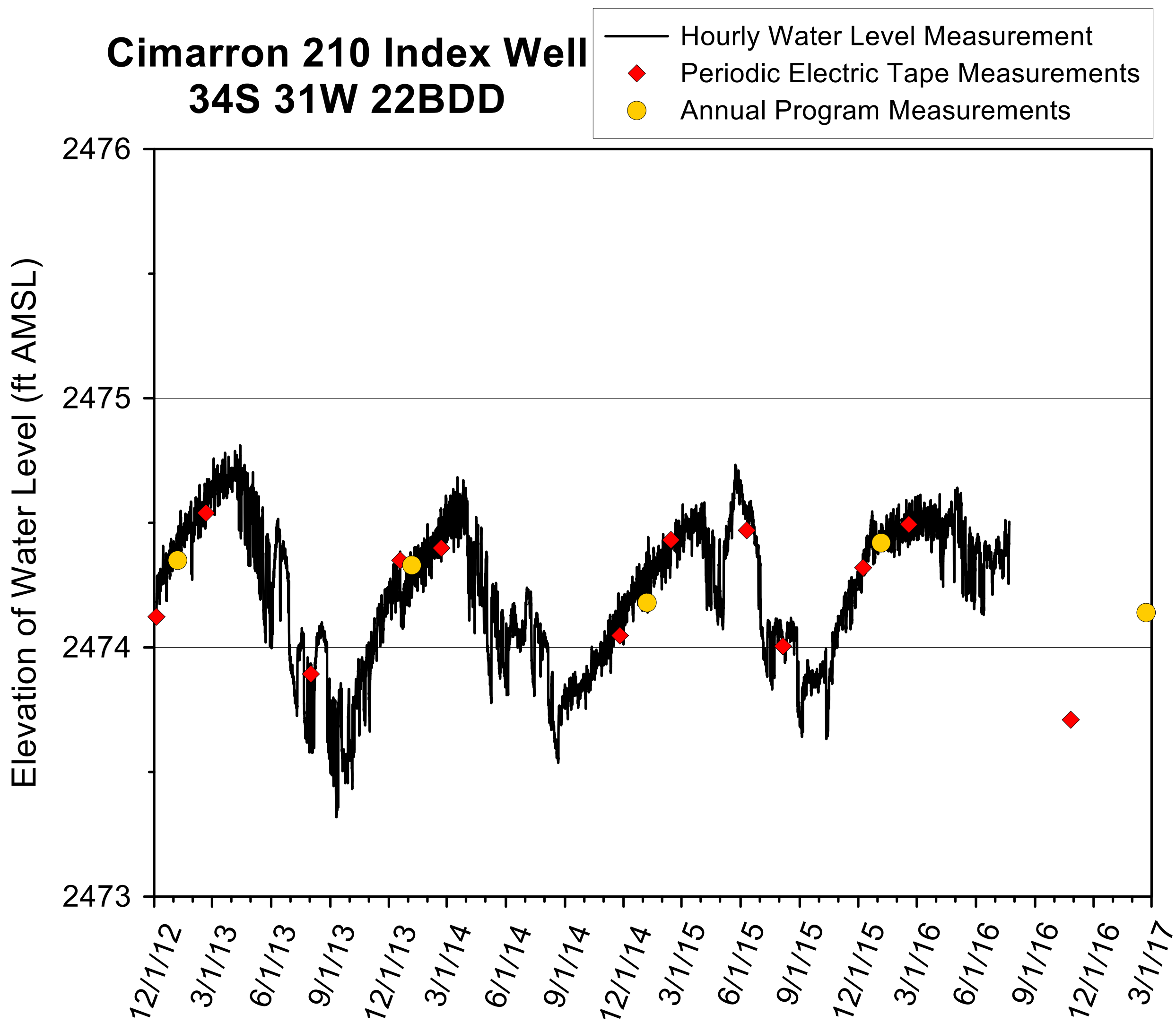

Figure 11—Cimarron 210 index well hydrograph—total data run to 7/22/16. A water-level elevation of 2,474 ft corresponds to a depth to water of 55.0 ft below land surface (lsf); the top of the 10-ft screen is 200 ft below lsf (elevation of 2,329 ft); and the bottom of the aquifer is 345 ft below lsf (elevation of 2,184 ft).

Table 8—General characteristics of the Cimarron 210 index well hydrograph and local water-use data.

		2013	2014	2015	2016	Min	Max
Minimum Water-Level Elevation	Feet	2,473.3	2,473.5	2,473.6	2,473.7[b]	2,473.3 (2013)	2,473.7[b] (2016)
	Date	9/10/13	8/21/14	10/12/15	10/26/16		
Maximum Observed Recovery Elevation	Feet	2,474.8	2,474.7	2,474.7	2,474.6	2,474.6 (2016)	2,474.8 (2013)
	Date	4/13/13	3/17/14	5/23/15	5/3/16		
Apparent Recovery	Feet	NA	1.4	1.2	1.0	1.0 (2016)	1.4 (2014)
Annual Change in Maximum Recovery	Feet	NA	-0.1	+0.06	-0.1	-0.01 (2014, 2016)	+0.06 (2015)
Recovery Season	Start	NA	10/5/13	8/21/14	9/5/15		
	End	4/13/13	4/2/14	5/24/15	5/9/16		
	Length (Days)	NA	179.0	276.4	246.6	179.0 (2014)	276.4 (2015)
Pumping During Recovery Season	Length (Days)	NA	7.5	29.5	18.0	7.5 (2014)	29.5 (2015)
Length of Pumping Season	Days	174.4	141.4	104.0	NA[c]	104.0 (2015)	174.4 (2013)
2 mi Radius Water Use[a]	Irrigated Acres	70	70	70	NA	70	70
	Total (ac-ft)	116	73	53	NA	53 (2015)	116 (2013)
	Use per Irrigated Acre (ft)	1.7	1.0	0.76	NA	0.76 (2015)	1.7 (2013)

[a]2012 Irrigated Acres—70, Total—81 ac-ft, Use per Irrigated Acre—1.16 ft
[b] Hand measurement, sensor malfunction
[c] Sensor malfunction

Table 9—Annual water-level measurement[a] comparison with transducer measurements, Cimarron 210 index well.

Date	**WL Elevation (ft)**	**Indicated Annual WL Change (ft)[b]**	**Method**
1/6/2013	2,474.35	NA	Steel tape
	2,474.41[c]	NA	Transducer
1/5/2014	2,474.33	-0.02 (-0.13)	Steel tape
	2,474.21[c]	-0.20	Transducer
1/6/2015	2,474.18	-0.15 (+0.06)	Steel tape
	2,474.24[c]	+0.03	Transducer
1/5/2016	2,474.42	+0.24 (NA)	Steel tape
	2,474.34[c]	+0.10	Transducer
1/5/2017	NA[d]		
	NA[e]		
2/20/2017	2474.14		Electric tape
	NA[e]		

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=370434100405203).
[b] Value in ( ) is the decline in the maximum recovered water level measured by the index well transducer.
[c] Average of values over time interval 0800–1600.
[d] Gate locked and no annual measurement was taken.
[e] Sensor recorded spurious data after July 22, 2016. Cable failed to connect to sensor on October 26, 2016. Sensor and cable removed for repairs. New sensor and cable installed February 20, 2017.

3.2.2. Haskell County Index Well

Figure 12—Aerial view of Haskell County index well site, an additional annual network well, and nearby points of diversion. Pumping wells that are monitored by DWR are not marked, and observation wells monitored by DWR are not shown.

Figure 12 is an aerial view of the Haskell County site (T. 27 S., R. 31 W., 36 BDC) at a scale that shows the index well, an additional nearby annual network well, and the location of wells with active water rights. The Haskell County site is the most extensively monitored of the original three index well sites because of its location within an area of concentrated DWR monitoring.

3.2.2.1. *Hydrograph and General Observations*

Figure 13 shows the complete hydrograph for the Haskell index well, table 10 summarizes its general characteristics, and table 11 compares the manual and transducer measurements from the well. The confined nature of the aquifer zone in which the index well is screened is indicated by the hydrograph form (see Butler et al. [2014]—Section 4.3) and by the 90–120+ ft change in water level during each pumping season, despite the absence of high-capacity pumping wells in the immediate vicinity of the index well (closest pumping well is almost half a mile away). Continuous water-level measurement at the

Haskell well unexpectedly terminated on January 12, 2014, as a result of sensor failure. On February 20, the sensor was removed from the well and a replacement sensor was installed on March 26, 2014.

The 2015–2016 recovery started on August 16, 2015, the last date of pumping for the 2015 irrigation season that had a significant effect on the index well, and ended February 15, 2016. Other than pumping periods of a few days in late August and early December, only a minor amount of pumping took place during the 2015–2016 recovery. The 2016 pumping season started earlier in the vicinity of the Haskell site than at most other index well sites, with a major break from April 9 to May 9. The early start of pumping is likely due to a combination of winter wheat irrigation and pre-planting irrigation of other crops, whereas the break in pumping could be caused by decreased water use during planting of summer crops and spring rains. After pumping resumed on May 10, there were occasional breaks in pumping of a few to several days, the longest being from June 26 to July 6. The 2016–2017 recovery season began on August 25, 2016, and continued with occasional pumping periods of a few days in mid-October and mid-November to early December until February 21, 2017.

Until 2013, the minimum recorded water-level elevation at the Haskell index well declined each year. However, the minimum 2013, 2014, and 2015 water-level elevations were, respectively, 3.2 ft, 2.0 ft, and 8.7 ft higher than that in 2012. That pattern continued in 2016 as the minimum 2016 water-level elevation was 1.2 ft lower than that in 2015 but 7.5 ft higher than that in 2012. The most likely explanation is the cessation of pumping early in the 2013 and 2014 irrigation seasons and no pumping during the 2015 and 2016 irrigation seasons at two nearby irrigation wells as a result of court decisions (May 21, 2013, Garetson Brothers versus Kelly and Diana Unruh, District Court of Haskell County Kansas, Case No. 12-CV-09; May 5, 2014, Garetson Brothers and Foreland Real Estate, LLC versus American Warrior Inc., and Rick Koehn, District Court of Haskell County Kansas, Case No. 12-CV-09; February 1, 2017, Garetson Brothers versus Kelly Unruh et al., District Court of Haskell County Kansas, Case No. 12-CV-09). Water use for 2016 will be available later in 2017 and, as a result of the court decision, is expected to be among the lowest during the monitoring period. In 2015, water use within the 2 mi radius surrounding the index well was 5,498 ac-ft, the lowest use year during the monitoring period, and 3,195 ac-ft below the average for the period (8,693 ac-ft). The 2015 water use was applied on the fewest irrigated acres during the monitoring period, resulting in the lowest average water use per acre irrigated during the monitoring period (table 10). In 2016, the index well recorded a year-to-year decline in the maximum recovered water level of 2.2 ft, the second smallest decline observed during the monitoring period. The decline in the maximum recovered water level in 2017 (2.7 ft) was the third smallest observed during the monitoring period, in keeping with the expectation that the 2016 water use will be well below average for the monitoring period.

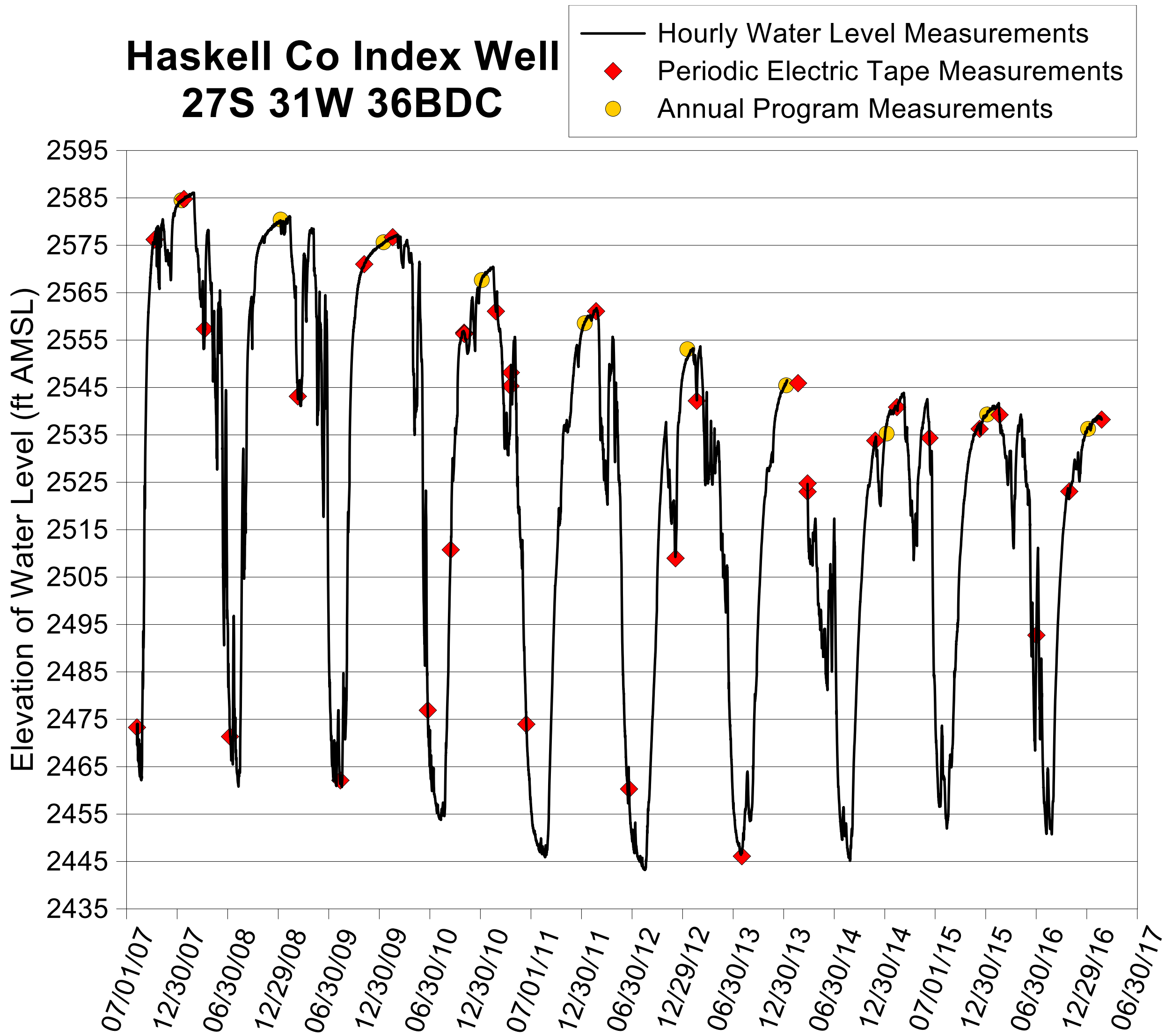

Figure 13—Haskell County index well hydrograph—total data run to 2/21/17. A water-level elevation of 2,445 ft corresponds to a depth to water of 392.85 ft below land surface (lsf); the top of the screen is 420 ft below lsf (elevation of 2,417.85 ft); and the bottom of the aquifer is 433 ft below lsf (elevation of 2,404.85 ft). The screen terminates 3 ft above the bottom of the aquifer. Break in monitoring from January to March 2014 was the result of sensor failure (see text).

Table 10—General characteristics of the Haskell County index well hydrograph and local water-use data.

		2007	2013	2014	2015	2016	Min	Max
Minimum Water-Level Elevation	Feet	2,462.1	2,446.4	2,445.2	2,451.9	2,450.7	2,443.2	2,462.1
	Date	8/23/07	7/29/13	8/27/14	8/12/15	8/25/16	(2012)	(2007)
Maximum Recovery Elevation	Feet	NA	2,553.6	2,545.9[a]	2,543.9	2,541.7	2,541.7	2,586.1
	Date	NA	3/4/13	2/20/14[a]	3/8/15	2/15/16	(2016)	(2007)
Apparent Recovery	Feet	NA	110.4	99.5[a]	98.7	89.8	89.8 (2016)	124.0 (2007)
Annual Change in Maximum Recovery	Feet	NA	-8.1	-7.7	-2.0	-2.2	-2.0 (2014)	-8.7 (2012)
Recovery Season	Start	NA	8/18/12	7/29/13	8/28/14	8/16/15		
	End	NA	3/4/13	2/20/14[a]	3/10/15	2/15/16		
	Length (Days)	NA	197.9	203.0[a]	193.3	183.0	174.9 (2011)	203.0 (2014)
Pumping During Recovery Season	Days	NA	36.3	35.0	32.6	21.1	5.2 (2010)	41.5 (2008)
Length of Pumping Season	Days	NA	150.0	149.6[a]	160.5	191.7	149.6 (2014)	193.7 (2011)
2 mi Radius Water Use	Irrigated Acres	6,475	6,751	5,822	5,435	NA	5,435 (2015)	7,755 (2008)
	Total Use (ac-ft)	8,764.0	8,265.0	7,816.2	5,497.8	NA	5,497.8 (2015)	10,560.4 (2011)
	Irrigation Use Only (ac-ft)	8,762.1	8,251.9	7,800.3	5,490.0	NA	5,490.0 (2015)	10,556.8 (2011)
	Use per Irrigated Acre (ft)	1.35	1.22	1.34	1.01	NA	1.01 (2015)	1.73 (2011)

[a] Sensor failed on 1/12/14 and was not replaced until 3/26/14. Maximum recovery level, recovery end date, and length of 2013–2014 recovery season and 2014 pumping season are all based on hand measurement taken on 2/20/14.

Table 11—Annual water-level measurement[a] comparison with transducer measurements, Haskell County index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/16/2013	2,553.09[d]	-5.48[d] (-8.1)	Steel tape
	2,551.22[c]	-7.60	Transducer
1/8/2014	2,545.46	-7.63[d] (-7.7)	Steel tape
	2,545.94[c,e]	-5.28	Transducer
1/6/2015	2,535.29[f]	-10.17[f] (NA[g])	Steel tape
	2,537.27[c,f]	-8.67[f]	Transducer
1/4/2016	2,539.31	+4.02 (-2.2)	Steel tape
	2,539.36[c]	+2.09	Transducer
1/3/2017	2,536.28	-3.03 (NA)	Steel tape
	2,536.31[c]	-3.05	Transducer

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=373925100395301).
[b] Value in ( ) is the decline in the maximum recovered water level measured by the index well transducer.
[c] Average of values over time interval 0800–1600.
[d] Suspect 2013 annual measurement value.
[e] Data taken from 2-hour telemetry data, sensor not downloadable after 8/1/13 because of sensor failure.
[f] Measurement affected by 18-day pumping period ending on 12/15/14.
[g] Sensor failed on 1/12/14 and was replaced on 3/26/14.

3.2.3. Hugoton Index Wells

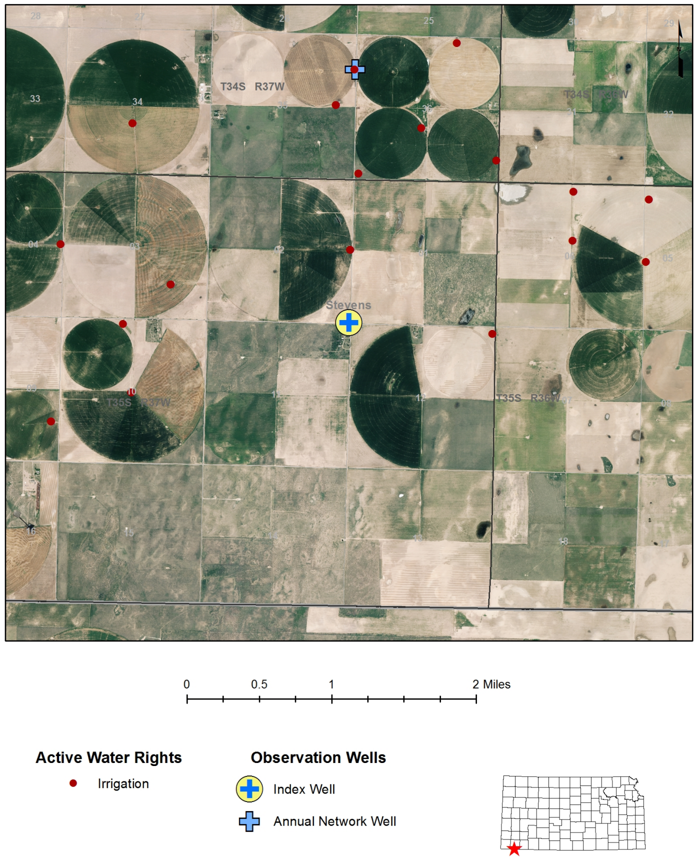

Figure 14—Aerial view of Hugoton index well site, an additional annual program well, and nearby points of diversion.

Figure 14 is an aerial view of the Hugoton site (T. 35 S., R. 37 W., 2 DDD) at a scale that shows the index well site, an additional annual program well, and nearby wells with active water rights. The site includes four wells, one near the water table and three at increasingly greater depths in the HPA; the second deepest well, screened at 485–495 ft below lsf, was first equipped with a transducer-datalogger unit (henceforth, Hugoton 495 or Hugoton 495 index well). On August 1, 2013, the third deepest well, screened at 303–313 ft below lsf, was similarly instrumented (henceforth, Hugoton 313 or Hugoton 313 index well). The water level has dropped below the bottom of the screen (140 ft below lsf) at the water-table well, so that a sensor could not be installed in the well.

3.2.3.1. *Hydrograph and General Observations*

Figure 15 shows the hydrographs for the two Hugoton index wells, table 12 summarizes the general characteristics of the Hugoton 495 hydrograph, and table 13 compares the manual and transducer measurements from Hugoton 495. The large rapid drops and rises after commencement and cessation, respectively, of pumping are similar to the behavior observed at the Haskell index well and indicate that the intervals in which both wells are screened act as a confined aquifer. This interpretation was confirmed through an analysis of water-level fluctuations induced by variations in barometric pressure using the BRF software developed earlier in this program (Bohling et al., 2011).

The 2015–2016 recovery started on August 17, 2015, and ended February 26, 2016. Other than pumping periods of a few to several days in late August and September, only a minor amount of pumping took place during the 2015–2016 recovery. The 2016 pumping season began on February 26 with a seven-day pumping period. Pumping began again on March 21 for about another seven days and then continued until April 26. There was little further pumping until May 9 when there were periods of a few to several days of pumping throughout the remainder of May and June. Widespread pumping in the area began on July 6 and continued until August 29. The hydrographs from Hugoton 495 and Hugoton 313 indicate that both intervals are affected by the same pumping stresses. The larger responses in Hugoton 495 (76 ft of drawdown at peak of 2016 pumping season) indicate that interval is more heavily stressed, and the elevation difference indicates the pumping induces downward flow from the shallower interval. There were two extended pumping periods during the 2016–2017 recovery: a five-day period beginning on September 20 and a period from October 20 to November 11. The recovery continued until March 8, 2017. Water-use data for 2016 will be available later in 2017. In 2015, water use within the 2 mi radius surrounding the Hugoton site was 3,190 ac-ft, the lowest water use during the monitoring period. The 2015 water use was applied on 2,987 acres, the largest area during the monitoring period, resulting in water use per acre irrigated of 1.1 ft, the lowest during the monitoring period (table 12).

The Liberal and Hugoton sites are the two sites that are collaboratively run by the KGS and the USGS. Unfortunately, these two sites have had more problems with data collection than the other sites. Both water-level sensors at the Hugoton site were misprogrammed in February 2014, so hourly water-level data were not acquired from February 20, 2014, to November 24, 2014. However, 15-minute data were collected with these sensors via the telemetry system and are used to fill in that interval. The telemetry system went down from November 11, 2014, to November 24, 2014, so no data were collected during that period. On November 3, 2015, the KGS water-level sensors were removed from both wells by USGS personnel and the site barometer was turned off; data collection was then done with the USGS sensors that had been placed in the well earlier. There was no discussion before the sensors were removed; the KGS discovered that the sensors were removed during a site visit on December 8, 2015. After contacting the USGS, the KGS was informed that the sensors had been taken to the Hays office. Those were retrieved by the KGS at a later date and downloaded. On December 8, 2015, USGS personnel visited the site and took manual measurements (the KGS had been at the site earlier in the day and had also taken manual measurements). After the manual measurements, the USGS inserted step adjustments of -0.59 ft and -0.47 ft to the data from Hugoton 313 and Hugoton 495, respectively. Such adjustments based on a single manual measurement are not consistent with KGS practices. The KGS therefore reinstalled the removed transducers in both wells on May 12, 2016, and will independently collect data with those sensors. Other than the period from November 1, 2015, to May 12, 2016, when the KGS transducers were not in the wells, the data from the KGS transducers are used to avoid problems such as those described here and in the Liberal site section of this report.

Previous water-level data were collected at this well by the USGS in 1999 and 2000; estimates of the water-level depths were obtained from McMahon (2001, fig. 8) after adjusting land surface elevations using recent elevation measurements (subtracted 12 ft from McMahon [2001, table 2] elevations). During the two pumping seasons in which McMahon (2001) reports measurement, the same relative pattern was observed as in 2013–2016 (Hugoton 313 response muted with respect to Hugoton 495). After the 1999 pumping season, the water levels at both Hugoton 313 and 495 recovered to an elevation of approximately 2,970 ft. The recent monitoring data indicate that water levels in early 2017 at both wells are recovering to near 2,915 ft, a loss of about 55 ft in 17 years (more than 3 ft/yr); water levels in the closest annual measurement program well (T. 34 S., R. 37 W., 35 AAD 01) declined about 47 ft over that same period.

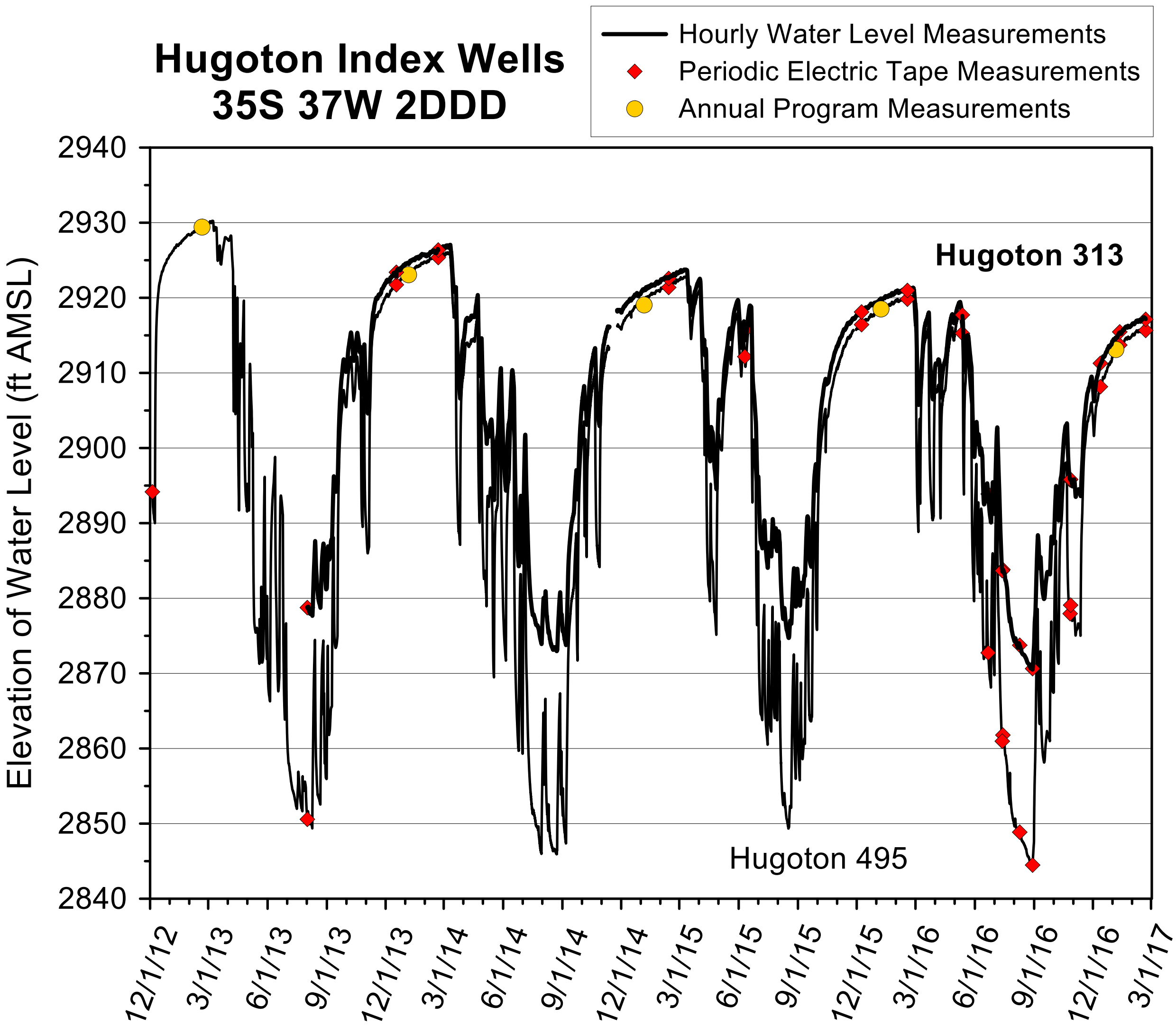

Figure 15—Hydrographs of Hugoton index wells—total data run to 2/20/17. A water-level elevation of 2,930 ft corresponds to a depth to water of 170 ft below land surface (lsf). For the Hugoton 495 well, the top of the 10-ft screen is 485 ft below lsf (elevation of 2,615 ft). For the Hugoton 313 well, 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).

Table 12—General characteristics of the Hugoton 495 index well hydrograph and local water-use data.

		2013	2014	2015[c]	2016	Min	Max
Minimum Water-Level Elevation	Feet	2,849.4	2,845.9[b]	2,849.3	2,844.5	2,844.5 (2016)	2,849.4 (2013)
	Date	8/9/13	8/22/14	8/17/15	8/29/16		
Maximum Observed Recovery Elevation	Feet	2,930.2	2,926.1[b]	2,922.8	2,920.2	2,920.2 (2016)	2,930.2 (2013)
	Date	3/7/13	3/10/14	3/9/15	2/26/16		
Apparent Recovery	Feet	NA	76.7	76.9	70.9	70.9 (2016)	76.9 (2015)
Annual Change in Maximum Recovery	Feet	NA	-4.1	-3.3	-2.6	-4.1 (2014)	-2.6 (2016)
Recovery Season	Start	NA	9/4/13	9/6/14	8/17/15		
	End	3/8/13	3/11/14	3/12/15	2/26/16		
	Length (Days)	NA	188.1	186.8	193.3	186.8 (2015)	193.3 (2016)
Pumping During Recovery Season	Length (Days)	NA	39.3	13.2[d]	29.1	13.2[d] (2015)	39.3 (2014)
Length of Pumping Season	Days	153.6	179.0	179.6	194.8	153.6 (2013)	194.8 (2016)
2 mi Radius Water Use[a]	Irrigated Acres	2,531	2,616	2,987	NA	2,531 (2013)	2,987 (2015)
	Total (ac-ft)	3,685	3,539	3,190	NA	3,190 (2015)	3,685 (2013)
	Use per Irrigated Acre (ft)	1.45	1.35	1.07	NA	1.07 (2015)	1.45 (2013)

[a]2012 Irrigated Acres—2,700, Total—3,828.39 ac-ft, Use per Irrigated Acre—1.42 ft
[b]Based on 15-minute telemetry data, hourly sensor data not available as a result of a programming error.
[c]USGS removed KGS sensors 11/03/15; KGS sensors reinstalled May 12, 2016.
[d]Telemetry and sensor data missing from 11/11/14 to 11/25/14.

Table 13—Annual water-level measurement[a] comparison with transducer measurements, Hugoton 495 index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/6/2013	2,926.37[c,d]	NA	Transducer
2/19/2013	2,929.85	NA	Steel tape
	2,929.22[c]	NA	Transducer
1/5/2014	2,923.07	NA (-4.1)	Steel tape
	2,923.18[c]	-3.19	Transducer
1/5/2015	2,919.05	-4.02 (-3.3)	Steel tape
	2,919.55[c]	-3.63	Transducer
1/4/2016	2,918.51	-0.54 (-2.6)	Steel Tape
	2,918.24[c,e]	-1.31	Transducer
1/5/2017	2,913.11	-5.40 (NA)	Steel Tape
	2,912.71[c,e]	-5.53	Transducer

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id= 370130101180902).

[b] Value in ( ) is the decline in the maximum recovered water level measured by the index well transducer.

[c] Average of values over time interval 0800–1600.

[d] Date of annual water-level survey, this site was a UTM (unable to measure) site due to a cable problem that has since been fixed. The transducer value was included to enable an estimate of the 2013–2014 change to be calculated.

[e] USGS removed KGS sensors 11/03/15; KGS sensors reinstalled May 12, 2016.

3.2.4. Liberal Index Wells

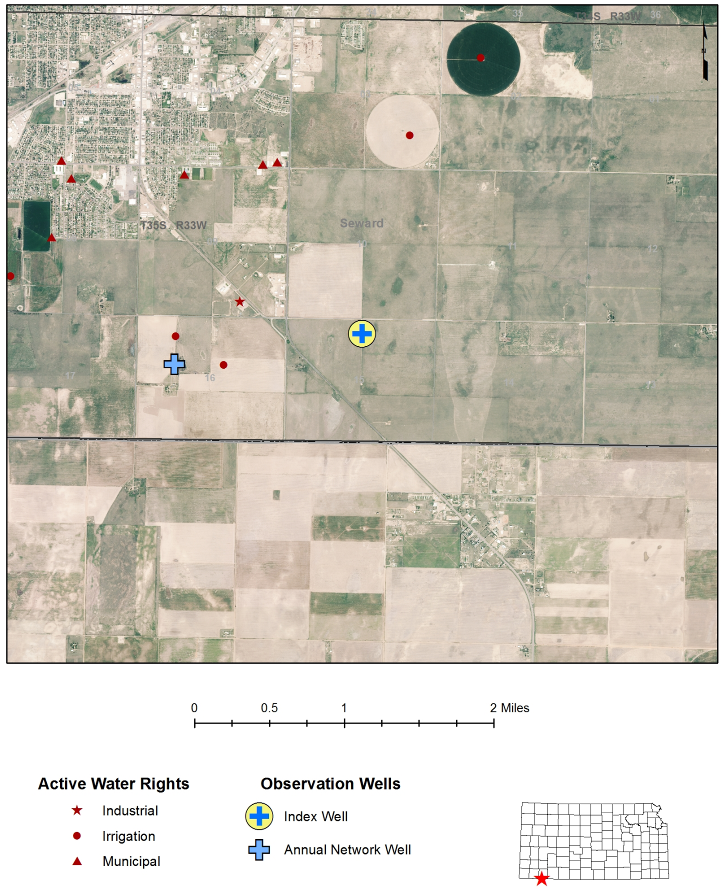

Figure 16—Aerial view of Liberal index well site, an additional annual program well, and nearby Kansas points of diversion in the area. The solid horizontal black line less than a mile south of the Liberal site marks the Kansas-Oklahoma border.

Figure 16 is an aerial view of the Liberal site (T. 35 S., R. 33 W., 15 ABC) at a scale that shows the index well site, an additional annual program well, and the nearby wells with active water rights in Kansas (Oklahoma wells not shown). The site includes four wells in the HPA; the second deepest well, screened at 426–436 ft below lsf, was first equipped with a transducer-datalogger unit (henceforth, Liberal 436 or Liberal 436 index well). In the first week of August 2013, the shallow well, screened at 140–160 ft below lsf, was similarly instrumented (henceforth, Liberal 160 or Liberal 160 index well). The fields in the immediate vicinity of the site appear to be dryland farmed.

3.2.4.1. *Hydrograph and General Observations*

Figure 17 shows the hydrographs for the two Liberal index wells, table 14 summarizes the general characteristics of the Liberal 436 hydrograph, and table 15 compares the manual and transducer measurements from Liberal 436. The confined nature of the aquifer zone in which Liberal 436 is screened is indicated by the hydrograph form and the relatively small (< 0.35 ft) amplitude fluctuations, which are produced by variations in barometric pressure, superimposed on water levels (particularly evident during the recovery period). This interpretation was confirmed through an analysis using the BRF software developed earlier in this program (Bohling et al., 2011). The interval in which Liberal 160 is screened is likely unconfined as the amplitude of the fluctuations produced by variations in barometric pressure is, in general, considerably larger than that observed in Liberal 436, which would be expected for an unconfined aquifer with a relatively large (>125 ft) depth to water. Hydraulic conditions in the screened interval at the Liberal 160 well will be explored further in 2017.

Interpretation of the 2015 and 2016 data from the two Liberal wells is difficult because of a series of problems that arose beginning in August 2014. As described in previous reports (Butler et al., 2015; Butler, Whittemore, Reboulet, et al., 2016), the sensor in the Liberal 160 well was misprogrammed so hourly water-level data were not acquired from August 20, 2014, to November 25, 2014 (interval A-B on fig. 17). Fortunately, 15-minute data collected with the sensor were available via telemetry and were used to fill in that interval. However, the KGS learned in May 2016 that the values recorded by the sensor were significantly adjusted by the USGS. Thus, the values in the period from A to B on fig. 17 are adjusted values that differ from the recorded values by an amount that exceeds 0.5 ft at times. On July 22, 2015 (D on fig. 17), USGS personnel removed the KGS transducer-datalogger unit from Liberal 160 and replaced it with another transducer. The values recorded by that transducer were considerably noisier than the previously acquired data; the USGS later adjusted these data but the justification for the adjustments is not clear. Despite the lack of compelling justification for the adjustments, the adjusted data are plotted here. Similarly, on June 10, 2015 (F on fig. 17), USGS personnel removed the KGS transducer-datalogger unit from Liberal 436 and replaced it with another transducer. The values recorded by that transducer were again considerably noisier than the previously acquired data. Again, the USGS later adjusted these data but the justification for the adjustments is unclear; the adjusted data are plotted here. Given the uncertainty about the quality of the USGS transducer data, the KGS sensors were reinstalled in both wells on May 12, 2016 (E and G on fig. 17). The KGS transducer-datalogger unit in Liberal 436 malfunctioned on October 26, 2016 (H on fig. 17). The unit was replaced during the February 20, 2017, download (I on fig. 17). Provisional data from the USGS transducer are plotted on fig. 17 for the October 26, 2016, to February 20, 2017, period.

The USGS collected water-level data at this well in 1999 and 2000; estimates of the water-level depths were obtained from McMahon (2001, fig. 8) after adjusting land surface elevations based on recent elevation measurements (added 7 ft to McMahon [2001] elevations). After the 1999 pumping season, the water level at Liberal 436 recovered to an elevation of approximately 2,683 ft. The recent manual water-level measurements indicate that the water level in early 2017 at Liberal 436 is recovering to near 2,658 ft, a loss of about 25 ft in 17 years (1.5 ft/yr), which is consistent with the 28-ft decline over this same period measured at a nearby well of the annual measurement program (T. 35 S., R. 33 W., 16 BCA 01). For Liberal 160, the water level recovered to an elevation of approximately 2,706 ft after the 1999 pumping season; the recent manual water-level measurements indicate that the water level in early 2017 at Liberal 160 is recovering to an elevation of approximately 2,691.0 ft, a loss of about 15 ft in 17 years (less than 1 ft/yr).

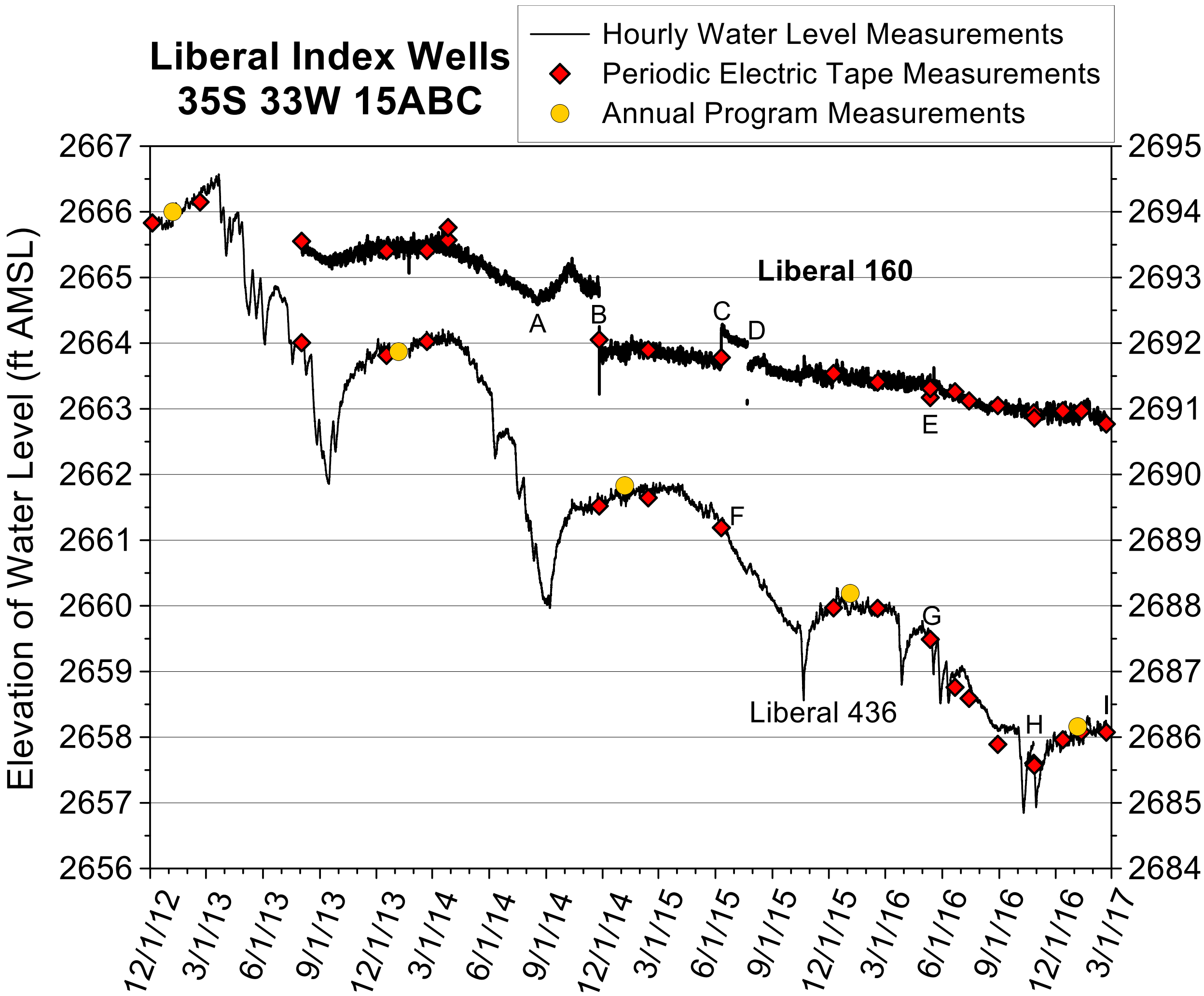

Figure 17—Hydrographs of Liberal index wells—total data run to 2/20/17. The Liberal 436 plot corresponds to the left y-axis; a water-level elevation of 2,664 ft corresponds to a depth to water of 157 ft below land surface (lsf); the top of the 10-ft screen is 426 ft below lsf (elevation of 2,395 ft). 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). Interruption of continuous monitoring at the Liberal 436 index well shortly after the 2014 annual program measurement discussed in a previous annual report (Butler et al., 2015). Values from A to B on Liberal 160 plot are values generated by the USGS and not actual measurements; apparent step change in water level in Liberal 160 on 11/25/14 (marked by B) is undoubtedly due to a change in transducer position in well. Transducer inadvertently mispositioned in well from C to D on Liberal 160 plot. KGS transducers replaced with USGS transducers at D and E for Liberal 160 and Liberal 436 plots, respectively; see text for further discussion. KGS transducers placed back in wells on May 12, 2016 (E and G for Liberal 160 and Liberal 436 plots, respectively). KGS transducer in the Liberal 436 index well malfunctioned on 10/26/16 (H) and was removed from well; transducer replaced on 2/20/17 (I).

Table 14—General characteristics of the Liberal 436 index well hydrograph and local water-use data.

		2013	2014	2015	2016	Min	Max
Minimum Water-Level Elevation	Feet	2,661.8	2,660.0	2,659.4[b]	2,656.8	2,656.8 (2016)	2,661.8 (2013)
	Date	9/15/13	9/6/14	10/21/15	10/10/16		
Maximum Recovery Elevation	Feet	2,666.6	2,664.2	2,661.9	2,660.1	2,660.1 (2016)	2,666.6 (2013)
	Date	3/21/13	3/17/14	3/3/15	2/2/16		
Apparent Recovery	Feet	NA	2.4	1.9	0.7	0.7 (2016)	2.4 (2014)
Change in Maximum Recovery	Feet	NA	-2.4	-2.3	-1.8	-1.8 (2016)	-2.4 (2014)
Recovery Season	Start	NA	10/15/13	9/7/14	10/21/15		
	End	3/22/13	4/7/14	4/9/15	3/23/16		
	Length (Days)	NA	174.3	213.3	154.0	154.0 (2016)	213.3 (2015)
Pumping During Recovery Season	Length (Days)	NA	6.3	5.7	12.0	5.7 (2015)	12.0 (2016)
Length of Pumping Season	Days	188.1	152.3	NA[b]	220.9	152.3 (2014)	220.9 (2016)
2 mi Radius Water Use[a]	Irrigated Acres	481	481	481	NA	481	481
	Total (ac-ft)	1,286.81	1,317.62	1,654.3	NA	1,286.8 (2013)	1,654.3 (2015)
	Irrigation Use Only (ac-ft)	821.0	749.0	688.0	NA	688.0 (2015)	821.0 (2013)
	Use per Irrigated Acre (ft)	1.75	1.56	1.43	NA	1.43 (2015)	1.75 (2013)

[a] 2012 Irrigated Acres—0/359 (Kansas/Oklahoma), Total—1,280.06 ac-ft, Irrigation use only—0/675 ac-ft, Use per Irrigated Acre—0/1.88 ft

[b] USGS removed KGS sensors June 10, 2015, (Liberal 436) and July 22, 2015, (Liberal 160). KGS sensors reinstalled May 12, 2016.

Table 15—Annual water-level measurement[a] comparison with transducer measurements, Liberal 436 index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/6/2013	2,666.00	NA	Steel tape
	2,665.88[c]	NA	Transducer
1/5/2014	2,663.87	-2.13 (-2.4)	Steel tape
	2,663.87[c]	-2.01	Transducer
1/5/2015	2,661.83	-2.04 (-2.3)	Steel tape
	2,661.67[c]	-2.2	Transducer
1/4/2016	2,660.19	-1.64 (-1.8)	Steel tape
	2,660.26[c,d,e]	-1.41[d,e]	Transducer
1/5/2017	2,658.16	-2.03 (NA)	Steel tape
	2,657.98[c,e]	-2.28[e]	Transducer

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id= 370033100534202).

[b] Value in ( ) is the decline in the maximum recovered water level measured by the index well transducer.

[c] Average of values over time interval 0800–1600.

[d] USGS removed KGS sensors June 10, 2015, (Liberal 436) and July 22, 2015, (Liberal 160). KGS sensors reinstalled May 12, 2016.

[e] Measurements from USGS 15-minute data readings, KGS cable connection issues caused removal of sensor and cable October 26, 2016. Reinstallation occurred February 20, 2017.

3.2.5. Rolla Index Well

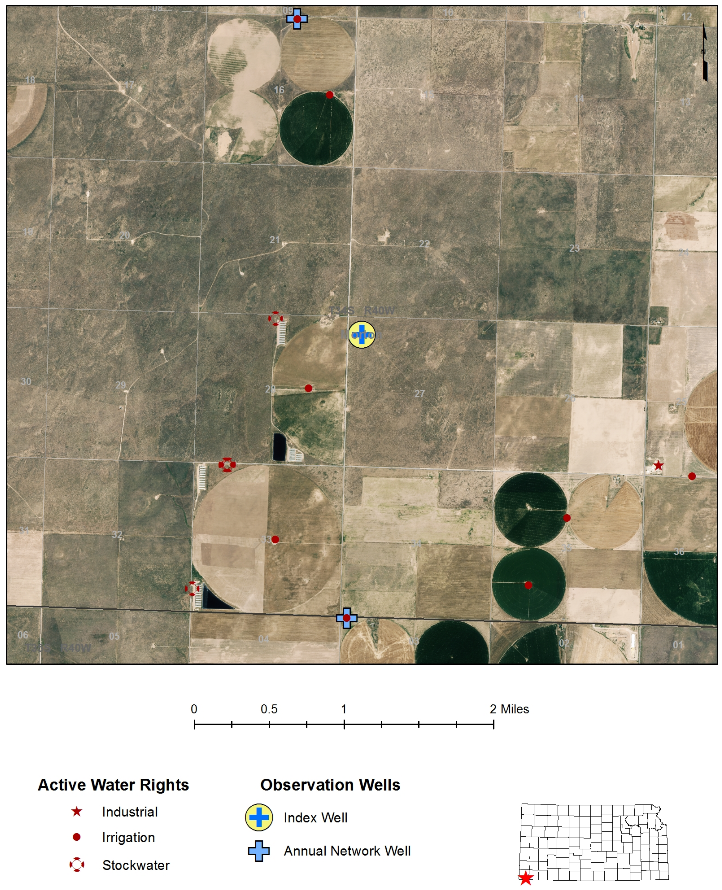

Figure 18—Aerial view of Rolla index well site, two additional annual program wells, and nearby points of diversion.

Figure 18 is an aerial view of the Rolla site (T. 34 S., R. 40 W., 27 BBB) at a scale that shows the index well site, two additional annual program wells, and the nearby wells with active water rights. The site includes two wells in the HPA, one near the water table and one near the base. The deeper well, for which the screened interval is 356–366 ft, has been equipped with a transducer-datalogger unit (henceforth, Rolla 366 or Rolla index well).

3.2.5.1. *Hydrograph and General Observations*

Figure 19 shows the hydrograph for the Rolla index well, table 16 summarizes its general characteristics, and table 17 compares the manual and transducer measurements from the well. The relatively large (up to 0.7 ft) amplitude fluctuations superimposed on the water levels (particularly evident during recovery periods), which are similar to those observed at the Thomas County index well, and the hydrograph form are indications that the interval in which the well is screened is behaving as an unconfined aquifer. This interpretation was confirmed through an analysis using the BRF software developed earlier in this program (Bohling et al., 2011). Although the periodic electric tape measurements are consistent with the hourly transducer measurements, the 2014, 2015, and 2017 annual program measurements appear to be questionable; the 2016 annual program measurement is consistent with the hourly transducer measurements.

The 2015–2016 recovery began on September 19, 2015, and ended on April 4, 2016; there was little pumping during the recovery period. The 2016 pumping season began with a week-long period of pumping in April. Other than week-long pumping periods in late May and late June, there was little pumping until sustained widespread pumping began on July 7. That sustained widespread pumping continued until August 30. Other than three pumping periods of a few to several days in early September, early October, and late November, there has been little pumping during the 2016–2017 recovery. Water levels were continuing to recover at the time of the February 21, 2017, download used for this report.

Water-use data for 2016 will be available later in 2017. The reported 2015 use (1,147.8 ac-ft for a 2 mi radius centered on the index well) was the lowest during the monitoring period. The water use for 2016 appears to have been less than or equal to that in 2015 as the minimum water-level elevation in 2016 was just 0.2 ft below that of 2015.

The USGS collected water-level data at this well in 1999 and 2000; estimates of the water-level depths were obtained from McMahon (2001, fig. 8) after adjusting land surface elevations using recent elevation measurements (14 ft added to McMahon [2001, table 2] elevations). After the 1999 pumping season, the water level at Rolla 366 recovered to an elevation of approximately 3,197 ft. The recent monitoring data indicate that the water level in early 2017 is recovering to near 3,187.7 ft, a loss of about 9.3 ft in 17 years (0.55 ft/yr); the water level in the closest annual measurement program well (about 2 mi south—T. 35 S., R. 40 W., 03 BBB 03 and 02 [well redrilled in 2003]) declined 9.2 ft over this same period.

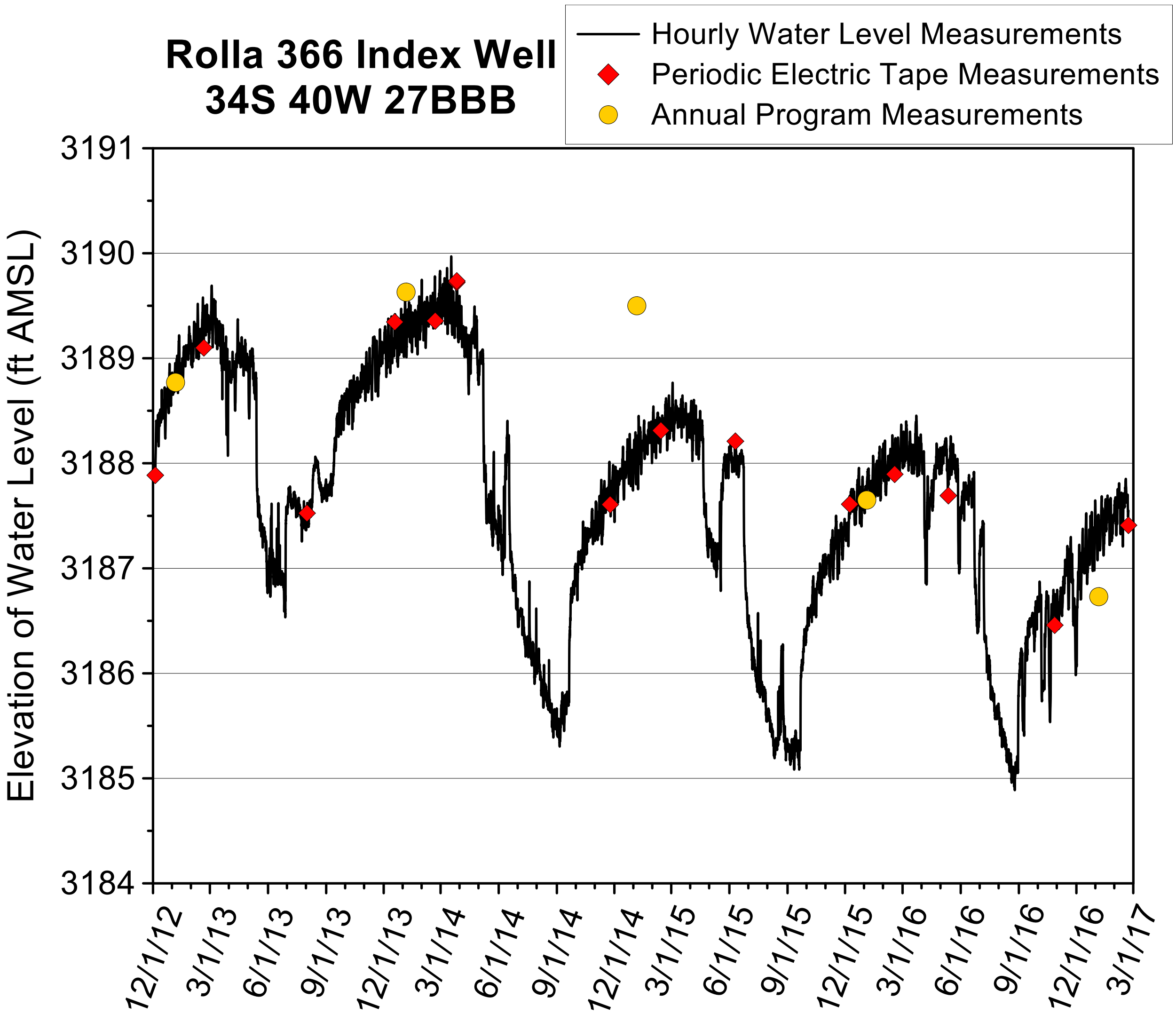

Figure 19—Rolla 366 index well hydrograph—total data run to 2/21/17. A water-level elevation of 3,188 ft corresponds to a depth to water of 187 ft below land surface (lsf). The top of the 10-ft screen is 356 ft below lsf (elevation of 3,019 ft), and the bottom of the aquifer is 399 ft below lsf (elevation of 2,976 ft). Note the suspect 2014, 2015, and 2017 annual program measurements.

Table 16—General characteristics of the Rolla 366 index well hydrograph and local water-use data.

		2013	2014	2015	2016	Min	Max
Minimum Water-Level Elevation	Feet	3,186.5	3,185.3	3,185.1	3,184.9	3,184.9 (2016)	3,186.5 (2013)
	Date	6/28/13	9/5/14	9/19/15	8/25/16		
Maximum Recovery Elevation	Feet	3,189.7	3,190.0	3,188.8	3,188.5	3,188.5 (2016)	3,190.0 (2014)
	Date	3/3/13	3/17/14	3/3/15	3/22/16		
Apparent Recovery	Feet	NA	3.5	3.5	3.4	3.4 (2016)	3.5 (2014, 2015)
Change in Maximum Recovery	Feet	NA	+0.3	-1.2	-0.3	-1.2 (2015)	+0.3 (2014)
Recovery Season	Start	NA	9/12/13	9/20/14	9/19/15		
	End	3/9/13	3/17/14	4/20/15	4/4/16		
	Length (Days)	NA	185.6	212.1	197.9	185.6 (2014)	212.1 (2015)
Pumping During Recovery Season	Length (Days)	NA	5.3	8.5	14.4	5.3 (2014)	14.4 (2016)
Length of Pumping Season	Days	186	187	153.0	148.3	148.3 (2016)	187 (2014)
2 mi Radius Water Use[a]	Irrigated Acres	1,331	1,331	832	NA	832 (2015)	1,331 (2013, 2014)
	Total (ac-ft)	1,553.6	1,295.9	1,147.8	NA	1,147.8 (2015)	1,553.6 (2013)
	Irrigation Use Only (ac-ft)	1,448.0	1,211.0	1,052.0	NA	1,052.0 (2015)	1,448.0 (2013)
	Use per Irrigated Acre (ft)	1.09	0.91	1.26	NA	0.91 (2014)	1.26 (2016)

[a]2012 Irrigated Acres—1,405, Total—2,063.16 ac-ft, Irrigation use only—1,948 ac-ft, Use per Irrigated Acre—1.39 ft

Table 17—Annual water-level measurement[a] comparison with transducer measurements, Rolla 366 index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/5/2013	3,188.77	NA	Steel tape
	3,188.87[c]	NA	Transducer
1/5/2014	3,189.63[d]	+0.86[d] (+0.27)	Steel tape
	3,189.08[c]	+0.21	Transducer
1/5/2015	3,189.50[e]	-0.13[d,e] (-1.2)	Steel tape
	3,188.15[c]	-0.93	Transducer
1/4/2016	3,187.65	-1.85[e] (-0.3)	Steel tape
	3,187.77[c]	-0.38	Transducer
1/5/2017	3,186.73[f]	-0.92[f] (NA)	Steel tape
	3,187.28[c]	-0.49	Transducer

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id= 370402101394401).
[b] Value in ( ) is the change in the maximum recovered water level measured by the index well transducer.
[c] Average of values over time interval 0800–1600.
[d] Suspect 2014 annual measurement value.
[e] Suspect 2015 annual measurement value.
[f] Suspect 2017 annual measurement value.

3.2.6. Willis Technology Farm Index Well

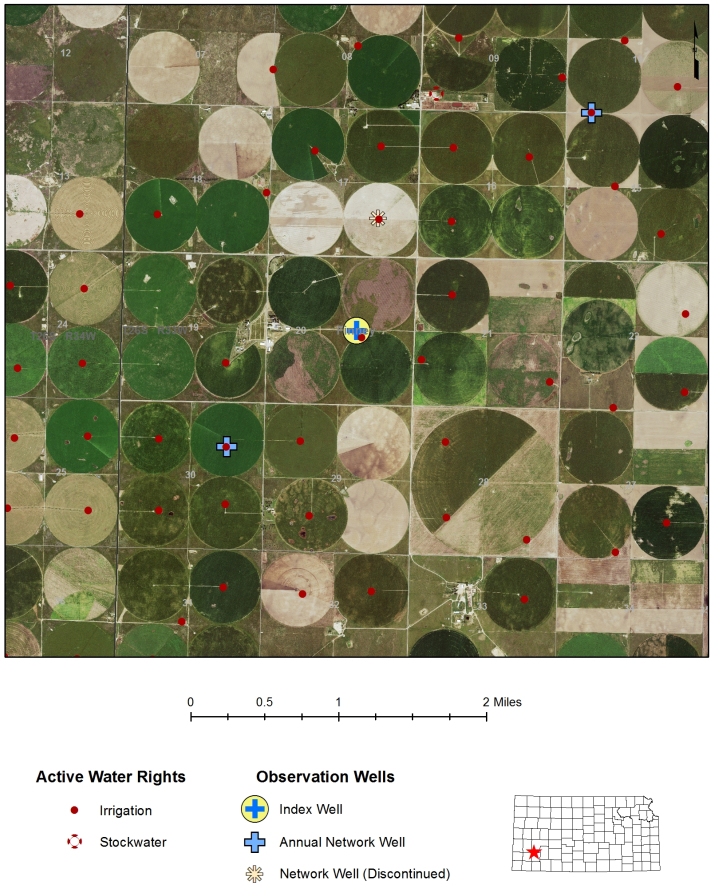

Figure 20—Aerial view of Willis Technology Farm index well site, additional annual program wells, and nearby points of diversion.

Figure 20 is an aerial view of the Willis Technology Farm site (T. 26 S., R. 33 W., 20 DBB – location designation in WWC5 [20 ACC] is incorrect) at a scale that shows the index well, the nearby annual program wells, and the nearby wells with active water rights. The well was originally drilled as an irrigation well in May 2014. However, the slots were sized incorrectly for the material opposite the screened interval, so the well pumped sand and could not be used. The well was left unplugged and a replacement well was drilled nearby. The KGS was offered the well as an index well in early summer 2016. A transducer-datalogger unit was installed in the well and monitoring began on July 29, 2016. Telemetry equipment was installed in the well that same day, allowing real-time viewing of the water-level data from the KGS website.

3.2.6.1. *Hydrograph and General Observations*

Figure 21 shows the complete hydrograph for the Willis Technology Farm index well, and table 18 summarizes its general characteristics. The large amplitude fluctuations superimposed on the water levels, particularly during the latter stages of the recovery period, are an indication of an unconfined aquifer, an interpretation that was supported by an analysis using the BRF software developed earlier in this program (Bohling et al., 2011).

The monitoring period has been short, so further interpretation of the hydrograph will be deferred to subsequent reports. The 2016–2017 recovery began on August 28, 2016. In addition to short pumping periods very shortly after the start of recovery and at the end of September and in early October, there was a 13-day pumping period beginning on September 5 and a 5-day pumping period beginning on October 22. The well appeared near recovery at the time of the latest download used in this report (February 21, 2017). On March 8, 2017, a nearby well was turned on for two days. Whether that is the start of the pumping season is not clear at the time of this report (March 11, 2017).

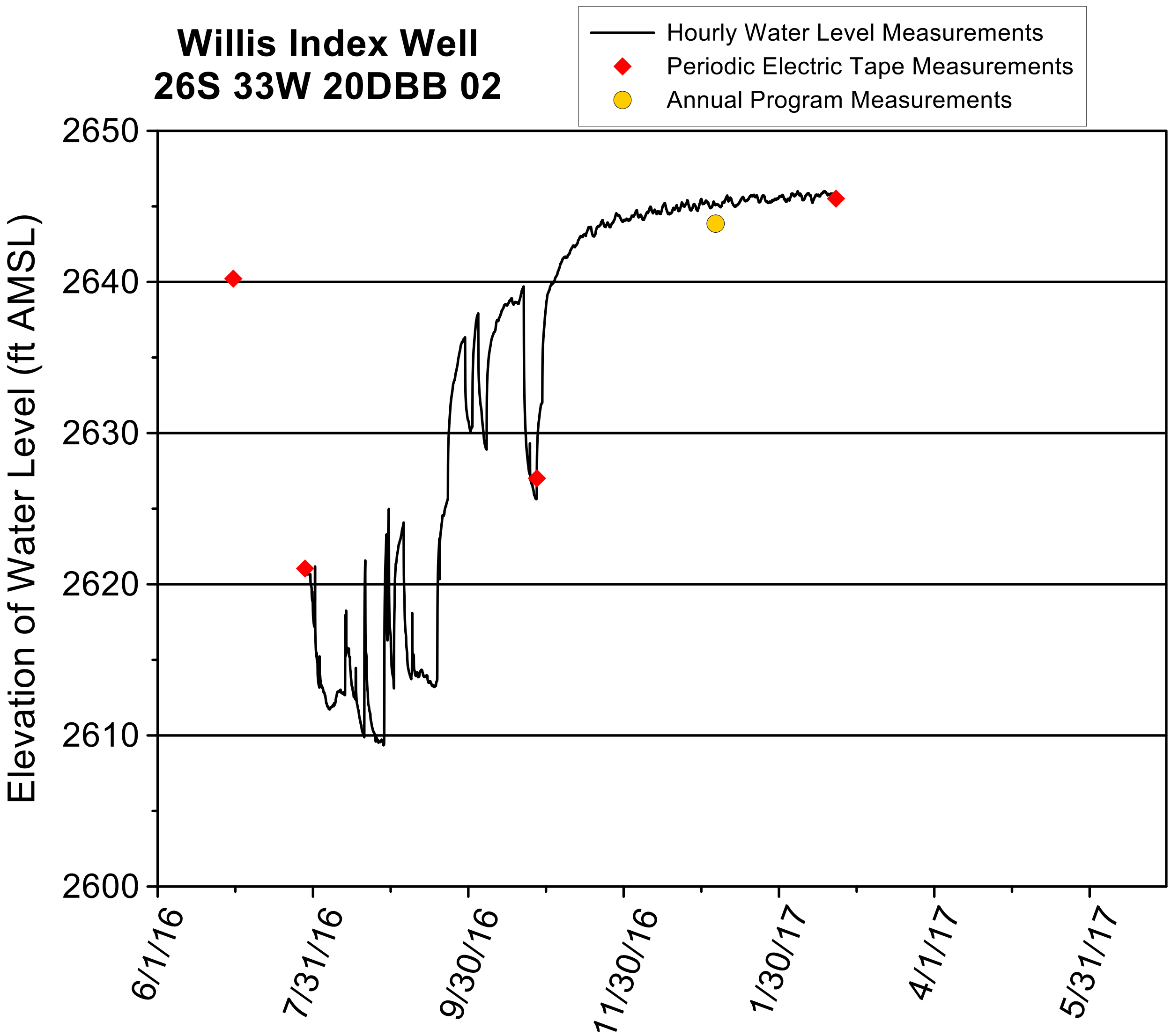

Figure 21—Willis Technology Farm index well hydrograph—total data run to 2/21/17. A water-level elevation of 2,640 ft corresponds to a depth to water of 300 ft below land surface (lsf). The top of the 220 ft screen is 262 ft below lsf (elevation of 2,678 ft), and the bottom of the aquifer is 502 ft below lsf (elevation of 2,438 ft).

Table 18—General characteristics of the Willis Technology Farm index well hydrograph and local water-use data.

		2016
Minimum Water-Level Elevation	Feet	2,609.34
	Date	8/28/16
Maximum Observed Recovery Elevation	Feet	NA
	Date	NA
Apparent Recovery	Feet	NA
Annual Change in Maximum Observed Recovery	Feet	NA
Recovery Season	Start	8/28/16
	End	NA
	Length (Days)	NA
Pumping During Recovery Season	Length (Days)	NA
Length of Pumping Season	Days	NA
2 mi Radius Water Use[a]	Irrigated Acres	NA
	Irrigation Use Only (ac-ft)	NA
	Use per Irrigated Acre (ft)	NA

[a]2015 Irrigated Acres—4,901, Irrigation use only—5,312.90 ac-ft, Use per Irrigated Acre—1.08 ft.

3.3. GMD4 Index Wells

Seven index wells are located in GMD4. The Thomas County index well is one of the original three index wells. Monitoring at the Colby and the Sheridan-6 (SD-6) LEMA index wells was initiated in 2014 and 2012, respectively. Table 19 summarizes characteristics of these seven wells.

Table 19—Characteristics of the GMD4 index wells (underlined wells are described in SD-6 subsection).

Site	2017 WL elev. (ft)[a]	2017 Saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2015 Water Use (ac-ft)		
					1 mi circle	2 mi circle	5 mi circle
Baalman	2,712.5	77.5	262	260–270	578	2,196	13,285[d]
Beckman[b]	2,682.6[c]				593	2,562[h]	13,042[e]
Colby	3,027.1	100.1-150.1	250–300	156–175	577[j]	2,345[k]	11,292[l]
Moss[b]	2,626.3[c]	53.3	243	205–245	279	2,242	14,390[f]
Seegmiller[b]	2,740.2[c]	72.2	265	225–265	712	2,715	14,181[e]
Steiger[b]	2,849.8[c]	61.8	177	145–185	190	977[i]	9,988[g]
Thomas	2,967.1	63.7	284	274–284	844	2,304	11,011

[a] 2017 annual tape water-level measurements from WIZARD database.
[b] Not an annually measured index well.
[c] 2017 WL measurements from hand measurements taken 02/21/2017.
[d] Includes 808.58 ac-ft of non-irrigation stock water.
[e] Includes 537.92 ac-ft of non-irrigation stock water.
[f] Includes 482.04 ac-ft of non-irrigation stock water and 389.05 ac-ft of municipal water.
[g] Includes 39.06 ac-ft of non-irrigation stock water and 3.57 ac-ft of recreation water.
[h] Includes 160.63 ac-ft of non-irrigation stock water.
[i] Includes 19.76 ac-ft of non-irrigation stock water.
[j] Includes 269.73 ac-ft of municipal water.
[k] Includes 1,109.64 ac-ft of municipal water and 428.06 ac-ft of contamination remediation water.
[l] Includes 1,266.93 ac-ft of municipal, 428.06 ac-ft of contamination remediation water, and 35.34 ac-ft of non-irrigation stock water.

3.3.1. Colby Index Well

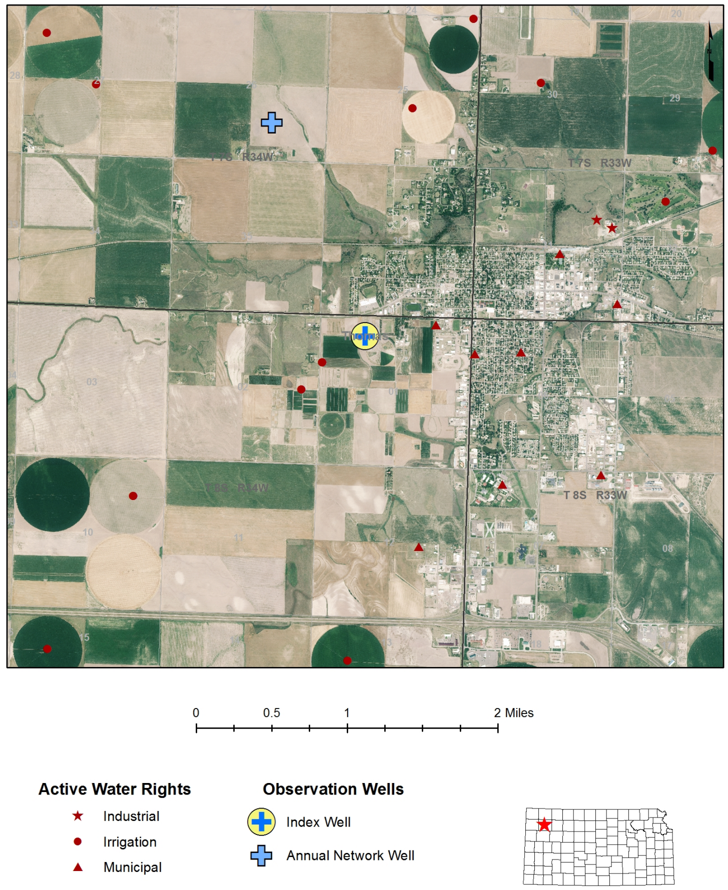

Figure 22—Aerial view of Colby index well site, an additional annual program well, and nearby points of diversion.

Figure 22 is an aerial view of the Colby index well site (T. 08 S., R. 34 W., 01 BAC) at a scale that shows the site of the index well, an additional annual program well, and the nearby wells with active water rights. The index well terminates 175 ft below land surface. Information about the screened interval was not available, so in October 2016 we used the KGS video logger to identify the screened interval for the well (156.4–175 ft below land surface). We found that the screen consists of alternating pairs of vertical slots 1–2" in length (the two slots in a pair are 180 degrees apart); one pair of slots starts as soon as the previous ends but the position is shifted by 90 degrees. The well has been part of the annual measurement program since at least 1997. Based on well logs to the bottom of the aquifer in the general vicinity, the base of the aquifer at the Colby index well should be between 250 and 300 ft below land surface.

3.3.1.1. *Hydrograph and General Observations*

Figure 23 shows the hydrograph for the Colby index well, table 20 summarizes its general characteristics, and table 21 compares the manual and transducer measurements from the well. The relatively large (up to

1.0 ft) amplitude fluctuations superimposed on the water levels are similar to those observed at the Thomas County index well and are an indication that the interval in which the well is screened is behaving as an unconfined aquifer.

The 2015–2016 recovery began on September 4, 2015, and ended on March 28, 2016. There was sporadic pumping throughout the recovery period. The 2016 pumping season began with an initial pumping period of slightly less than two weeks. This was followed by a period of little pumping from April 11 to June 9, 2016. This break in pumping was likely due to planting of summer crops and late spring rains that affected both irrigation wells and nearby public water supply wells (such as for lawn and garden watering). Other than short breaks in late June and mid-July, sustained pumping continued until the end of the main pumping season on September 4, 2015. The 2016–2017 recovery continued at the time of this report (March 6, 2017). In addition to an extended period of pumping from October 17 to November 8, 2016, there has been sporadic pumping throughout the recovery period. Water-use data for 2016 will be available later in 2017. In 2015, water use within the 2-mi radius surrounding the index well was 2,345 ac-ft, the majority of which appears to have been municipal pumping for the city of Colby; irrigation pumping was only a little over a third of the total water use. Water use for municipal and industrial needs is likely responsible for much of the sporadic pumping during the recovery season.

The Colby index well has been measured manually by facility staff and GMD4 personnel on a weekly to quarterly basis since May 1947 (well was redrilled in August 1984). The water level was 114 ft below land surface in early May 1947. In early January 2017, the water level was close to 150 ft below land surface. The water level changed little from 1947 to the mid-1960s, after which it decreased in a relatively constant manner until the mid-1980s (depth to water in late January 1986 was 125 ft below land surface). In the late 1980s, the declines accelerated; the declines further increased in the early 2000s (depth to water was 134 ft below land surface in late January 2001).

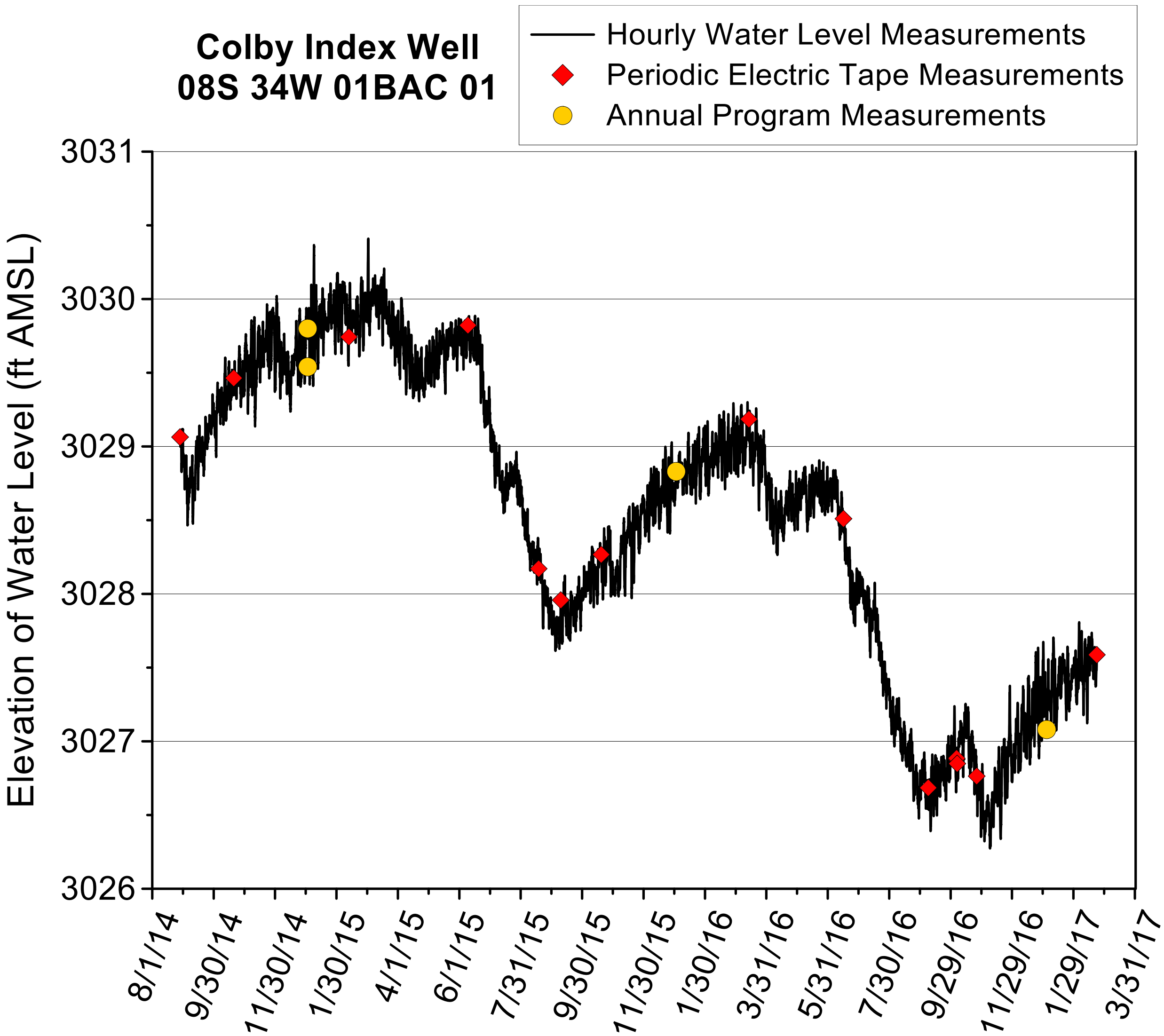

Figure 23—Colby index well hydrograph—total data run to 2/21/17. A water-level elevation of 3,029 ft corresponds to a depth to water of 148 ft below land surface (lsf). Total depth of the well is 175 ft below lsf (elevation of 3,002 ft). The screened interval extends from 156 to 175 ft below lsf. The base of the aquifer is estimated to be 250–300 ft below lsf (see text).

Table 20—General characteristics of the Colby index well hydrograph and local water-use data.

		2014	2015	2016
Minimum Water-Level Elevation	Feet	3,028.5	3,027.6	3,026.3
	Date	9/4/14	9/4/15	11/7/16
Maximum Observed Recovery Elevation	Feet	NA	3,030.4	3,029.3
	Date	NA	3/3/15	3/12/16
Apparent Recovery	Feet	NA	1.9	1.7
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-1.1
Recovery Season	Start	NA	9/10/14	9/4/15
	End	NA	3/18/15	3/28/16
	Length (Days)	NA	189	203
Pumping During Recovery Season	Length (Days)	NA	35.5	9.7
Length of Pumping Season	Days	NA	170	218
2 mi Radius Water Use[a]	Irrigated Acres	695	719	NA
	Total (ac-ft)	2,575	2,345	NA
	Irrigation Use Only (ac-ft)	855	807	NA
	Use per Irrigated Acre (ft)	1.23	1.12	NA

[a]2013 Irrigated Acres—712, Total—2,661.97 ac-ft, Irrigation use only—967.42 ac-ft, Use per Irrigated Acre—1.36 ft

Table 21—Annual water-level measurement[a] comparison with transducer measurements, Colby index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/2/2014	3,030.59	NA	Steel tape
	NA	NA	Transducer
1/2/2015	3,029.80	-0.79 (NA)	Steel tape
	3,029.79[c]	NA	Transducer
1/2/2016	3,028.83	-0.97 (-1.11)	Steel tape
	3,028.84[c]	-0.95	Transducer
1/3/2017	3,027.08	-1.75 (NA)	Steel tape
	3,027.11[c]	-1.73	Transducer

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=392329101040201).
[b] Value in ( ) is the change in the maximum recovered water level measured by the index well transducer.
[c] Average of values over time interval 0800–1600.

3.3.2. Sheridan-6 LEMA Index Wells

Collaboration with GMD4 on the continuous monitoring of water levels at five observation wells within the Sheridan-6 (SD-6) Local Enhanced Management Area (LEMA) continued in 2016 (see fig. 24 for aerial views of the SD-6 LEMA with the index wells). The KGS formally took over the collection of water-level data for these wells in mid-year 2014 and maintenance of sensors in late 2015 and early 2016. Initially, each SD-6 well had a transducer in the water column connected to a datalogger on top of the well. As described in a previous report (Butler et al., 2015), all but one well had anomalous water-level spikes, primarily during the summer, that appeared to be related to high temperatures in the datalogger housings. The KGS worked with GMD4 to help mitigate this problem. In June 2014, miniature temperature sensors were placed inside the datalogger housing at each of the five wells to measure temperature on five-minute intervals. As a result of earlier activities, which included painting the datalogger housings white and shifting the position of the housings to reduce solar exposure, only two wells displayed anomalous water-level spikes in the summer of 2014 during periods of high temperatures.

Given the problems with the equipment in the SD-6 LEMA wells, we began replacing the existing monitoring equipment in the second half of 2015 and early 2016. The previous equipment has been replaced with integrated pressure transducer-datalogger units that are similar to those used at all the other index wells. These units remain submerged in the water column at all times and thus are not affected by surface temperature extremes. After a period during which both sets of equipment were in all but the Beckman index well, the original equipment was removed in summer 2016. Data from the original transducer are used until the KGS transducer-datalogger unit was placed in the well. After that, data from the KGS transducer-datalogger unit are used. In October 2016, telemetry equipment was installed at the Seegmiller well to allow real-time monitoring from the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/ index.shtml).

Hydrographs for the four LEMA wells without telemetry equipment up until the time of the download for this report (February 21, 2017) can be viewed on the KGS website (www.kgs.ku.edu/HighPlains/lema/sd6.html); anomalous water-level spikes have been removed from those hydrographs.

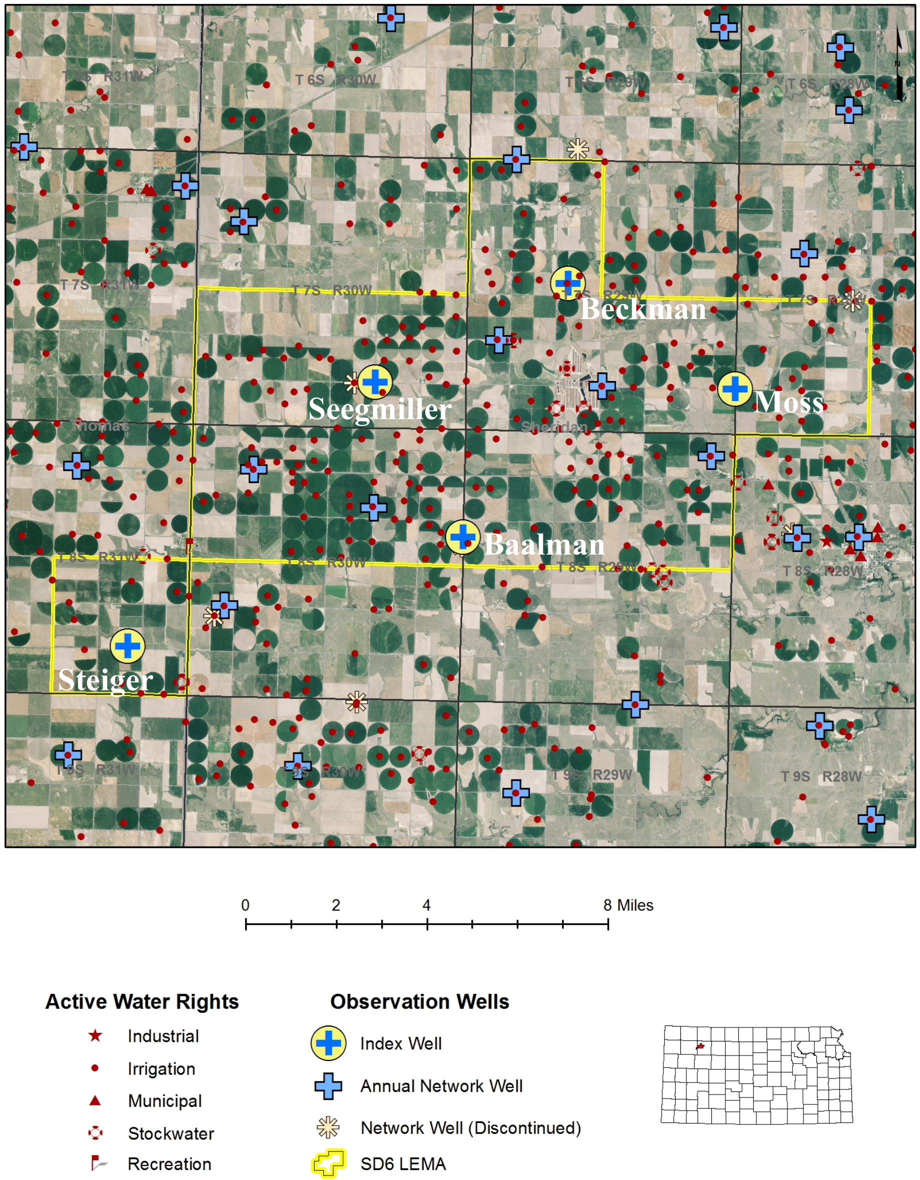

Figure 24—Aerial view of the SD-6 index wells, additional annual program wells, and points of diversion.

3.3.2.1. *Baalman Index Well*

The Baalman index well (T. 8 S., R. 30 W., 13 DAA) is located in an area of moderate groundwater use in the southern portion of the SD-6 area (fig. 24). Monitoring originally began on May 5, 2012, in an existing well, Baalman index well 1. This was a small diameter (1.25 in Sch 80) well, making it difficult to obtain manual measurements with the transducer in the well; in addition, the well had an apparent blockage in the casing. A new well (henceforth, Baalman index well) was drilled in August 2015 (951 ft from the first well) and monitoring in that well began on August 19, 2015. The hydrograph from the Baalman index well 1 can be found in the previous annual report (Butler, Whittemore, Reboulet, et al., 2016). Given the apparent problems with that well, only the hydrograph from the new Baalman index well will be presented in this and future reports.

3.3.2.1.1. Hydrograph and General Observations

Figure 25 shows the hydrograph for the Baalman index well, and table 22 summarizes its general characteristics. An analysis of water-level fluctuations induced by variations in barometric pressure using the BRF software developed earlier in this program (Bohling et al., 2011) indicates that the aquifer in the vicinity of Baalman index well behaves as an unconfined aquifer.

The 2015–2016 recovery began before August 15, 2015, and ended on June 7, 2016. There appears to have been no pumping during the recovery period. The 2016 pumping season began with an initial pumping period of slightly less than two weeks that likely involved just one well. After that, there was more general pumping from multiple wells. Other than a weeklong break August 5–12 and sporadic shorter breaks in June and early July, sustained pumping continued until the end of the pumping season on August 21, 2016. The 2016–2017 recovery was continuing at the time of the download used for this report (February 21, 2017). There appears to have been no observable pumping during the recovery period. Water levels appear to be converging on a water level that is less than that at the start of the pumping season, an indication that the aquifer in this vicinity may be laterally bounded by lower permeability units (Butler, Stotler, et al., 2013).

Water use data for 2016 will be available later in 2017. The reported 2015 use (2,196 ac-ft for a 2 mi radius centered on the index well) was 476 ac-ft and 386 ac-ft less than in 2014 and 2013, respectively, the first two years of the SD-6 LEMA, and 1,698 ac-ft less than in 2012. Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.79 ft (9.4 in)/acre in the vicinity of the Baalman index well.

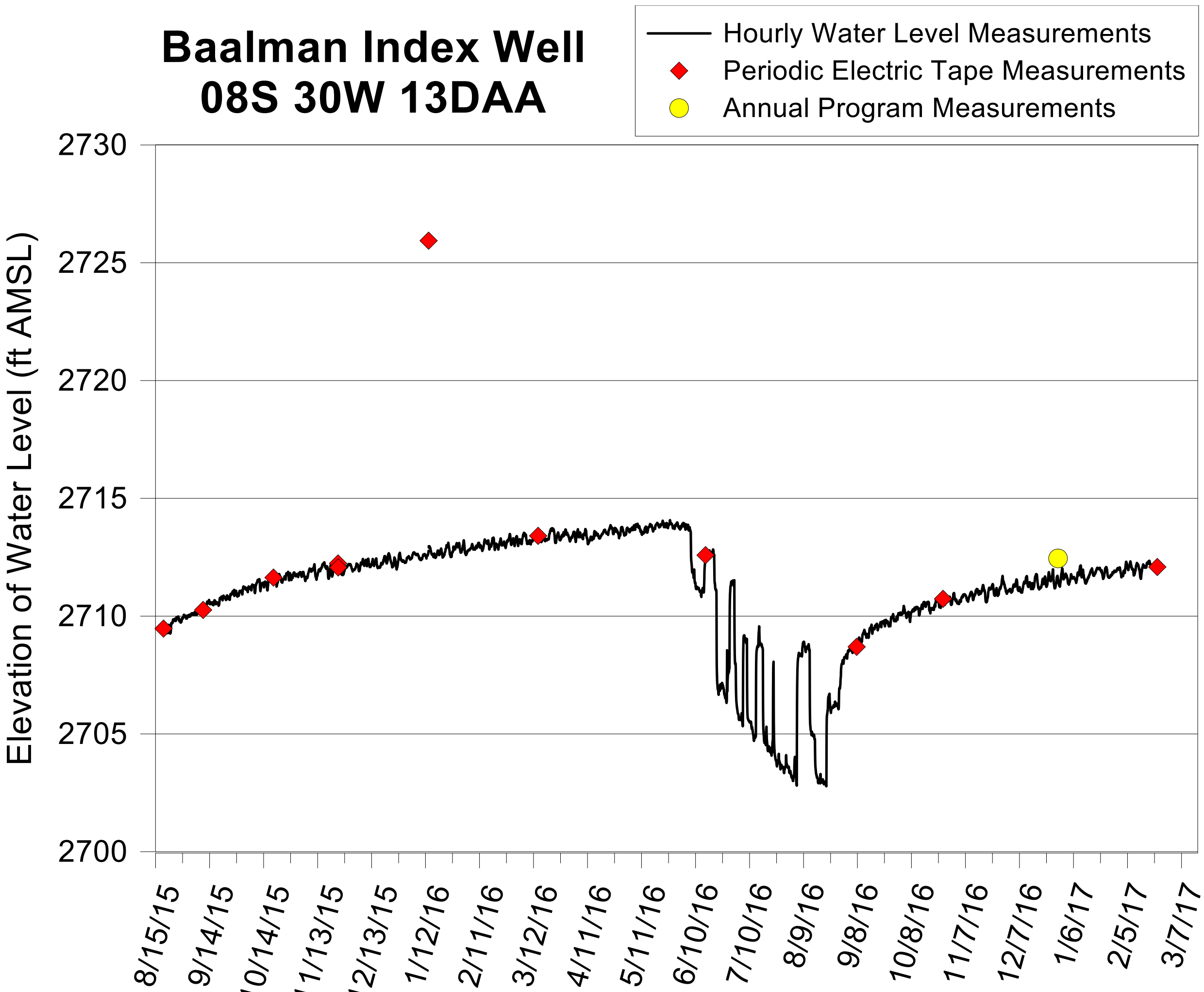

Figure 25—Baalman index well hydrograph—total data run to 2/21/17. A water-level elevation of 2,712 ft corresponds to a depth to water of 185 ft below land surface (lsf); the top of the 10-ft screen is 260 ft below lsf (elevation of 2,637 ft); and the bottom of the aquifer is 262 ft below lsf (elevation of 2,635 ft). The difference between the electric tape measurement in January 2016 and the hourly measurement from the transducer is due to a malfunctioning electric tape.

Table 22—General characteristics of the Baalman index well hydrograph and local water-use data.

		2015	2016
Minimum Water-Level Elevation	Feet	NA	2,702.8
	Date	NA	8/21/16
Maximum Observed Recovery Elevation	Feet	NA	2,714.1
	Date	NA	5/26/16
Apparent Recovery	Feet	NA	NA
Annual Change in Maximum Observed Recovery	Feet	NA	NA
Recovery Season	Start	NA	NA
	End	NA	6/7/16
	Length (Days)	NA	NA
Pumping During Recovery Season	Length (Days)	NA	0
Length of Pumping Season	Days	NA	82
2 mi Radius Water Use[a]	Irrigated Acres	3,161	NA
	Total (ac-ft)	2,196.0	NA
	Use per Irrigated Acre (ft)	0.69	NA

[a]2012 Irrigated Acres—3,081, Total Water Use—3,893.9 ac-ft, Use per Irrigated Acre—1.26 ft;
2013 Irrigated Acres—3,134, Total Water Use—2,581.5 ac-ft, Use per Irrigated Acre—0.82 ft;
2014 Irrigated Acres—3,150, Total Water Use—2,671.9 ac-ft, Use per Irrigated Acre—0.85 ft.

3.3.2.2. *Beckman Index Well*

The Beckman index well (T. 7 S., R. 29 W., 16 CBD) is located in an area of relatively high groundwater use in the northern portion of the SD-6 area (fig. 24). The well was installed in the gravel pack of an irrigation well; the stickup (portion of casing above land surface) for the index well is located about 10 ft from the irrigation well. Monitoring began on April 29, 2013, but has been interrupted three times by battery problems with the now-replaced datalogger unit. Well construction information for the Beckman index well is not available.

3.3.2.2.1. Hydrograph and General Observations

Figure 26 shows the complete hydrograph for the Beckman index well, and table 23 summarizes its general characteristics. The large, abrupt changes in water level are associated with the operation of the adjacent irrigation well. Given the position of the well in the gravel pack of the irrigation well, linear and nonlinear well losses are undoubtedly responsible for a significant portion of those changes. Other nearby pumping wells appear to have a limited effect on water levels in the Beckman index well, as indicated by the relatively small drawdown produced by pumping at nearby wells in 2016. An analysis of water-level fluctuations induced by variations in barometric pressure using the BRF software developed earlier in this program (Bohling et al., 2011) indicates that the aquifer at this site behaves as an unconfined aquifer.

The calibration specifications for the original transducer-datalogger unit appeared to have been changed between the cessation of monitoring on October 1, 2014, and the resumption of monitoring on October 30, 2014. The 2015 pumping-induced responses, as measured by the transducer, were considerably less than those during the 2014 pumping season. The manual measurement in August 2015, however, indicates that the pumping-induced responses were similar between the two years. Although the 2015 transducer measurements appear questionable, the timing of the pumping events should be correct. The transducer and associated datalogger were replaced by a KGS transducer-datalogger unit on January 14, 2016. However, that transducer-datalogger unit operated inefficiently so batteries ran down quickly, resulting in a monitoring gap from May 26 to June 15, 2016. The unit was replaced on September 7, 2016.

The 2015–2016 recovery began on September 6, 2015, and ended late May or early June 2016. Other than short (1.5 day) pumping periods in mid-September and mid-October 2015 and some pumping at distant wells in early spring of 2016, there was little pumping during the recovery period. The irrigation well adjacent to the Beckman index well was not pumped during the 2016 pumping season; relatively continuous pumping occurred at distant wells until August 29, 2016. Recovery continued at the time of the download for this report (February 21, 2017).

Water-use data for 2016 will be available later in 2017. The reported 2015 use (2,561.6 ac-ft for a 2-mi radius centered on the index well) was 790 ac-ft and 580 ac-ft less than in 2013 and 2014, respectively, the first two years of the SD-6 LEMA, and 3,091 ac-ft less than in 2012. Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been less than 0.75 ft (9 in)/acre in the vicinity of the Beckman well.

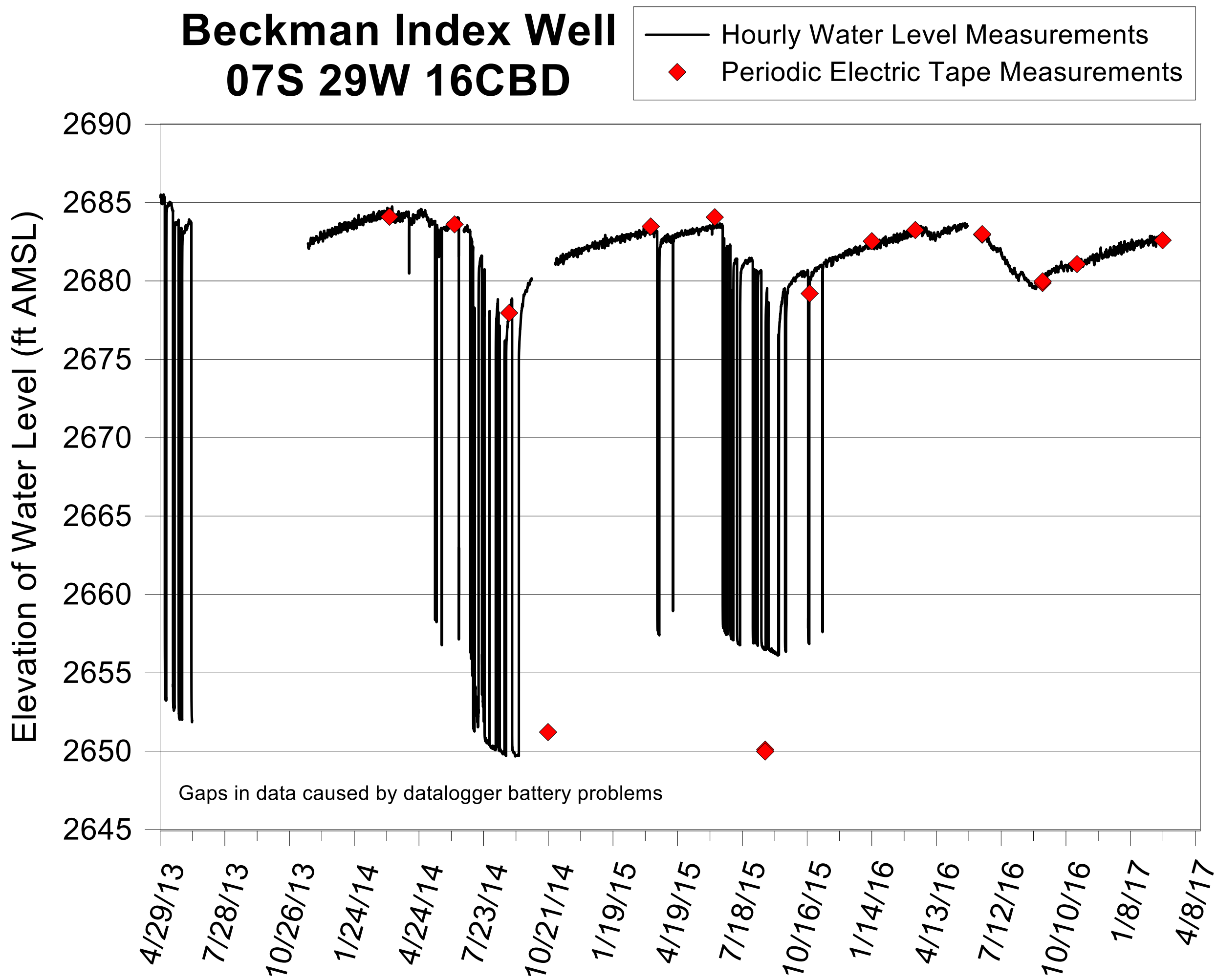

Figure 26—Beckman index well hydrograph—total data run to 2/21/17. A water-level elevation of 2,650 ft corresponds to a depth to water of 230.15 ft below land surface (lsf). The difference between the electric tape measurement in the summer of 2015 and the hourly measurements from the transducer is thought to be caused by a change in calibration specifications associated with the resumption of monitoring in late October 2014.

Table 23—General characteristics of the Beckman index well hydrograph and local water-use data.

		2014	2015	2016
Minimum Water-Level Elevation	Feet	2,649.7[b]	NA[c]	2,679.5
	Date	9/5/14[b]	NA[c]	8/29/16
Maximum Observed Recovery Elevation	Feet	2,684.8	NA[c]	NA[d]
	Date	3/17/14	NA[c]	NA[d]
Apparent Recovery	Feet	NA	NA[c]	NA[d]
Annual Change in Maximum Observed Recovery	Feet	NA	NA[c]	NA[d]
Recovery Season	Start	NA	9/9/14[b]	9/6/15
	End	5/2/14	6/20/15	NA[d]
	Length (Days)	NA	284[b]	NA[d]
Pumping During Recovery Season	Length (Days)		>2.7	3.2
Length of Pumping Season	Days	130[b]	78	NA[d]
2 mi Radius Water Use[a]	Irrigated Acres	3,740	3,624	NA
	Total (ac-ft)	3,141.9	2,561.6	NA
	Irrigation Use Only (ac-ft)	2,919.3	2401.0	NA
	Use per Irrigated Acre (ft)	0.78	0.66	NA

[a] 2012 Irrigated Acres—3,730, Total use—5,652.9 ac-ft, Irrigation use—5,402.7 ac-ft, Use/Irrigated Acre—1.45 ft
2013 Irrigated Acres—3,837, Total use—3,351.9 ac-ft, Irrigation use—3,123.8 ac-ft, Use/Irrigated Acre—0.81 ft
[b] Value may be affected by missing data from 10/1/14 to 10/30/14.
[c] Values affected by calibration issues and thus not reported.
[d] Values affected by missing data from 5/26/16 to 6/15/16.

3.3.2.3. *Moss Index Well*

The Moss index well (T. 7 S., R. 29 W., 25 DDD) is located in an area of relatively moderate groundwater use in the eastern portion of the SD-6 area (fig. 24). The well is screened over the bottom 38 ft of the High Plains aquifer, which was approximately 53 ft thick in January 2017. Monitoring began on May 22, 2012, and has continued with few problems beyond occasional spurious values produced by datalogger overheating. The transducer-datalogger unit prone to overheating was replaced on August 18, 2015.

3.3.2.3.1. Hydrograph and General Observations

Figure 27 shows the complete hydrograph for the Moss index well and table 24 summarizes its general characteristics. The effect of individual pumping wells is muted on the Moss hydrograph as a result of the relatively small amount of water use in the immediate vicinity of the well (1-mi circle water use in table 19). The relatively large (exceeding 0.5 ft) amplitude fluctuations superimposed on the water levels (particularly evident during recovery periods), which are similar to those observed at the Thomas County index well, are an indication that the interval in which the well is screened is behaving as an unconfined aquifer. This interpretation was confirmed through an analysis using the BRF software developed earlier in this program (Bohling et al., 2011).

The 2015–2016 recovery began on September 8, 2015, and ended on June 14, 2016; there appeared to be very little pumping during the recovery period. Other than occasional periods of reduced pumping, the longest of which was a six-day period beginning on August 5, pumping was sustained until the end of the pumping season on August 24, 2016. Recovery continued at the time of the download for this report (February 21, 2017).

Water-use data for 2016 will be available later in 2017. The reported 2015 use (2,242 ac-ft for a 2-mi radius centered on the index well) was 231 ac-ft and 358 ac-ft less than in 2013 and 2014, respectively, the first two years of the SD-6 LEMA, and 1,820 ac-ft less than in 2012. Since the establishment of the SD-6 LEMA, the average water use per irrigated acre has been 0.93 ft (11.2 in)/acre in the vicinity of the Moss well.

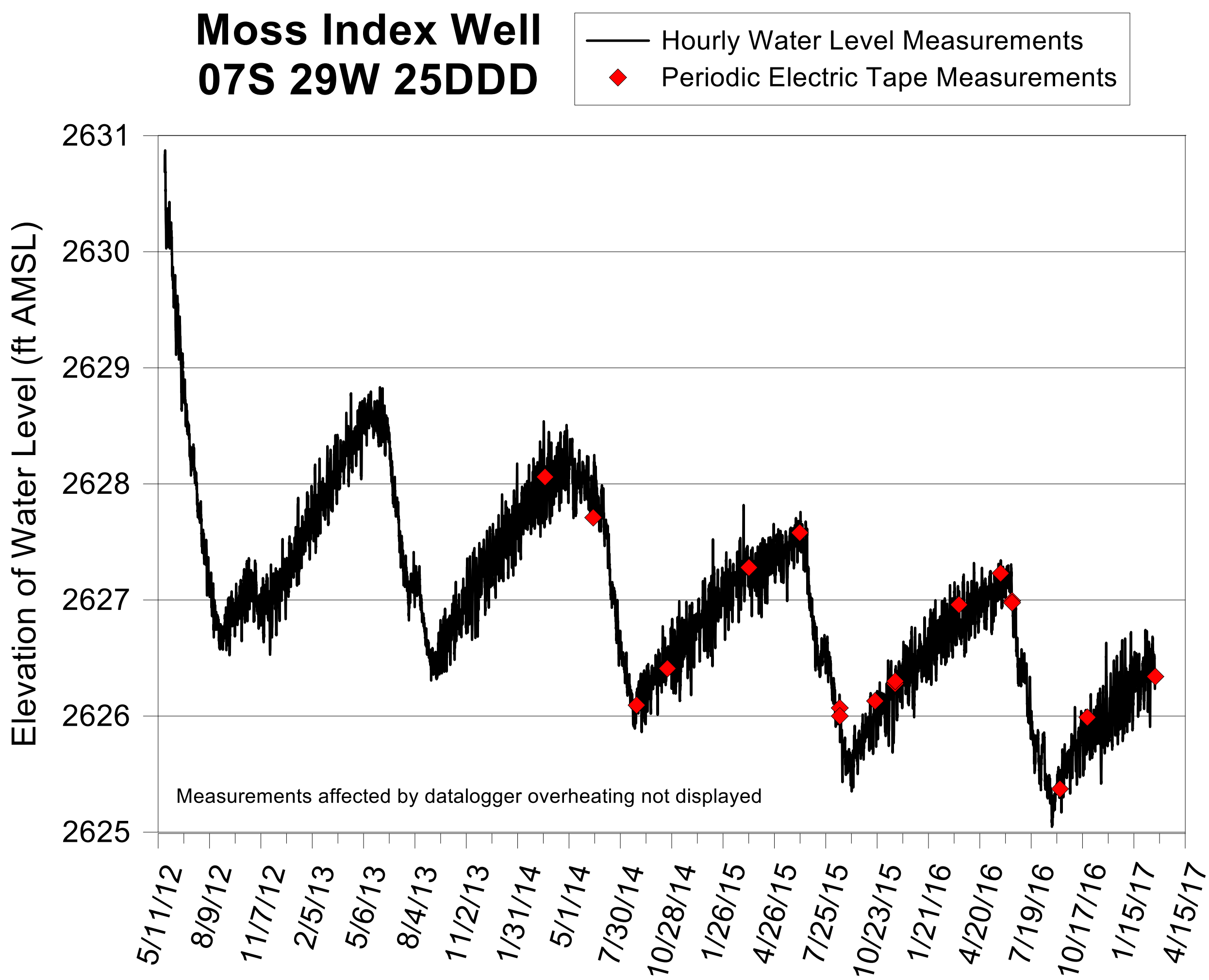

Figure 27—Moss index well hydrograph—total data run to 2/21/17. A water-level elevation of 2,627 ft corresponds to a depth to water of 191.44 ft below land surface (lsf); the top of the 40-ft screen is 205 ft below lsf (elevation of 2,613.4 ft); and the bottom of the aquifer is 243 ft below lsf (elevation of 2,575.4 ft).

Table 24—General characteristics of the Moss index well hydrograph and local water-use data.

		2012	2013	2014	2015	2016	Min	Max
Minimum Water-Level Elevation	Feet	2,626.5	2,626.3	2,625.9	2,625.4	2,625.1	2,625.1	2,626.5
	Date	9/13/12	9/1/13	9/5/14	9/8/15	8/24/16	(2016)	(2012)
Maximum Observed Recovery Elevation	Feet	NA	2,628.8	2,628.5	2,627.8	2,627.3	2,627.3	2,628.8
	Date	NA	6/13/13	3/17/14	3/3/15	5/26/16	(2016)	(2013)
Apparent Recovery	Feet	NA	2.3	2.2	1.9	1.9	1.9 (2015, 2016)	2.3 (2013)
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-0.3	-0.7	-0.5	-0.3 (2014)	-0.7 (2015)
Recovery Season	Start	NA	8/31/12	9/12/13	8/24/14	9/8/15		
	End	NA	5/21/13	5/1/14	6/22/15	6/14/16		
	Length (Days)	NA	263.2	231.0	301.8	280.0	231.0 (2014)	301.8 (2015)
Pumping During Recovery Season	Length (Days)	NA	15.7	0	0	0	0 (2014, 2015, 2016)	15.7 (2013)
Length of Pumping Season	Days	NA	114	115	78	72	72 (2016)	115 (2014)
2 mi Radius Water Use	Irrigated Acres	2,725	2,577	2,644	2,629	NA	2,577 (2013)	2,725 (2012)
	Total (ac-ft)	4,062.2	2,473.2	2,599.9	2,241.9	NA	2,241.9 (2015)	4,062.2 (2012)
	Use per Irrigated Acre (ft)	1.49	0.96	0.98	0.85	NA	0.85 (2016)	1.49 (2012)

3.3.2.4. *Seegmiller Index Well*

The Seegmiller index well (T. 7 S., R. 30 W., 27 DDD) is located in an area of relatively high groundwater use in the northwest portion of the SD-6 area (fig. 24). The well is screened over the bottom 40 ft of the High Plains aquifer, which was approximately 72 ft thick in January 2017. Monitoring began on May 15, 2012, and has continued with few problems beyond occasional spurious values produced by datalogger overheating. The transducer-datalogger unit prone to overheating was replaced on August 18, 2015. On October 5, 2016, the transducer-datalogger unit in the well was replaced by a unit that was compatible with telemetry equipment. On October 25, 2016, telemetry equipment was installed in the well, allowing real-time viewing of the water-level data from the KGS website.

3.3.2.4.1. Hydrograph and General Observations

Figure 28 shows the complete hydrograph for the Seegmiller index well, and table 25 summarizes its general characteristics. The impact of individual pumping wells is very clear on the Seegmiller hydrograph. The hydrograph form and the relatively large (exceeding 0.5 ft) amplitude fluctuations superimposed on the water levels (particularly evident during recovery periods), which are similar to those observed at the Thomas County index well, are indications that the interval in which the well is screened is behaving as an unconfined aquifer. This interpretation was confirmed through an analysis using the BRF software developed earlier in this program (Bohling et al., 2011).

The 2015–2016 recovery began on September 5, 2015, and ended on June 9, 2016; other than a six-day pumping period in early April 2016, there was little pumping during the recovery period. Sustained pumping began on June 21 and largely continued, with a few one- to four-day stoppages in late June and early July, until July 28, after which there was a 13-day period of infrequent pumping. The pumping season concluded with a 25-day period of sustained pumping ending on September 5, 2016, during which most of the wells in the area were active until the last six days. Recovery continued at the time of the download for this report (February 21, 2017).

Water-use data for 2016 will be available later in 2017. The reported 2015 use (2,715 ac-ft for a 2-mi radius centered on the index well) was 159 ac-ft and 421 ac-ft less than in 2013 and 2014, respectively, the first two years of the SD-6 LEMA, and 2,756 ac-ft less than in 2012. Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.8 ft (10 in)/acre in the vicinity of the Seegmiller well.

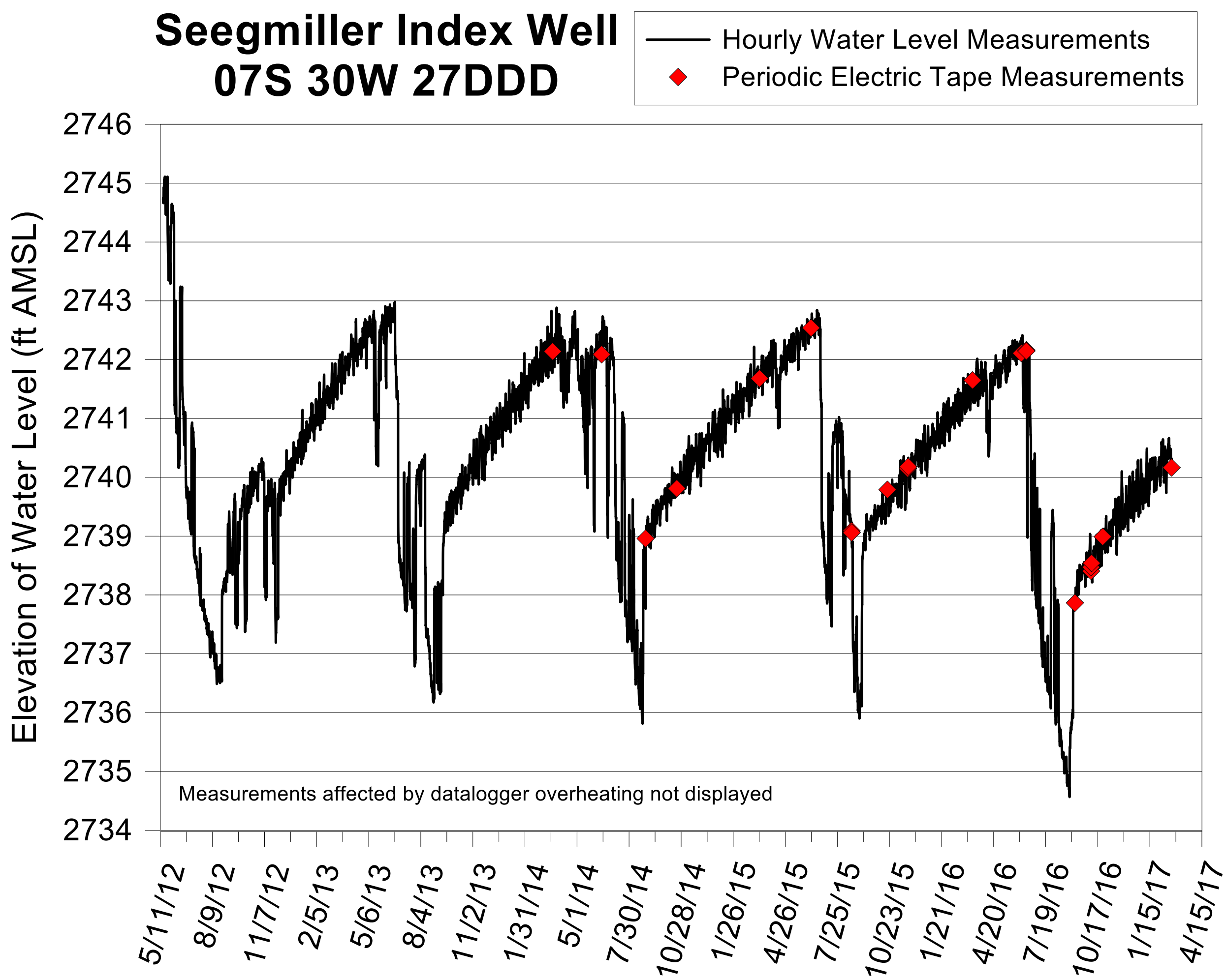

Figure 28—Seegmiller index well hydrograph—total data run to 2/21/17. A water-level elevation of 2,740 ft corresponds to a depth to water of 195.69 ft below land surface (lsf); the top of the 40-ft screen is 225 ft below lsf (elevation of 2,710.7 ft); and the bottom of the aquifer is 265 ft below lsf (elevation of 2,670.7 ft).

Table 25—General characteristics of the Seegmiller index well hydrograph and local water-use data.

		2012	2013	2014	2015	2016	Min	Max
Minimum Water-Level Elevation	Feet	2,736.5	2,736.2	2,735.8	2,736.0	2,734.6	2,734.6	2,736.5
	Date	8/16/12	8/26/13	8/22/14	9/1/15	8/29/16	(2016)	(2012)
Maximum Observed Recovery Elevation	Feet	NA	2,743.0	2,742.9	2,742.8	2,742.4	2,742.4	2,743.0
	Date	NA	6/20/13	3/26/14	6/19/15	6/8/16	(2016)	(2013)
Apparent Recovery	Feet	NA	6.5	6.7	7.0	6.4	6.4 (2016)	7.0 (2015)
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-0.1	-0.1	-0.4	-0.1 (2014, 2015)	-0.4 (2016)
Recovery Season	Start	NA	8/25/12	9/11/13	8/22/14	9/5/15		
	End	NA	6/20/13	3/31/14	6/25/15	6/9/16		
	Length (Days)	NA	299.4	201.2	306.8	278	201.2 (2014)	306.8 (2015)
Pumping During Recovery Season	Length (Days)	NA	23.1	0	5.4	5.7	0 (2014)	23.1 (2013)
Length of Pumping Season	Days	NA	82.5	144.5	71.6	87	71.6 (2015)	144.5 (2014)
2 mi Radius Water Use	Irrigated Acres	3,716	3,573	3,674	3,682	NA	3,573 (2013)	3,716 (2012)
	Total (ac-ft)	5,470.5	2,874.1	3,135.7	2,715.0	NA	2,715.0 (2016)	5,470.5 (2012)
	Use per Irrigated Acre (ft)	1.47	0.80	0.85	0.74	NA	0.74 (2015)	1.47 (2012)

3.3.2.5. Steiger Index Well

The Steiger index well (T. 8 S., R. 31 W., 26 DCD) is located in an area of relatively low groundwater use in the southwest portion of the SD-6 area (fig. 24). The well is screened over the bottom 32 ft of the High Plains aquifer, which was approximately 62 ft thick in January 2017. Monitoring began on May 15, 2012, and has continued with few problems beyond spurious values produced by datalogger overheating. The transducer-datalogger unit prone to overheating was replaced on August 18, 2015.

3.3.2.5.1. Hydrograph and General Observations

Figure 29 shows the complete hydrograph for the Steiger index well, and table 26 summarizes the local water-use data. The effect of individual pumping wells is difficult to discern on the Steiger hydrograph beyond the vicinity of A on fig. 29. In general, the Steiger hydrograph appears to be a response to regional pumping activity. The fluctuations superimposed on the water levels are produced by variations in barometric pressure. The small magnitude of these fluctuations (0.3 ft), relative to the magnitude of the fluctuations observed in the other SD-6 index wells, is due to the relatively shallow depth to water (117 ft) at the site and is an indication that the aquifer is behaving as an unconfined aquifer. This interpretation was confirmed through an analysis using the BRF software developed earlier in this program (Bohling et al., 2011). Individual pumping and recovery seasons are difficult to discern on the Steiger hydrograph so no conclusions can be reached regarding the duration of the pumping and recovery periods

Water use data for 2016 will be available later in 2017. The reported 2015 use (976.8 ac-ft for a 2-mile radius centered on the index well) was 109 ac-ft and 190 ac-ft less than in 2013 and 2014, respectively, the first two years of the SD-6 LEMA, and 913 ac-ft less than in 2012. Since the establishment of the SD-6 LEMA, the average water use per irrigated acre has been 0.86 ft (10.3 in)/acre in the vicinity of the Steiger well.

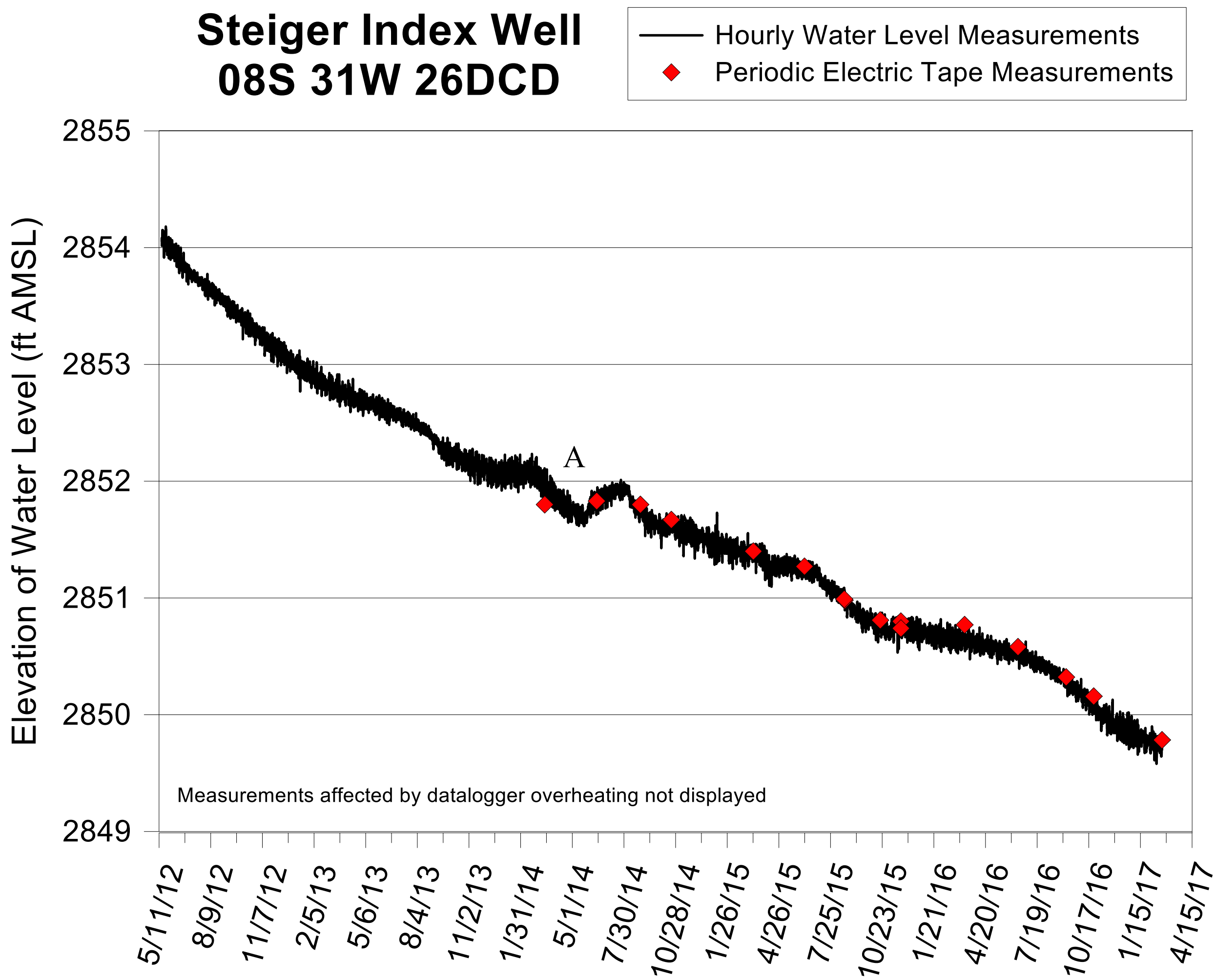

Figure 29—Steiger index well hydrograph—total data run to 2/21/17. A water-level elevation of 2,851 ft corresponds to a depth to water of 116.53 ft below land surface (lsf); the top of the 40-ft screen is 145 ft below lsf (elevation of 2,822.5 ft); and the bottom of the aquifer is 177 ft below lsf (elevation of 2,790.5 ft). A defined in text.

Table 26—Steiger index well local water-use data[a].

		2012	2013	2014	2015	2016	Min	Max
2-mi Radius Water Use	Irrigated Acres	1,237	1,237	1,225	1,238	NA	1,225 (2014)	1,238 (2015)
	Total (ac-ft)	1,889.6	1,086.2	1,166.8	976.8	NA	976.8 (2015)	1,889.6 (2012)
	Irrigation Use Only (ac-ft)	1,869.0	1,065.0	1,146.0	957.0	NA	957.0 (2015)	1,869.0 (2012)
	Use per Irrigated Acre (ft)	1.51	0.86	0.94	0.77	NA	0.77 (2015)	1.51 (2012)

[a]Individual pumping seasons are difficult to discern on the hydrograph so only local water-use data are reported here.

3.3.3. Sherman County Index Well

Figure 30—Aerial view of Sherman County index well site and nearby points of diversion.

Figure 30 is an aerial view of the Sherman County site (T. 10 S., R. 41 W., 01 DAA) at a scale that shows the recently drilled index well and nearby points of diversion. The index well site was chosen because it appeared to have sufficient saturated thickness, relative to the recorded declines in the area, to serve as a monitoring well for years to come. The recorded declines have varied over the nearby area. A little more than two miles to the northeast of the index well is an annual program well (T. 9 S., R. 40 W., 29 BBB) that has been measured since 1964. The water level has fallen approximately 81 ft over the monitoring period. A little more than two miles to the southwest of the index well is an annual program well (T. 10 S., R. 41 W., 15 CAD) that has also been measured since 1964. The water level has fallen 32.5 ft over the monitoring period.

The Sherman index well was drilled and completed December 6–15, 2016, with a mud rotary rig under, at times, bitterly cold conditions. The well was drilled/redrilled three times because of difficulties in keeping the hole open. Eventually, the well was redrilled using a 9.875 in drag bit to 335 ft below land surface (all following measurements are with respect to land surface). An ochre (weathered shale) was encountered at 323 ft (WWC-5 form for well provided in Appendix A—log description based on cutting samples taken every 10 ft). The bottom of the aquifer was assumed to be 323 ft. The screened interval of the well was set from 310 to 320 ft in a sequence of fine sand and medium clay mix; a sump was installed from 320 to 330 ft for accumulation of fines that might move into the well. The gravel pack was placed (tremied and poured into the borehole) from 300 to 330 ft, and grout was placed (tremied) from the top of the gravel pack to the surface. Given the difficult weather conditions, development was completed later.

The static water level in the well was 184.1 ft below land surface on January 31, 2017. Given the bottom of the aquifer is at 323 ft, the saturated interval at the Sherman County site is 138.9 ft thick. A transducer-datalogger unit and telemetry equipment will be installed in the Sherman County index well in early spring 2017, and an interpretation of the hydrograph will be provided in a subsequent report.

3.3.4. Thomas County Index Well

Figure 31—Aerial view of Thomas County index well site, additional annual program wells, and nearby points of diversion.

Figure 31 is an aerial view of the Thomas County site (T. 09 S., R. 33 W., 33 BBB) at a scale that shows the index well, two additional annual program wells, and the nearby wells with active water rights. The Thomas County site expansion wells, which are not shown on the figure, are discussed in Section 3.5.2.

3.3.4.1. *Hydrograph and General Observations*

Figure 32 shows the complete hydrograph for the Thomas County index well, table 27 summarizes its general characteristics, and table 28 compares the manual and transducer measurements from the well. The unconfined nature of the aquifer zone in which the index well is screened is indicated by the form of the hydrograph and by 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.

The 2015–2016 recovery was the third longest observed during the monitoring period at the Thomas well (September 11, 2015, to June 2, 2016), but more than 73 days shorter than the longest observed recovery (2009–2010). The 2016 pumping season began on June 2. Other than two shutdowns of a few to several days in July, sustained pumping essentially continued until the end of the pumping season on September 7, 2016. Other than some pumping at distant wells in late October and early November, there has been little pumping during the 2016–2017 recovery period, which continued at the time of this report (March 6, 2017). Note that as a result of the sensor failure at the Haskell County index well on January 12, 2014, the original sensor at the Thomas County index well, which was the same age, was replaced on March 27, 2014.

Unlike most of the other index wells, the minimum recorded water-level elevation at the Thomas index well has not declined every year. The minimum observed water-level elevation in 2016, which equaled the lowest previously recorded level over the monitoring period, was 0.1 ft below that of 2015 and 6.9 ft below that of 2010 (the highest recorded minimum water-level elevation during the monitoring period). Water-use data for 2016 will be available later in 2017. In 2015, water use within the 2-mi radius surrounding the index well (2,304 ac-ft) was the third lowest during the monitoring period and 540 ac-ft below the average for the period (2,844 ac-ft). The 2015 water use was applied on the second largest number of irrigated acres during the monitoring period, which was just slightly above (75 acres) the average irrigated acres over the monitoring period (3,023 ac); the water use per acre irrigated was the second lowest for the period (table 27). The maximum observed water level in 2016 was 0.1 ft below that of 2015 and 7.2 ft below that of 2010 (the highest maximum observed water level during the monitoring period). Given that the 2016 minimum water level (recorded on September 2) was 0.1 ft below the 2015 minimum recorded water-level elevation, the expectation is that the maximum observed water level at the end of the 2016–2017 recovery will be within a few tenths of a foot of that at the end of the 2015–2016 recovery.

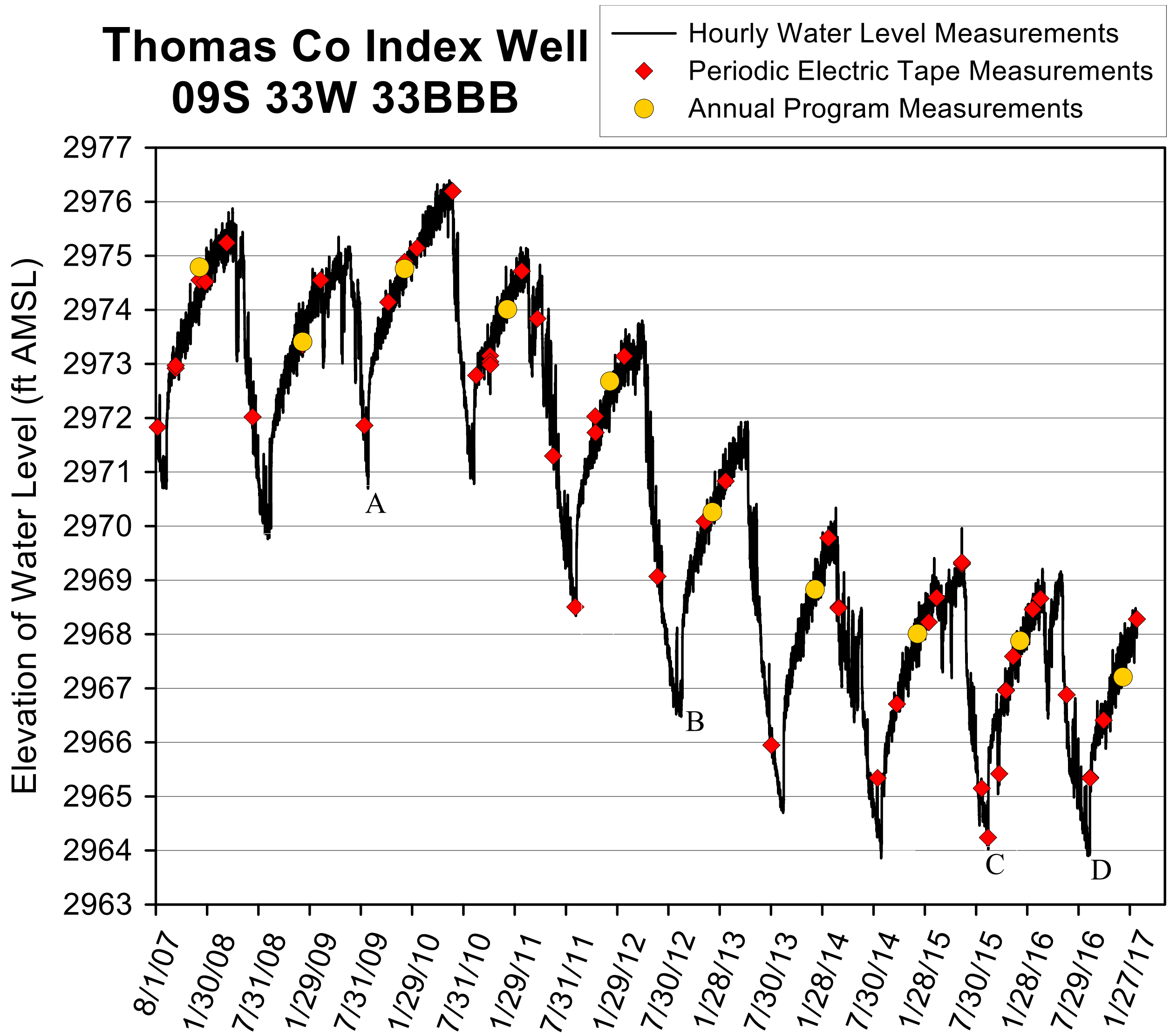

Figure 32—Thomas County index well hydrograph—total data run to 2/21/17. A water-level elevation of 2,968 ft corresponds to a depth to water of 219.56 ft below land surface (lsf); the top of the screen is 274 ft below lsf (elevation of 2,913.56 ft); and the bottom of the aquifer is 284 ft below lsf (elevation of 2,903.56 ft). The screen terminates at the bottom of the aquifer. A–D mark the start of the recovery periods defined in caption of fig. 47 (Section 4.1).

Table 27—General characteristics of the Thomas County index well hydrograph and local water-use data.

		2007	2013	2014	2015	2016	Min	Max
Minimum Water-Level Elevation	Feet	2,970.7	2,964.7	2,963.9	2,964.0	2,963.9	2,963.9	2,970.8
	Date	9/7/07	9/11/13	8/26/14	9/11/15	9/2/15	(2014, 2016)	(2010)
Maximum Recovery Elevation	Feet	NA	2,971.9	2,970.3	2,969.3	2,969.2	2,969.2	2,976.4
	Date	NA	5/7/13	3/17/14	6/9/15	3/22/16	(2016)	(2010)
Apparent Recovery	Feet	NA	5.4	5.6	6.1	5.2	4.4 (2011)	6.1 (2015)
Change in Maximum Recovery	Feet	NA	-1.9	-1.6	-1.0	-0.1	-1.9 (2013)	+1.0 (2010)
Recovery Season	Start	NA	9/17/12	9/13/13	8/28/14	9/11/15		
	End	NA	5/9/13	3/24/14	6/24/15	6/2/16		
	Length (Days)	NA	233.7	191.9	300.0	265	191.4 (2011)	301.4 (2010)
Pumping During Recovery Season	Length (Days)	NA	0[a]	7.6	9.7	24.7	0[a] (2013)	24.7 (2016)
Length of Pumping Season	Days	NA	127.0	156.1	79.5	96.7	63.2 (2009)	173.8 (2011)
2 mi Radius Water Use	Irrigated Acres	2,983	3,054	2,916	3,098	NA	2,916 (2014)	3,109 (2011)
	Total (ac-ft)	2,868.87	3,432.01	3,016	2,303.7	NA	1,917.2 (2009)	3,683.2 (2012)
	Use per Irrigated Acre (ft)	0.96	1.12	1.03	0.74	NA	0.65 (2009)	1.20 (2012)

[a] Could not confidently identify any pumping periods during recovery.

Table 28—Annual water-level measurement[a] comparison with transducer measurements, Thomas County index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/2/2013	2,970.14	-2.42 (-1.87)	Steel tape
	2,970.26[c]	-2.35	Transducer
1/2/2014	2,968.71	-1.43 (-1.64)	Steel tape
	2,968.73[c]	-1.53	Transducer
1/2/2015	2,967.89	-0.82 (-1.01)	Steel tape
	2,968.08[c]	-0.65	Transducer
1/2/2016	2,967.76	-0.13 (-0.12)	Steel tape
	2,967.78[c]	-0.30	Transducer
1/3/2017	2,967.09	-0.67 (NA)	Steel tape
	2,967.17[c]	-0.61	Transducer

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=383132100543101).
[b] Value in ( ) is the change in the maximum recovered water level measured by the index well transducer.
[c] Average of values over time interval 0800–1600.

3.4. GMD5 Index Well

There is currently one index well in GMD5. Characteristics of that well are summarized in Table 29.

Table 29—Characteristics of the GMD5 index well.

Site	2017 WL elev. (ft)[a]	2017 Saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2015 Water Use (ac-ft)		
					1 mi circle	2 mi circle	5 mi circle
Belpre	2,039.93	135–160[b]	175–200[b]	89–109	848	2,366	16,385

[a]2017 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html)
[b]Well not drilled to bedrock; depth to bedrock estimated from nearby well logs.

3.4.1. Belpre Index Well

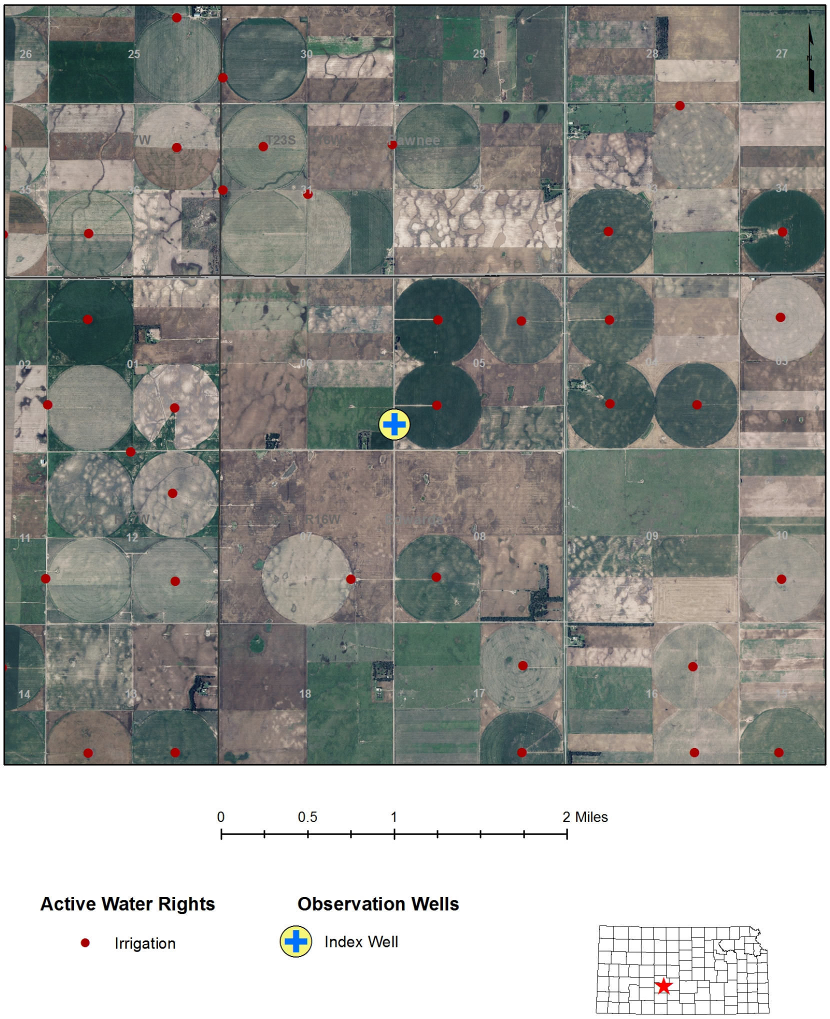

Figure 33—Aerial view of the Belpre index well site and nearby points of diversion.

Figure 33 is an aerial view of the Belpre index well site (T. 24 S., R. 16 W., 05 CCB 01—location designation in WWC-5 [05 CBB] is incorrect) at a scale that shows the site of the index well and the nearby wells with active water rights; there are no annual program wells within 2 mi of the Belpre well. The site includes two wells in the HPA, one screened near the water table and one screened deeper in the aquifer. The deeper well, for which the screened interval is 89–109 ft below land surface, has been equipped with a transducer-datalogger unit (henceforth, Belpre 109 or Belpre index well). Based on well logs to the bottom of the aquifer in the general vicinity, the base of the aquifer at the Belpre index well should be between 175 and 200 ft below land surface.

3.4.1.1. *Hydrograph and General Observations*

Figure 34a shows the hydrograph for the Belpre index well, table 30 summarizes its general characteristics, and table 31 compares the manual and transducer measurements from the well. The very small amplitude fluctuations superimposed on the water levels are an indication of unconfined conditions with a relatively shallow depth to water. The effect of individual nearby pumping wells is not discernible; the water-level response to pumping appears to be more integrated in nature than at most of the index wells.

The 2015–2016 recovery began on September 11, 2015, and ended on June 20, 2016. The recovery plot for 2015–2016 appears to have a more concave-downward curvature than that for 2014–2015 or for the continuing recovery. That increased curvature is likely a product of regional pumping activity during the recovery period. The 2016 pumping season was characterized by sustained pumping until the end of the pumping season on August 29, 2016. The 2016–2017 recovery continued at the time of this report (March 6, 2017). As with the 2014–2015 recovery, there has been little pumping during the recovery period. Water-use data for 2016 will be available later in 2017. In 2015, water use within the 2 mi radius surrounding the index well was 2,366 ac-ft. The 2015 water use was applied on 2,530 acres, resulting in water use per acre irrigated of 0.94 ft (table 30).

A noteworthy feature of the Belpre hydrograph is the numerous upward spikes, such as that marked by the asterisk on fig. 34a. Figure 34b shows an expanded view of the period in the vicinity of that spike. The first spike has a rapid rise of 11 hours (A) that is followed by a gradual decline lasting more than 11 days; this indicates a recharge event that is likely dissipated by lateral flow. The second spike has a similar rapid rise followed by a gradual decline. This pattern is thought to be an indication of focused recharge in the vicinity of the Belpre well. Further work, however, is needed before a more definitive assessment can be made. Both recharge events are associated with large precipitation events on the same day as the rapid water-level rise.

The Belpre index well has been measured manually by GMD5 staff on a quarterly basis since its installation in 1987. Although water levels in the well have risen and fallen over the last 29 years, the general trend has been downward with a total decline of 10.6 ft since January 1988 (decline rate of 0.37 ft/yr).

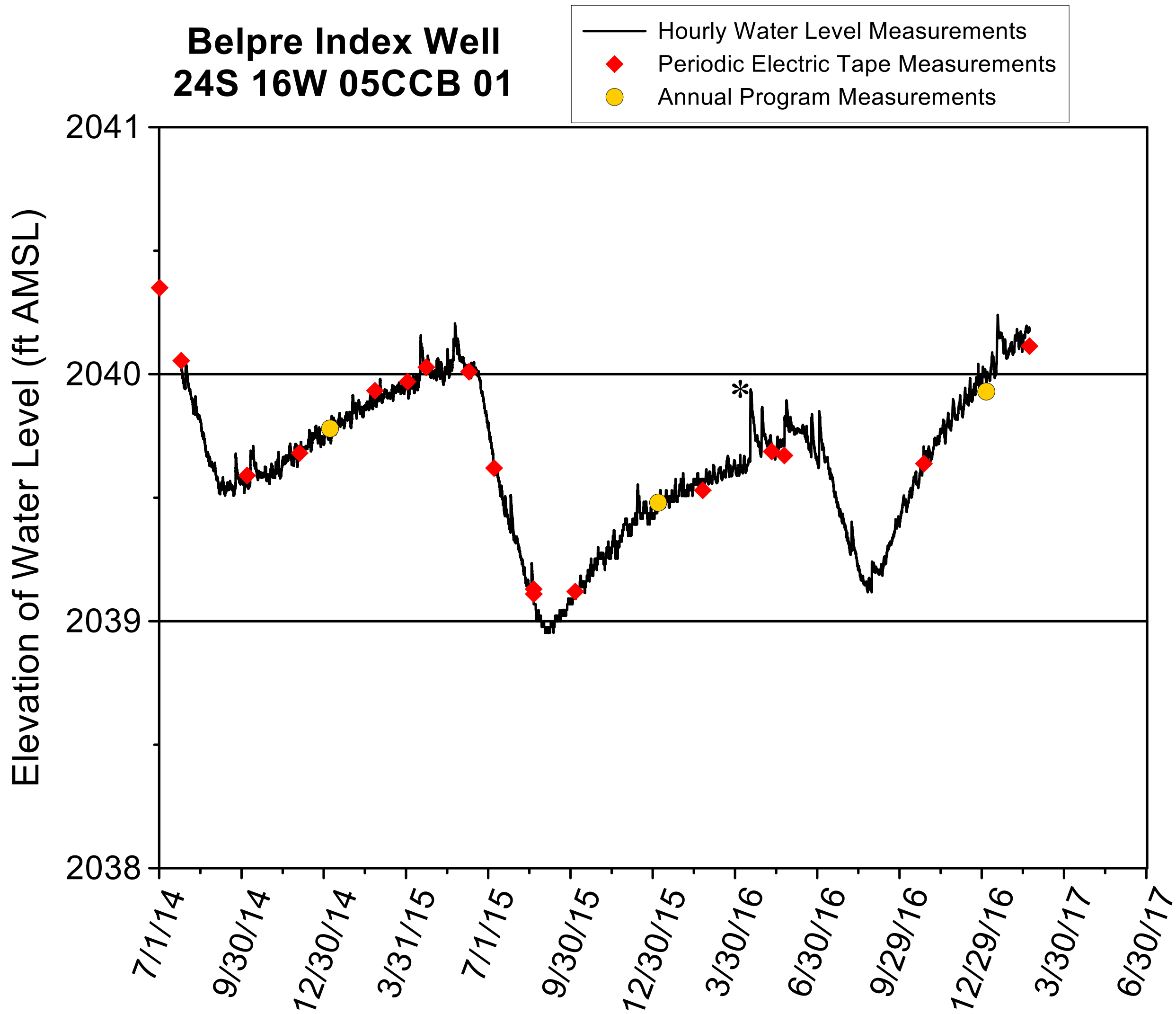

*Figure 34a—Belpre index well hydrograph—total data run to 2/20/17. A water-level elevation of 2,040 ft corresponds to a depth to water of 40 ft below land surface (lsf). The top of the 20-ft screen is 89 ft below lsf (elevation of 1,991 ft), and the bottom of the screen is 109 ft below lsf (elevation 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—see text). Note that the resolution of the datalogger was inadvertently reduced in the summer of 2015, producing the more pixelated plot after that time. The resolution was set to its original setting in 2016. * defined in text.*

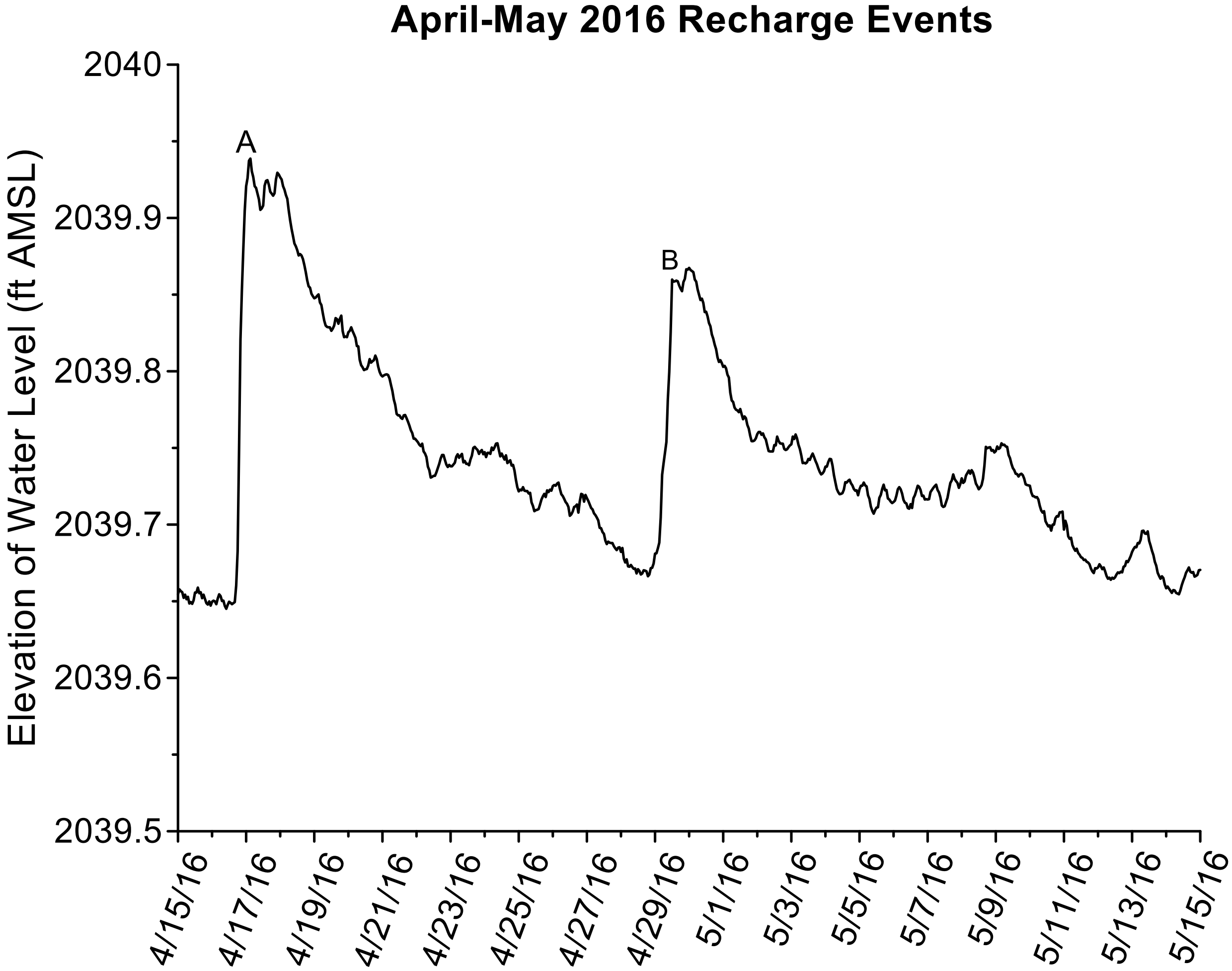

Figure 34b —Expanded view of Belpre index well hydrograph for the last half of April and the first half of May 2016 (interval beginning at the asterisk on fig. 34a). A-B *defined in text.*

Table 30—General characteristics of the Belpre index well hydrograph and local water-use data.

		2014	2015	2016	Min	Max
Minimum Water-Level Elevation	Feet	2,039.5	2,039.0	2,039.1	2,039.0	2,039.5
	Date	9/12/14 9/21/14	9/11/15	8/25/16 8/29/16	(2015)	(2014)
Maximum Recovery Elevation	Feet	NA	2,040.1	2,039.8	2,039.8	2,040.1
	Date	NA	6/1/15	6/6/16	(2016)	(2015)
Apparent Recovery	Feet	NA	0.6	0.8	0.6 (2015)	0.8 (2016)
Change in Maximum Observed Recovery	Feet	NA	NA	-0.3	NA	NA
Recovery Season	Start	NA	9/23/14	9/11/15		
	End	NA	6/20/15	6/20/16		
	Length (Days)	NA	269.7	282.9	269.7 (2015)	282.9 (2016)
Pumping During Recovery Season	Length (Days)	NA	5.6	13.0	5.6 (2015)	13.0 (2016)
Length of Pumping Season	Days	NA	83.0	70.3	70.3 (2016)	83.0 (2015)
2 mi Radius Water Use[a]	Irrigated Acres	2,332	2,530	NA	2,332 (2014)	2,530 (2015)
	Irrigation Use Only (ac-ft)	2,003.9	2,366.3	NA	2,003.9 (2014)	2,366.3 (2015)
	Use per Irrigated Acre (ft)	0.85	0.94	NA	0.85 (2014)	0.94 (2015)

[a]2013 Irrigated Acres—2,442, Irrigation use only—2,445.9 ac-ft, Use per Irrigated Acre—1.00 ft

Table 31—Annual water-level measurement[a] comparison with transducer measurements, Belpre index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/15/2014	2,040.45	NA	Electric tape
	NA	NA	Transducer
1/6/2015	2,039.78	-0.67 (NA)	Electric tape
	2,039.76[c]	NA	Transducer
1/5/2016	2,039.48	-0.30 (-0.29)	Electric tape
	2,039.48[c]	-0.28	Transducer
1/3/2017	2,039.93	0.45 (NA)	Electric tape
	2,039.97[c]	0.51	Transducer

[a] Electric tape measurements are from GMD5 quarterly water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=375926099064001).
[b] Value in ( ) is the change in the maximum recovered water level measured by the index well transducer.
[c] Average of values over time interval 0800–1600.

3.5. Expansion Wells

3.5.1. GMD1 Expansion Wells

Late in 2011, arrangements were made with landowners and GMD1 to install KGS pressure transducers in two old USGS recorder wells in the area of the Scott index well; the sensors were installed on February 22, 2012. One of the new locations (henceforth, well SC-8) is 6.5 mi south of the Scott index well, and the other (henceforth, well WH-1) is 22 miles to the west in Wichita County near Leoti. The water columns were short in both SC-8 and WH-1, 16 ft and 10 ft, respectively, at the onset of monitoring. The water table dropped below the bottom of the screen at WH-1 during 2013 and was still below the bottom of the screen on February 19, 2014. As a result, the transducer was removed from that well on February 19, 2014.

In March 2016, the GMD1 board decided to place transducer-datalogger units in additional wells across the district. At their request, we worked with Kyle Spencer (GMD1 manager) and the board to select the appropriate equipment to purchase; we also provided advice on installation and monitoring. The following six sites were chosen for monitoring (fig. 35): site 1—Scott County—T. 16 S, R. 33 W, 19 BBC 01 (part of the annual water-level measurement network); site 2—Wichita County—T. 18 S, R. 35 W, 14 DCD 01 (part of the annual water-level measurement network); site 3—Wallace County—T. 15 S, R. 39 W, 08 ACC 01 (part of the annual water-level measurement network); site 4—Greeley County—T. 16 S, R. 42 W, 12 BAA (not part of the annual network); site 5—Scott County—T. 18 S, R. 32 W, 17 DAD (not part of the annual network); site 6—Wichita County—T. 20 S, R. 38 W, 02 ACD 01 (part of the annual water-level measurement network). Transducer-datalogger units are now in all of the wells except site 6. GMD1 and KGS staff will periodically download these sensors, and we will assess the hydrographs in future reports. These wells will not necessarily be permanently monitored; the GMD1 board may move some or all of the units to other wells if the need arises. A barometer has been placed a short distance below land surface in the well at site 3.

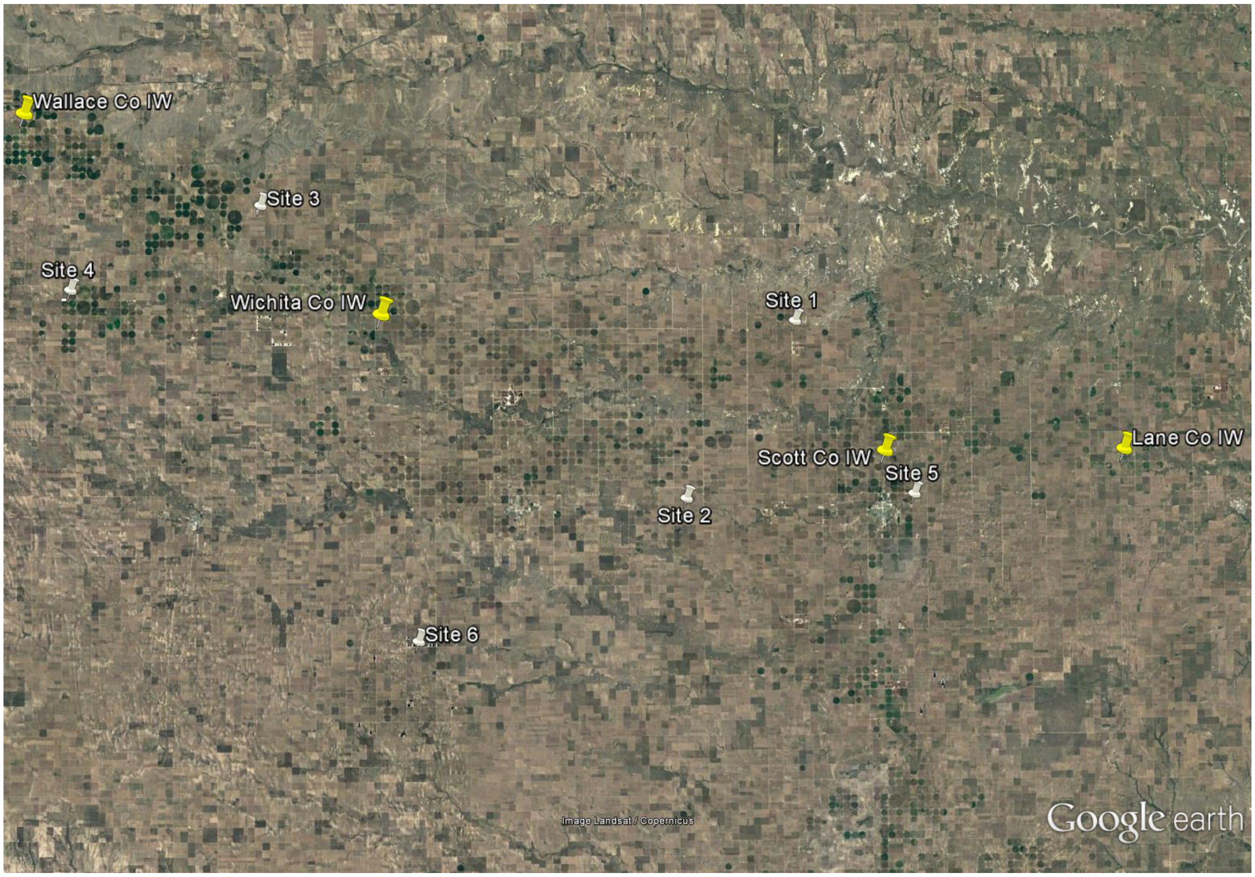

Figure 35—Aerial view of the GMD1 index well sites (yellow pins) and the new GMD1 expansion well sites (white pins).

3.5.1.1. *SC-8 Expansion Well*

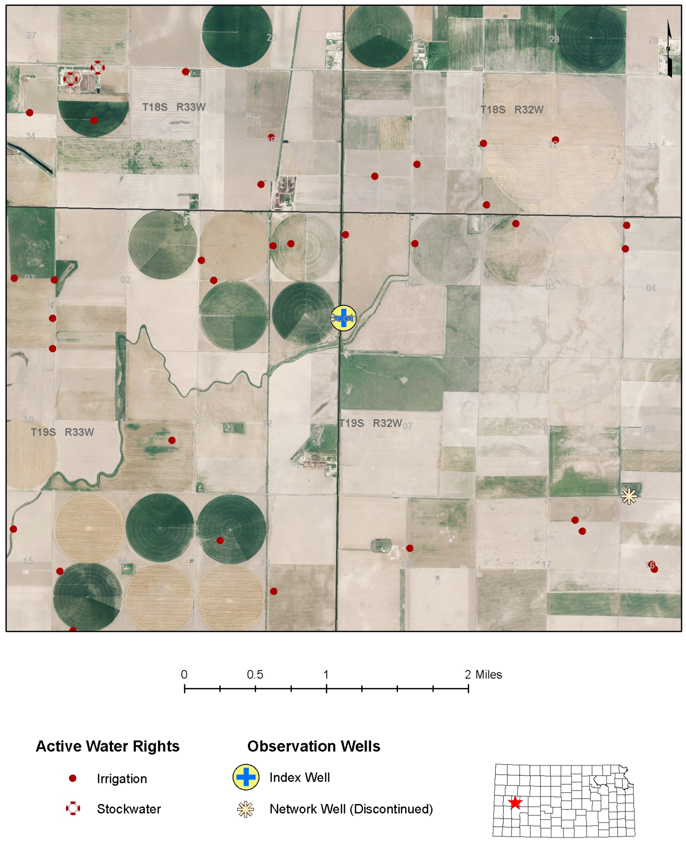

Figure 36—Aerial view of SC-8 expansion well site and nearby points of diversion.

Figure 36 is an aerial view of the SC-8 site (T. 19 S., R. 32 W., 6 CCB) at a scale that shows the index well site, a recently discontinued annual program well, and nearby wells with active water rights. The index well is located north of an old drainage channel (the landowner said that the old USGS recorder used to show a hydraulic connection—i.e., a water-level rise—when water flowed in the channel). In the autumn of 2012, a new irrigation well was installed in the field in which the well is located.

3.5.1.1.1. *Hydrograph and General Observations*

Figure 37 displays the complete hydrograph for the SC-8 well. The approximately five years of monitoring data show a record that is similar to the hydrographs of wells in the upper unconfined interval in the vicinity of the Haskell site (see, for example, wells HS-10, HS-13, and HS-14 in Appendix A of Buddemeier et al. [2010]). These hydrographs are thought to indicate a compartmentalized aquifer interval in which the monitoring well is at some distance from the closest pumping well in that aquifer compartment. If the SC-8 well had been closer to a nearby pumping well, water levels would have risen more after cessation of seasonal pumping before flattening out (see Butler, Stotler, et al. [2013] fig. 5 and related discussion). There is not a clear indication of commencement of pumping at a nearby well; water level responses are much more gradual, which may also indicate a relatively poor hydraulic connection with nearby pumping wells. The relatively large (up to 1.0 ft) amplitude fluctuations superimposed on the compartmentalized aquifer hydrograph are similar to those observed at the Thomas County index well and are an indication that the interval in which the well is screened is behaving as an unconfined aquifer. This interpretation was confirmed through an analysis using the BRF software developed earlier in this program (Bohling et al., 2011). In earlier reports, the hydrograph displayed a systematic deviation between the transducer and manual measurements. That deviation appears to have been introduced by an incorrect offset parameter for the transducer. Correcting the offset parameter produces a much better agreement between the transducer and manual measurements.

A noteworthy feature of the data collected in 2015 and 2016 is the large number of upward spikes in the water level, such as the one marked by A on figure 37. Smaller spikes can also be observed in 2013 and 2014 after removal of the fluctuations produced by variations in barometric pressure. These spikes, which typically are less than a day in duration, are associated with rainfall events and are likely produced by storm runoff flowing into and down the well casing. The added water is then dissipated quickly through lateral flow to the aquifer. We suspected that there was an opening in the well casing at the surface that allows the flow to enter the well. During our site visits in 2016, we identified points of entry in the concrete base to the well. Given the great potential for contamination by surface runoff, we recommend that monitoring cease and the well be plugged.

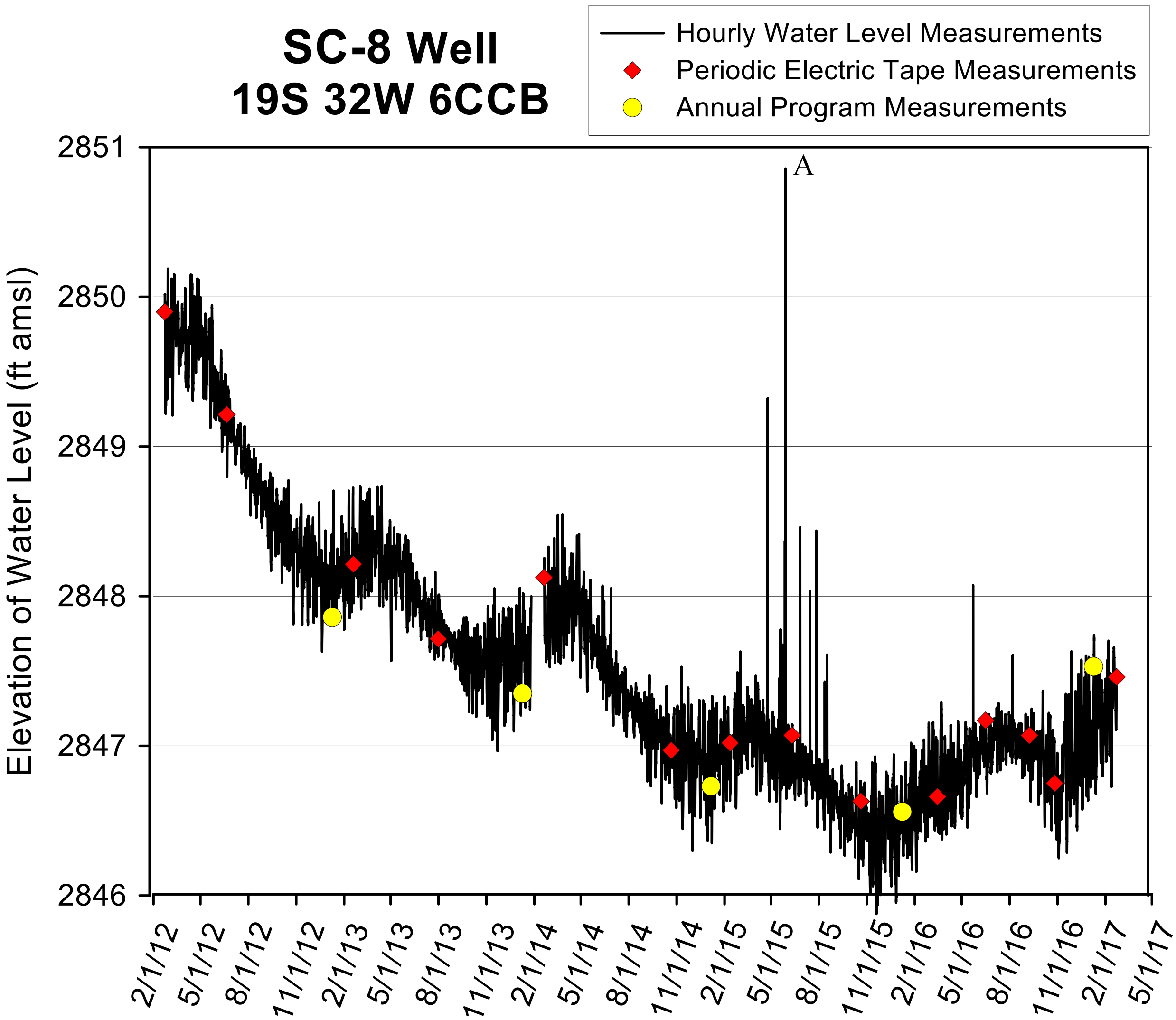

Figure 37—SC-8 well hydrograph—total data run until 2/22/17. A water-level elevation of 2,847 ft corresponds to a depth to water of 89 ft below land surface (lsf). The bottom of the well is approximately 102 ft below lsf (elevation of 2,835 ft). Note that transducer measurements have been corrected from earlier reports because of an incorrect offset parameter. A *defined in text.*

3.5.2. Thomas County Expansion Wells

Initially, five wells (TH3, TH7, TH8, TH9, and TH10) in the vicinity of the Thomas index well, including retired and active irrigation wells and a domestic well, were equipped with pressure transducers provided by DWR to monitor the 2009–2010 recovery; an additional well (TH11) was added to the network in the fall of 2010 (wells labeled "Monitored Transducer" on fig. 38). Two wells are no longer monitored as a result of plugging (TH3) and sensor failure (TH8), and one well is monitored only during the recovery season (TH7). Table 32 provides a summary of sensor installation dates and other significant events for the currently operating wells. Only three of the wells are operating in a near-continuous fashion. Figure 39 shows hydrographs from the Thomas index well and these three continuously operating expansion wells. Data from the closest expansion wells (TH9 and TH11) are briefly examined here. In future reports, the interpretation of the hydrographs from these wells will be presented every two years.

Table 32—Installation date and other notes for currently operating Thomas County expansion wells.

Well	Well Type	Sensor	Installation Date	Notes
TH7	Irrigation	DWR	9/30/09–4/18/10 11/23/10–4/6/11 11/4/11–2/23/12 9/27/13–4/9/14 10/21/14–5/1/15 10/20/15–4/8/16 11/23/16–Current	Active irrigation well, sensor installed and removed each year by KGS and GMD4 at landowner's request. Sensor not installed for the 2012–2013 recovery. Sensor still in well at time of this report (3/23/17).
TH9	Retired Irrigation	DWR	11/5/09–Current	Sensor removed 11/11 to 11/14/09 for well cap installation; operator error data gap from 11/23/10 to 2/23/11, 12/5/12 to 2/18/13, 6/11/15 to 8/19/15, and 8/26/15 to 9/10/15. Otherwise operating normally.
TH10	Former Domestic	DWR	8/12/09–9/12/13 8/28/14–Current	Unexplained break in data 6/22/10 to 9/15/10. Data cable eaten by vermin on 9/12/13; repaired and encased in conduit on 8/28/14.
TH11	Retired Irrigation	KGS	11/3/10–11/11/11 6/20/12–1/26/14 2/19/14–5/15/15 8/19/15–Current	Sensor fitting failed sometime after 11/11/11 download, water in housing. Sensor pulled for repairs and replaced on 6/20/12. Operator error data gap from 1/26/14 to 2/19/14. Sensor moved out of water, most likely by an animal, between 5/15/15 and 8/19/15.

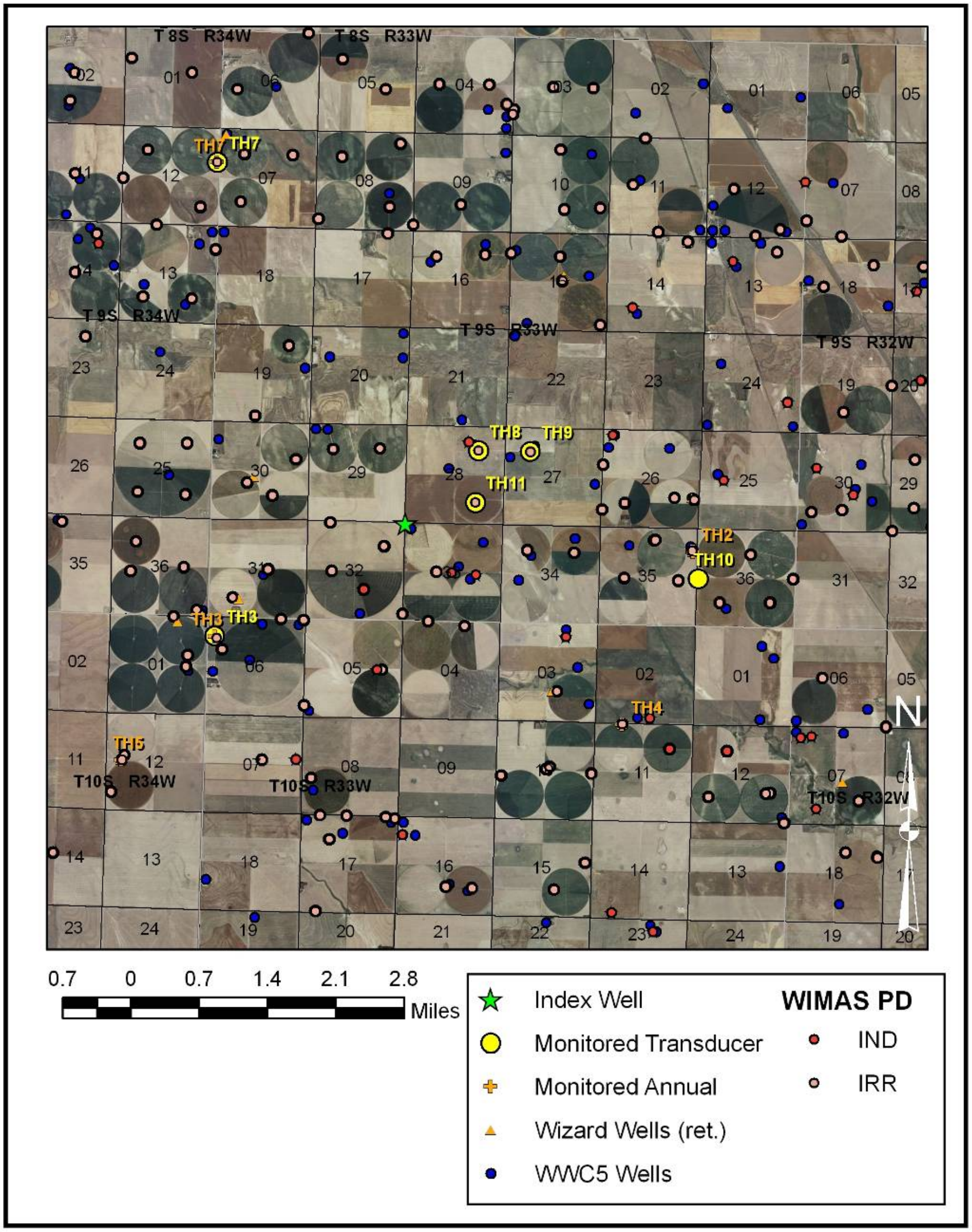

Figure 38—Aerial view of portion of Thomas County in the vicinity of the index well, showing the index well, nearby wells that have or had been equipped with transducers, surrounding annual program wells, and points of diversion in the area.

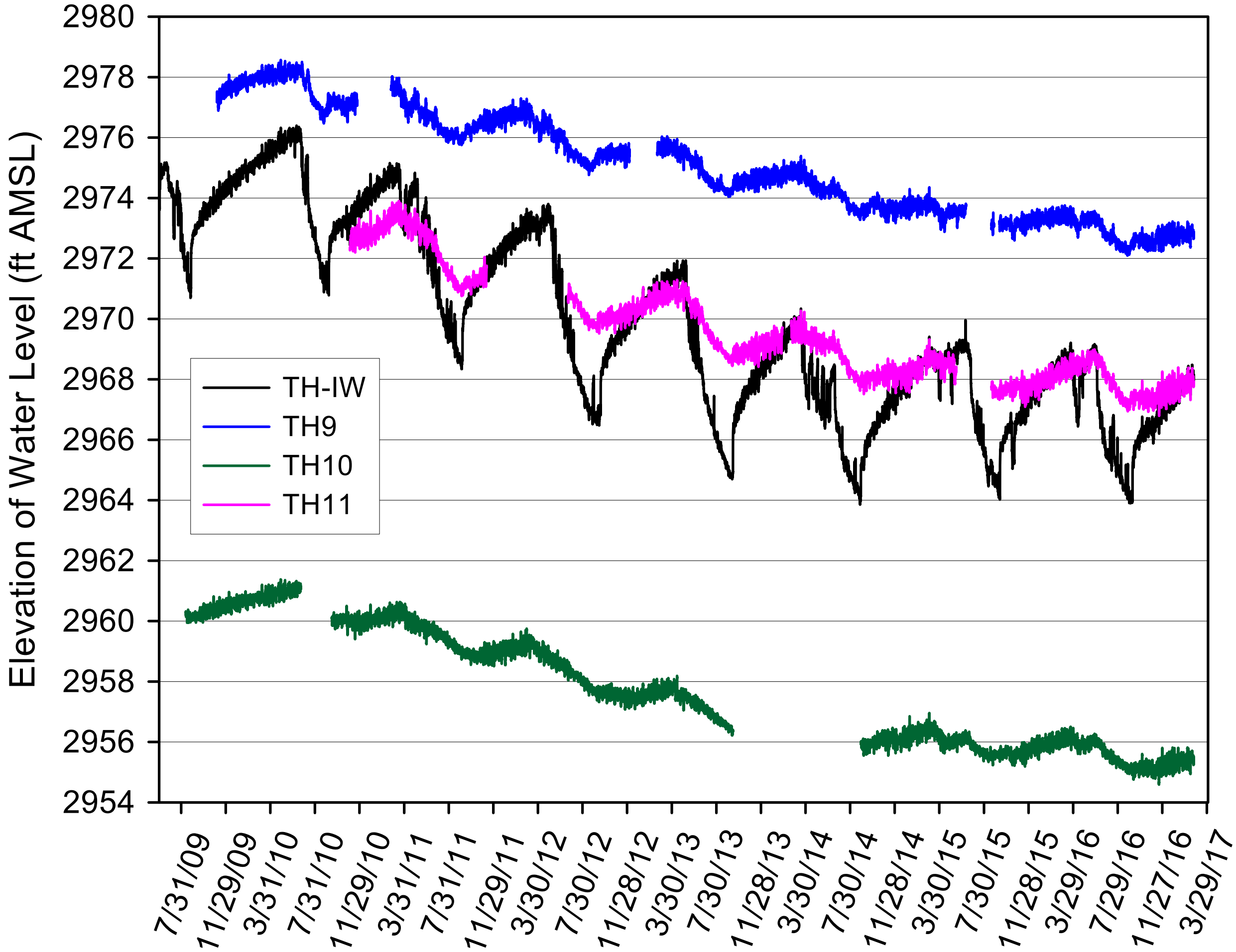

Figure 39—Hydrograph comparison from the Thomas index well (TH-IW) and currently continuously operating Thomas expansion wells—total data run to 2/21/17. The general water-level trend indicates west-to-east groundwater flow. The elevation of the water level in TH10 has been increased 6.75 ft over the elevation used in earlier reports as a result of a reassessment of the monitoring data and periodic manual measurements.

The hydrograph at well TH9 appears to be responding to many of the same pumping events as the Thomas index well (fig. 40a). The responses are more subdued and smoothed (indicating a greater distance to the pumping wells—the section in which TH9 is located and those to the immediate north and west are not irrigated [see fig. 38]) in the TH9 hydrograph but are still clearly apparent. However, there are a few instances where the responses are greater at the TH9 hydrograph (e.g., A and B on fig. 40a), a likely indication of pumping at a well closer to TH9. The rate of recovery of well TH9 is much slower than the Thomas index well. The slow rate of recovery coupled with the relatively large water-level response to changes in barometric pressure (similar to the magnitude of the response in the Thomas index well) make it difficult to assess whether the well has recovered before the start of the next irrigation season.

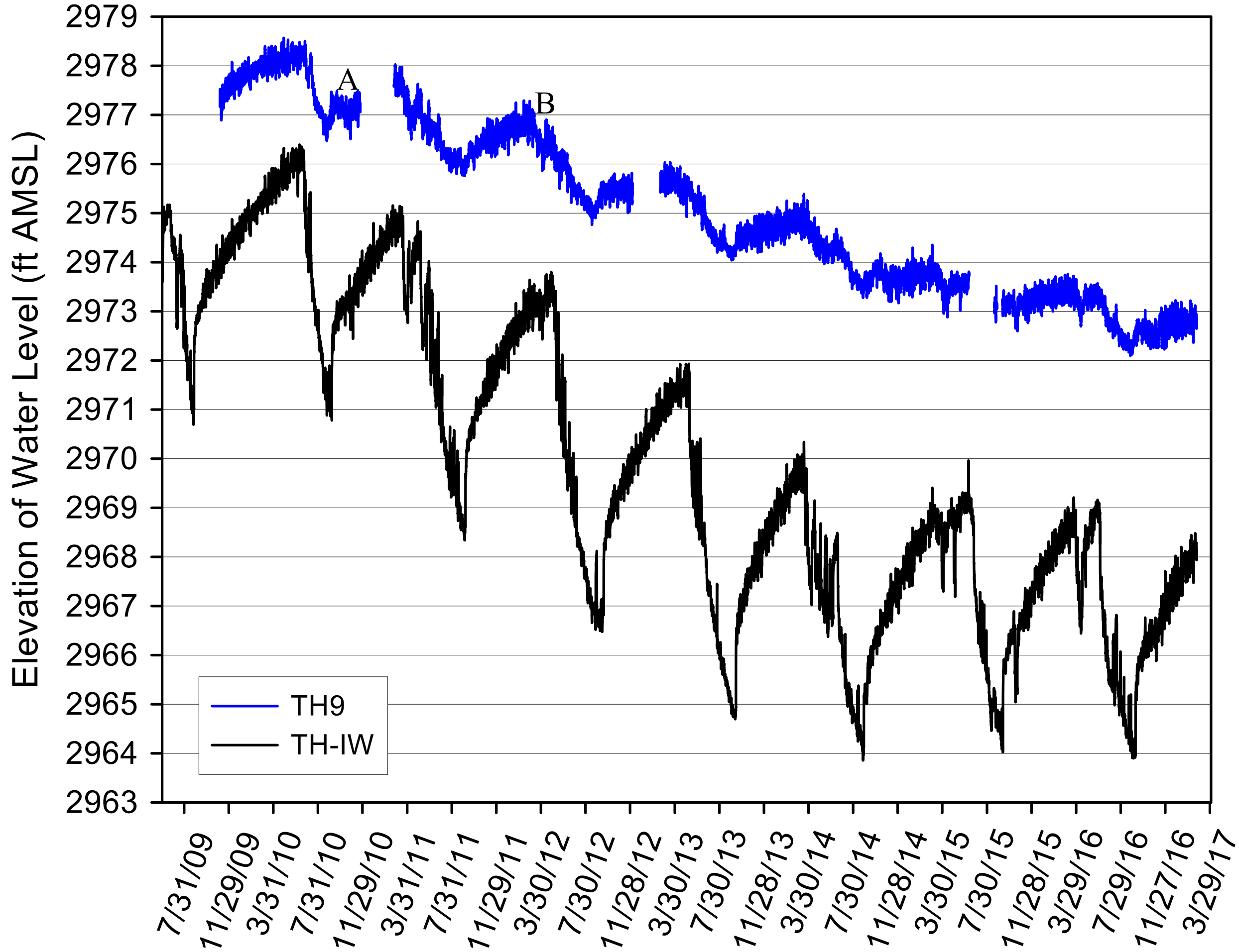

Figure 40a—Hydrograph comparison of Thomas index well (TH-IW) and expansion well TH9—total data run to 2/21/17. TH9 is located approximately 1.5 miles northeast of the index well (0.75 miles north, 1.25 miles east). A and B defined in text.

The hydrograph at well TH11 also appears to be responding to many of the same pumping events as the Thomas index well (fig. 40b), but the responses are again more subdued and smoothed. Although similar, the pumping-induced response at TH11 is slightly greater than at TH9, as would be expected given it is closer to active pumping wells, which are concentrated to the south and west of the Thomas index well (fig. 38).

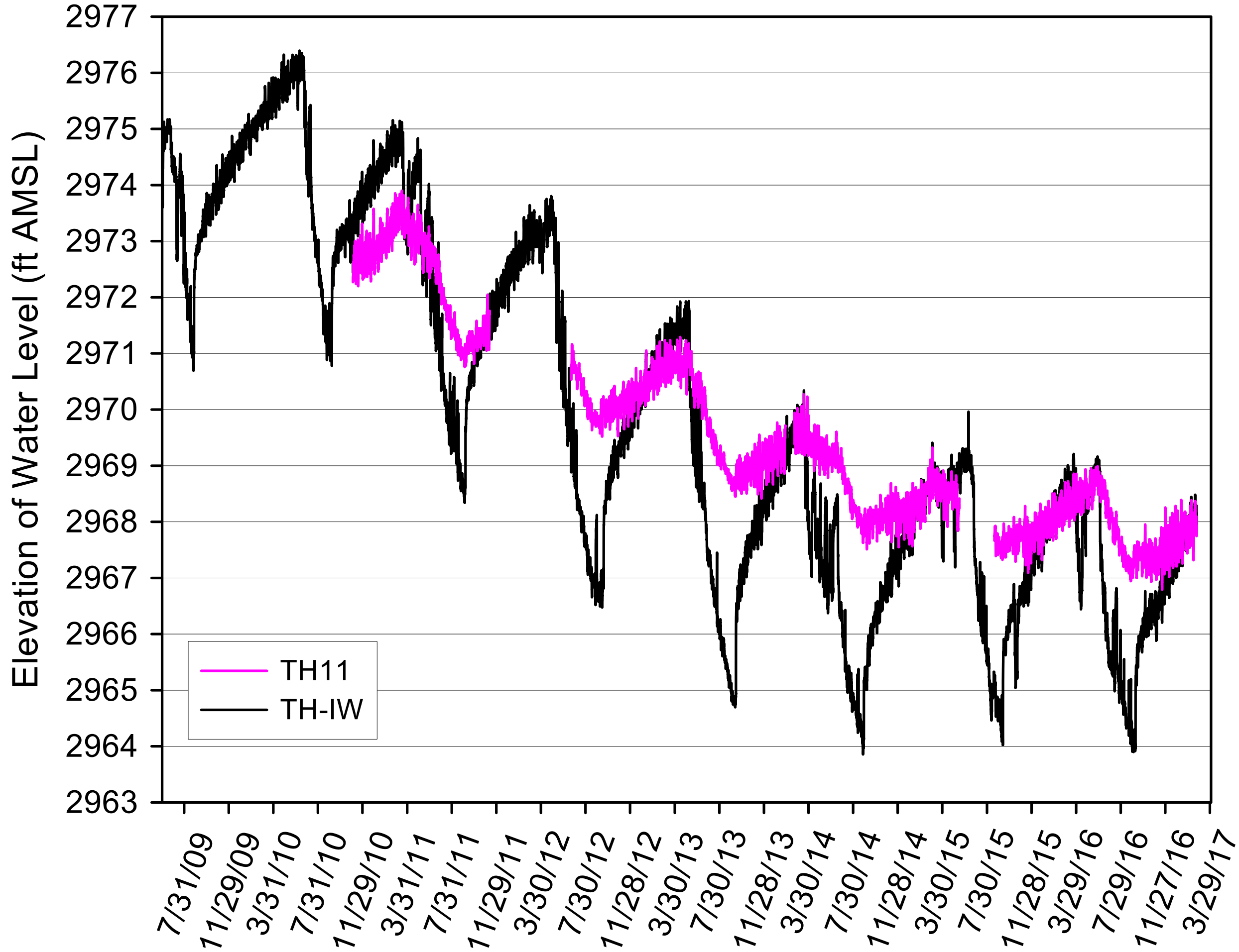

Figure 40b—Hydrograph comparison of Thomas index well (TH-IW) and expansion well TH11—total data run to 2/21/17. TH11 is about 0.70 miles east-northeast of the index well (0.25 miles north, 0.75 miles east).

3.5.3. Haskell County Expansion Wells

In late 2016 and early 2017, DWR personnel sent us the water-level data that had been acquired from the Haskell County expansion wells since our last report on those wells (Buddemeier et al., 2010). In that report, we examined the hydrographs from 23 wells in the vicinity of the Haskell index well (Appendix A.4 in Buddemeier et al. [2010]). The water level in a number of those wells has now dropped past the transducer and, presumably, the bottom of the screen, so monitoring has ceased. A number of other wells have very noisy data records, which make interpretation difficult. The key finding of our second analysis of the Haskell expansion wells is that the aquifer materials in the vicinity of the Haskell index well appear to be discontinuous over relatively small distances. We will illustrate that point using records from two wells (fig. 41): HS-4 (T. 27 S, R. 31 W, 25 CCD) and HS-29 (T. 27 S, R. 31 W, 35 ACB).

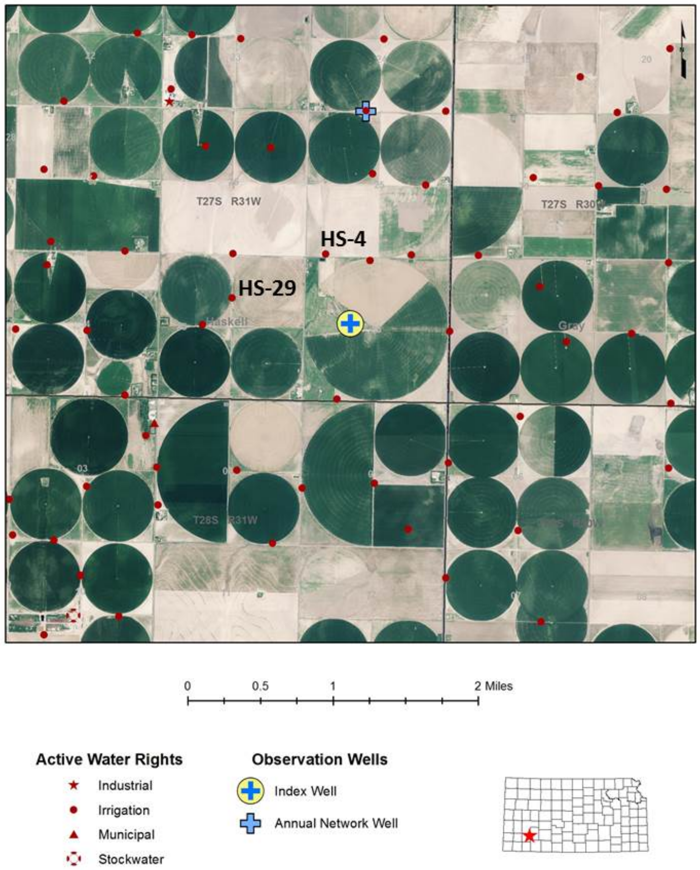

Figure 41—Haskell County index well site, an additional annual network well, the nearby points of diversion, and two of the observation wells monitored by DWR (HS-4 and HS-29).

Well HS-4 is located approximately 2,700 ft north-northwest of the Haskell index well and is screened at 380–420 ft below land surface (elevation 2,447.6 to 2,407.6 ft) (Buddemeier et al., 2010) in comparison with the screened interval depth of the Haskell index well of 420–430 ft (elevation 2,417.8 to 2,407.8 ft). Figure 42 shows the hydrograph for the well from the summer of 2009 to November 16, 2016. Comparison with the hydrograph from the Haskell County index well (fig. 13) shows that there is a good hydraulic connection between the two wells. The same pumping events are observed on both hydrographs and the increase in the annual minimum water-level elevation after the court-ordered cessation of nearby pumping beginning in 2013 is similar. The conclusion is that both wells are screened in a continuous permeable interval.

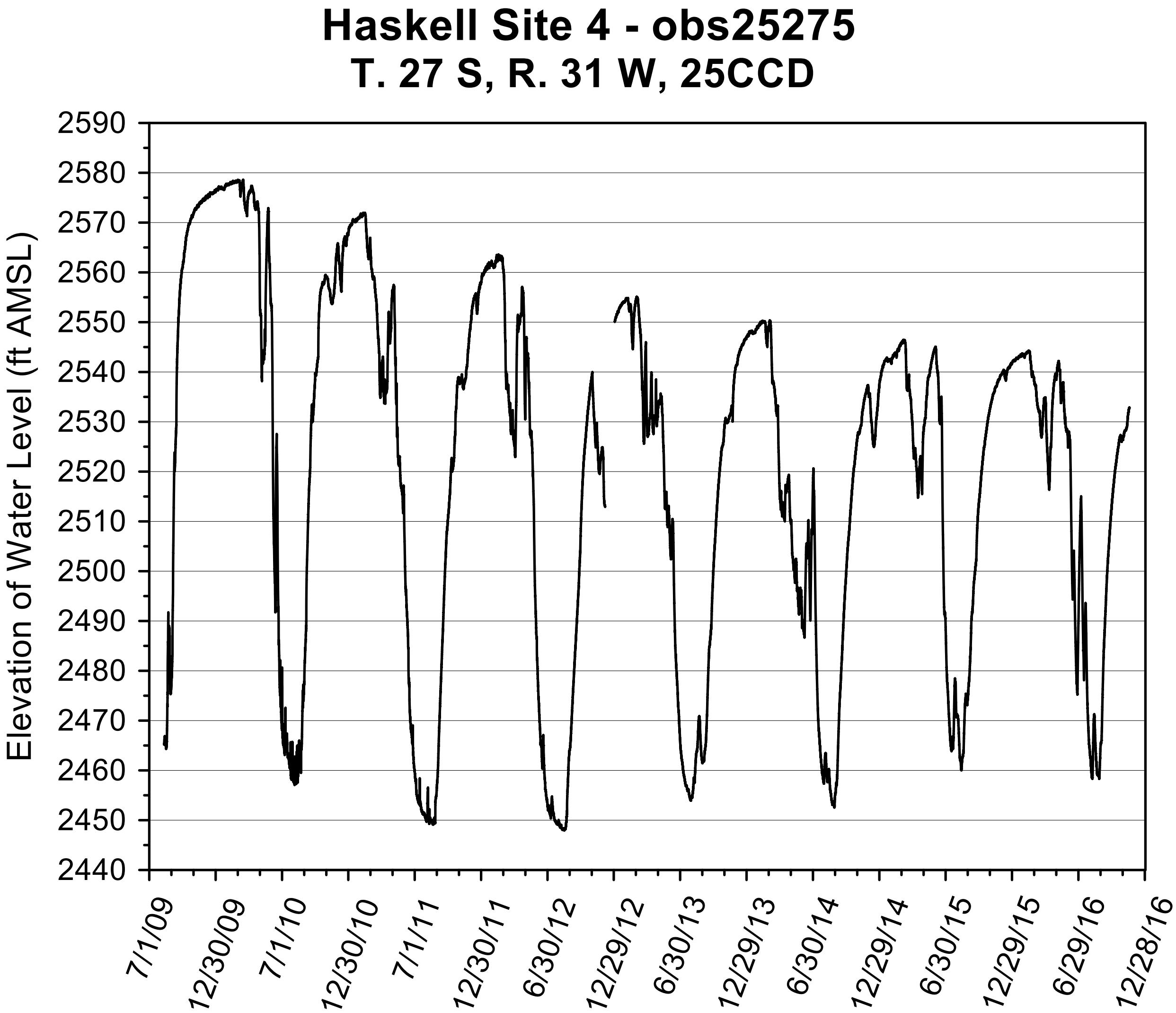

Figure 42—HS-4 well hydrograph—total data run to 11/16/16. A water-level elevation of 2,500 ft corresponds to a depth to water of 327.6 ft below land surface (lsf). The top of the 40 ft screen is 380 ft below lsf (elevation of 2,447.6 ft), and the bottom of the screen is 420 ft below lsf (elevation of 2,407.6 ft).

Well HS-29 is located approximately 4,400 ft west-northwest of the Haskell index well and is screened at 342-382 ft below land surface (elevation 2,498 to 2,458 ft) (Buddemeier et al., 2010). Figure 43 shows its hydrograph for the last two years (December 31, 2014, to November 10, 2016). Comparison with the hydrograph from the Haskell County index well (fig. 13) and that from HS-4 (fig. 42) shows that there appears to be virtually no connection between HS-29 and the two wells to its east. The drawdown at HS-29 appears to be produced by pumping at that well alone. For example, pumping began in the vicinity of the Haskell index well on March 10, 2015, but there was no response at well HS-29, where pumping began on April 15, 2015; a similar situation was observed in the spring of 2016. In addition, the water level in HS-29 appears to have recovered by late December, while it continues to recover until the start of the next irrigation season at the index well and HS-4. This relatively rapid recovery, the lack of response to nearby pumping, and the step changes in water level across the pumping periods are diagnostic indicators of an aquifer unit that is surrounded by low permeability materials. Thus, this well appears to be screened in an isolated aquifer compartment. Similar behavior has been observed at other expansion wells near the Haskell index well (e.g., fig. 2 in Butler, Stotler, et al., 2013). The elevation of the screened interval is higher at well HS-29 than at the Haskell index well and well HS-4 (elevation of the bottom of the screen at HS-29 is 10 ft higher than the elevation of the top of the screen at HS-4). The bedrock surface may be higher in the vicinity of well HS-29 than at the other wells and may be an important factor in promoting the compartmentalization.

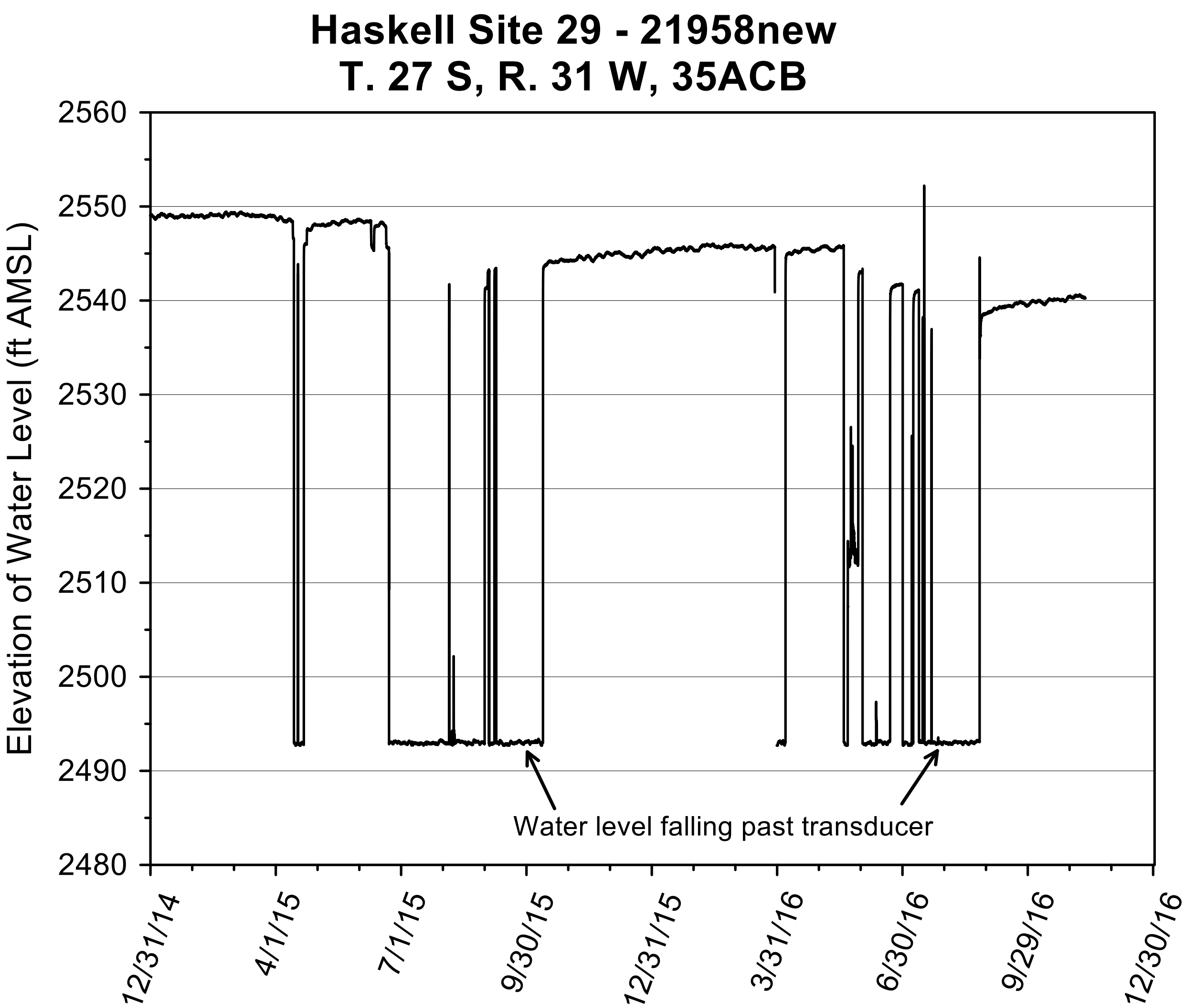

Figure 43—HS-29 well hydrograph—total data run to 11/10/16. A water-level elevation of 2,500 ft corresponds to a depth to water of 340 ft below land surface (lsf). The top of the 40 ft screen is 342 ft below lsf (elevation of 2,498 ft), and the bottom of the screen is 382 ft below lsf (elevation of 2,458 ft). During pumping periods, the water level falls past the transducer positioned at 2,492.6 ft (347.4 ft below lsf).

In summary, the major finding of this assessment of the Haskell County expansion wells is 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.

4. Interpretation of Water-Level Responses

4.1. Interpretation of Hydrographs from the Original Index Wells

An understanding of the primary mechanisms that control the changes in water level at the index wells is critical for reliable assessment of what the future holds for the portion of the HPA in the vicinity of each index well. A significant component of the activities for the last six years of this project has been directed at this issue. The major conclusions from those activities are described in previous annual reports (Butler et al., 2012, 2014, 2015; Butler, Whittemore, Reboulet, et al., 2016; Butler, Whittemore, et al., 2013) and a 2013 paper in the journal *Groundwater* (Butler, Stotler, et al., 2013). In this section, we briefly update the insights that have been gained from interpretation of the hydrographs from the original index wells.

4.1.1. Haskell County

The major conclusions concerning the future prospects of the HPA in the vicinity of the Haskell site were summarized in the publications cited in the previous paragraph and were largely based on conditions prior to the court-ordered shutdowns in pumping described in Section 3.2.2.1. The data from the 2016 pumping season indicate that conditions have improved over those described previously (e.g., Butler, Stotler, et al., 2013). The water column in the index well, which is screened near the bottom of the aquifer (screen terminates 3 ft above the aquifer bottom) and is more than 2,450 ft from the closest pumping well, was approximately 43 ft in height at the maximum observed drawdown for 2016 (water column height was likely considerably less in the immediate vicinity of the irrigation wells). This height was 5.5 ft greater than at the maximum observed drawdown in 2014, and 7.5 ft greater than that in 2012; these increases are undoubtedly a result of the court-ordered shutdowns described in Section 3.2.2.1. Continued monitoring at this site will allow us to get a more complete picture of the impact of the shutdowns. It is currently unknown whether any leakage from the underlying Dakota aquifer will mitigate the rate of water-level decline in the vicinity of the Haskell index well or whether the water levels in the Dakota aquifer are also declining at a similar or greater rate, meaning that upward leakage could either be minimal or downward leakage could occur. Some wells are completed in both the HPA and Dakota aquifer and could be producing more water from the Dakota as the HPA becomes depleted in the area of the Haskell index well. However, as discussed in Butler et al. (2015), the nature of the relationship between the Dakota aquifer and the HPA remains unclear.

4.1.2. Scott County

The 2016 water-level data helped us to continue to refine the assessment of conditions in the vicinity of the Scott index well. Figure 44a, which is an update of the plot presented in the previous annual report, is a plot of drawdown versus the logarithm of duration of pumping for pumping periods beginning at A (2009), B (2010), C (2011), D (2012), E (2013), F (2014), G (2015), and H (2016) on fig. 5. Although these data are relatively “noisy” as a result of pumps cutting on and off and the suspected clogged vent tube in 2015 (Butler, Whittemore, Reboulet, et al., 2016), a consistent picture still emerges for all eight pumping seasons. After nearly a day of pumping, water levels begin to level off. This leveling off is commonly seen in pumping tests in unconfined aquifers and is interpreted as delayed drainage from a falling water table (e.g., Kruseman and de Ridder, 1990). We originally tentatively interpreted the remaining portions of the plot as being affected by radial flow and aquifer boundaries. However, the data collected during the 2011 to 2016 pumping seasons have enabled us to reinterpret those portions of the plot. Figure 44b is a plot of drawdown versus the logarithm of duration of pumping for pumping periods beginning at C (2011), E (2013), F (2014), G (2015), and H (2016) on fig. 5 (2012 pumping period data are for a shorter interval so are not plotted). The coincidence of the 2011, 2013, and 2014 pumping period data indicates that the water-level changes are produced by pumping at the same well at essentially the same rate; the 2015 pumping period data, albeit much noisier, are relatively consistent with the data from these earlier periods. The 2016 pumping period data agree closely with those of the previous years until point A on figure 44b. At that point, the 2016 data steepen, which could be an indication of diminishing transmissivity. In addition, the coincidence (except for the later portions of the 2016 pumping season) and the relatively low noise level of the data (years other than 2015) reveal a continuous transition from the delayed-drainage period to the large-time response that was originally identified as a boundary deviation. The continuous transition, the semilog linear response at large times, and the distance to the nearest pumping well (more than 1,000 ft) all suggest that the late-time response is likely an indication of large-scale radial flow to the pumping well. Continuous monitoring will clarify the mechanisms producing the increased drawdown in the later stages of the 2016 pumping season.

The 2009 and 2010 pumping period data in fig. 44a are parallel to but earlier in time than the 2011–2014 data (noise in the 2015 data and the increased drawdown in the 2016 data make it difficult to assess conditions in those years). One explanation is that different pumping wells were operating during those years. However, given the reported pumping data in the area, a more likely explanation is that the specific yield (drainable porosity) changes (in this case, increases) as the water table falls. In either case, pumping-test theory holds that a shift in the time axis (analogous to the t/r^2 form of the Theis method—Kruseman and de Ridder [1990]) should result in the coincidence of drawdown plots from the different years. Figure 45 shows the result after 2009 pumping times have been multiplied by 1.56 (* on fig. 45—if the first explanation is valid, the distance to the pumping well in 2009 is 0.8 that of the 2011–2014 pumping periods; if the second explanation is valid, the specific yield has increased by a factor of 1.56 between 2009 and 2011) and 2010 pumping times have been multiplied by 1.25 (** on fig. 45—if first explanation is valid, distance to 2010 pumping well is about 0.9 that of the 2011–2014 pumping periods; if second explanation is valid, specific yield increased by a factor of 1.25 from 2010 to 2011). After the time adjustments, the coincidence of the 2009–2014 pumping period data indicates that the aquifer responded as a homogeneous unit in the vicinity of the Scott index well for that period and that decreases in saturated thickness during that period had a very minor, if any, effect on the tranmissivity of the HPA in the vicinity of the Scott index well. However, the need for the time adjustment indicates that the specific yield likely increased as the water table fell. Thus, the Scott well can serve as a “sentinel” well for recognizing when decreases in saturated thickness are affecting aquifer properties. Assessment of water-level changes at the Scott index well will continue in 2017; a particular focus will be assessing whether the increased drawdown in the later stages of the 2016 pumping season could be related to decreases in transmissivity.

The 2015 annual report (Butler, Whittemore, Reboulet, et al., 2016) presented an assessment of recovery data from six complete recovery seasons (2009–2010, 2011–2012, 2012–2013, 2013–2014, 2014–2015, and 2015–2016). Figure 46 presents an update of the recovery assessment with the near-completed 2016–2017 recovery season. The 2014–2015 recovery data have been corrected for the suspected clogged vent tube as described in Butler et al. (2015) and the 2015–2016 data have been corrected for the apparent sensor and cable problem as described in Butler, Whittemore, Reboulet, et al. (2016). The 2016–2017 recovery data appear slightly above the recovery data from previous years. The 2016–2017 recovery period was interrupted by a month-long pumping period in mid-October to mid-November so the plot begins at the end of that period, which may be responsible for the upward displacement relative to the recovery data from previous years. The water use in 2009 and 2012 differed by about 22% (largest use difference for the years shown in fig. 46); the durations of the 2009 and 2012 pumping periods differed by about 20%. Water-use data for 2016 are not yet available. The interpretation of the similarity of the recovery plots for six complete and one continuing recovery seasons, which hints at the possibility of inflow similar to that at the Thomas index well, will continue to be the focus of further work in 2017.

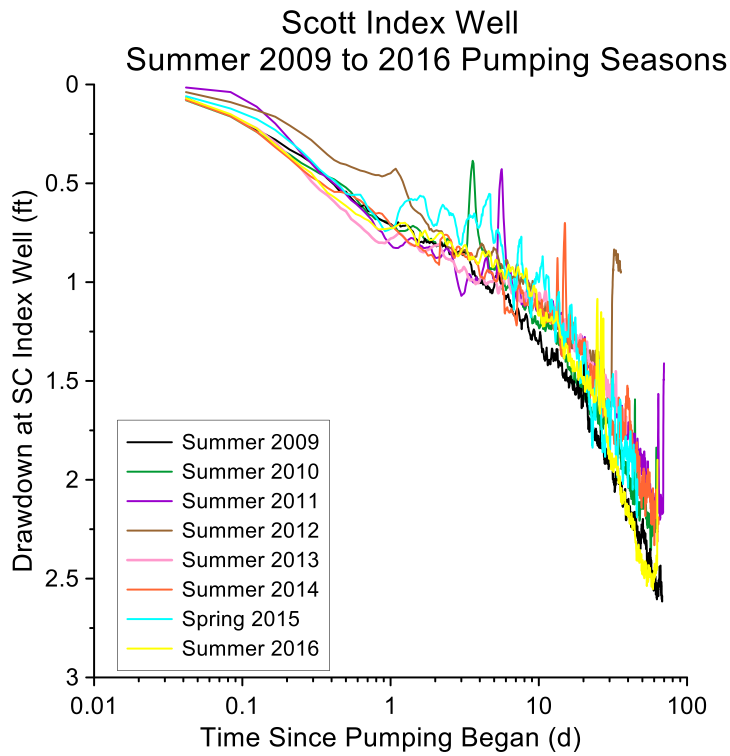

Figure 44a—Drawdown in the Scott index well versus the logarithm of pumping time for pumping periods beginning at points A (2009), B (2010), C (2011), D (2012), E (2013), F (2014), G (2015), and H (2016) on fig. 5.

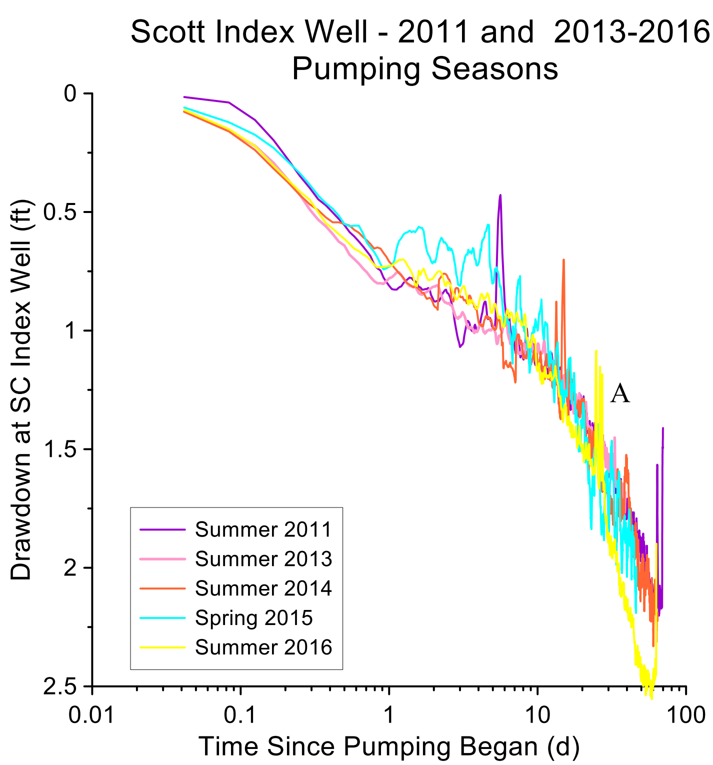

Figure 44b—Drawdown in the Scott index well versus the logarithm of pumping time for pumping periods beginning at points C (2011), E (2013), F (2014), G (2015), and H (2016) on fig. 5. A defined in text.

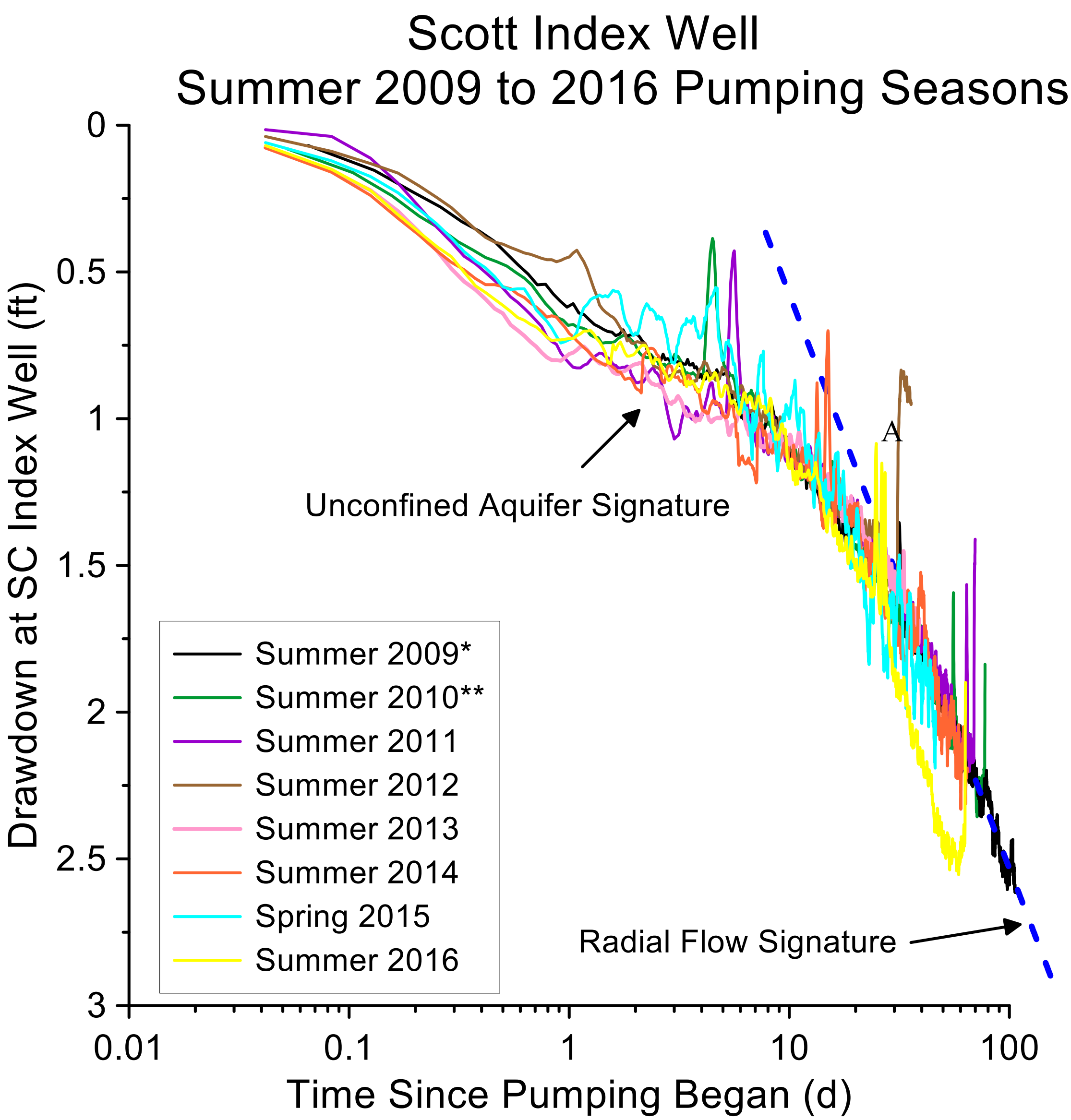

*Figure 45—Drawdown in the Scott index well versus the logarithm of pumping time for pumping seasons beginning at points A (2009), B (2010), C (2011), D (2012), E (2013), F (2014), G (2015), and H (2016) on fig. 5 with pumping time modified for 2009 and 2010. * and **—pumping times modified as explained in text. 2008 pumping period not plotted because of noise produced by pumping cutoffs and restarts. A defined in text.*

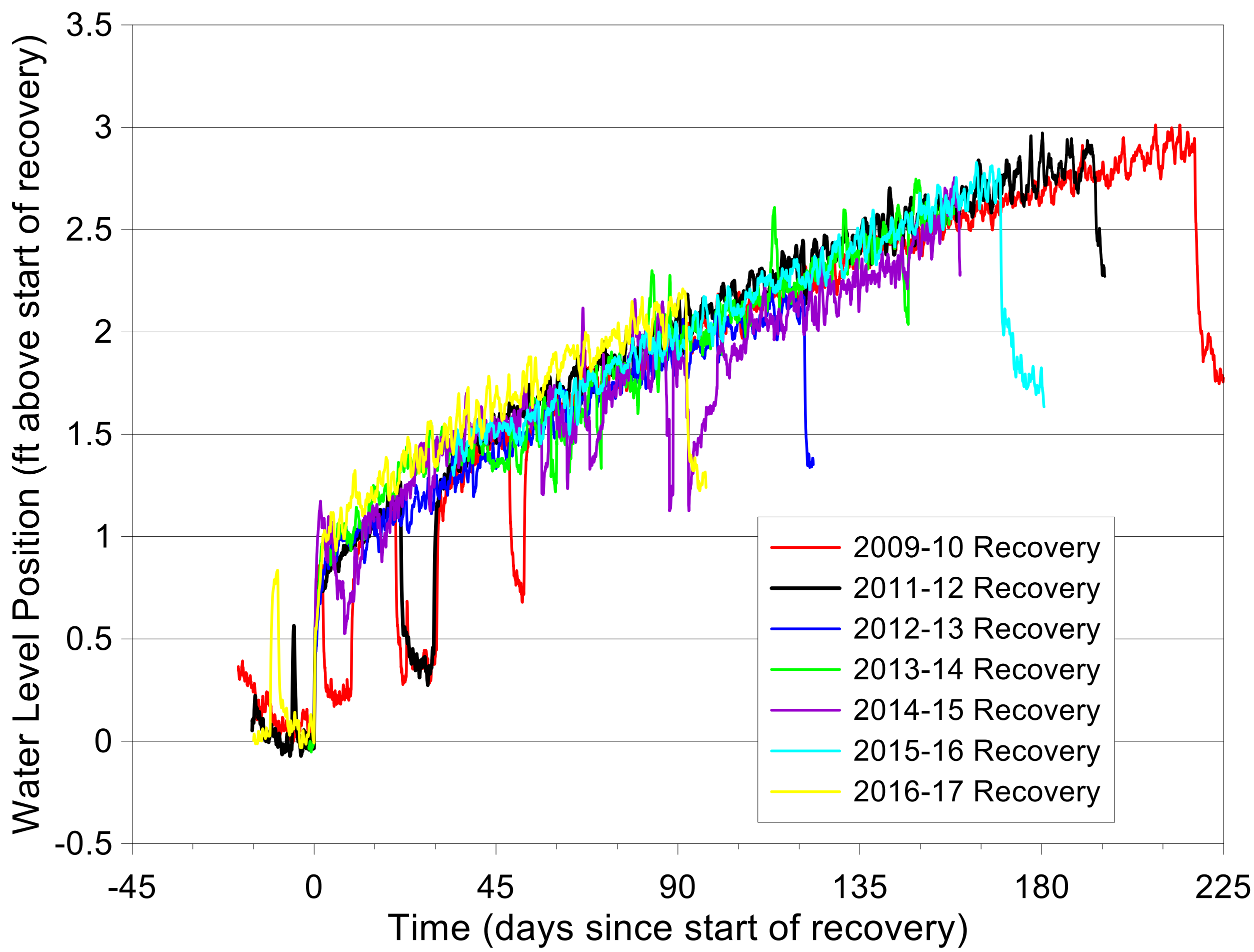

Figure 46—Water levels in the Scott index well for the 2009–2010, 2011–2012, 2012–2013, 2013–2014, 2014–2015 (corrected), 2015–2016 (corrected), and 2016–2017 recovery periods. Recovery for the 2009–2010, 2011–2012, 2012–2013, 2013–2014, 2014–2015, 2015–2016, and 2016–2017 recovery periods calculated from points I, J, K, L, M, N, and O, respectively, on fig. 5.

4.1.3. Thomas County

The major findings regarding the water-level data from the Thomas index well were summarized in the publications described in the first paragraph of this section. The most important finding was that there appears to be a significant amount of inflow into the unconfined aquifer at the Thomas site. Further assessments of that possibility were carried out using the 2016 data.

An assessment of six complete and one continuing recovery seasons was presented in the 2015 annual report (Butler, Whittemore, Reboulet, et al. 2016). The figure accompanying that assessment (fig. 37) showed the near-coincidence of superimposed recovery plots for the complete 2008–2009, 2009–2010, 2011–2012, 2012–2013, 2013–2014, and 2014–2015 recovery seasons and the then still continuing 2015–2016 recovery. Given that, the assessment in this report focuses on the recovery data for four years:

2009, 2012, and the two most recent years (2015 and 2016). The 2009 and 2012 pumping seasons bound the range of conditions (water use and pumping duration) observed during the monitoring period (table 4 in Butler, Whittemore, Reboulet, et al., 2016). Although the 2012 water use was 92% greater than that of 2009 and the irrigation season was close to 2.1 times longer, the rate of recovery after these irrigation seasons was essentially the same. The agreement between the superimposed recovery plots on fig. 47 is remarkable; the difference in the rate of water-level change between recovery periods is very small. The near-coincidence of recovery rates, particularly after the first 100 days of recovery, indicates that the recovery is not a function of withdrawals during the previous pumping season; some other mechanism, most likely inflow, must be primarily responsible for the water-level changes during recovery. A similar coincidence is seen when data from all the recovery seasons are included, a further indication that a mechanism beyond pumping in the previous irrigation season is responsible for the rise of water levels during the recovery period. The near-coincidence of recovery rates also indicates that the decreases in saturated thickness observed during the monitoring period have had virtually no effect on the transmissivity of the HPA in the vicinity of the Thomas index well.

In late 2014, we developed a new approach for estimating the inflow into the HPA in the vicinity of the Thomas site. We continued to refine that approach in 2016 as described in Section 5; an article based on the approach was published early in the year (Butler, Whittemore, Wilson, et al., 2016). The very high correlation between annual water-level change and water use for 2008–2015 shown later in Section 5.7.2 also fits the mechanism of nearly constant inflow.

Determination of the origins of the inflow into the unconfined aquifer at the Thomas County index well and the possible inflow into the unconfined aquifer at the Scott County index well is critical for assessing the continued viability of those portions of the High Plains aquifer as a water source for irrigated agriculture. Water samples have been taken and analyzed from the index wells. Water samples have also been collected at five active irrigation wells in the vicinity of the Thomas index well so that the chemistry of waters drawn from a larger vertical interval of the aquifer can be assessed. The results of the analyses of some of those samples and preliminary interpretations were reported in previous annual reports.

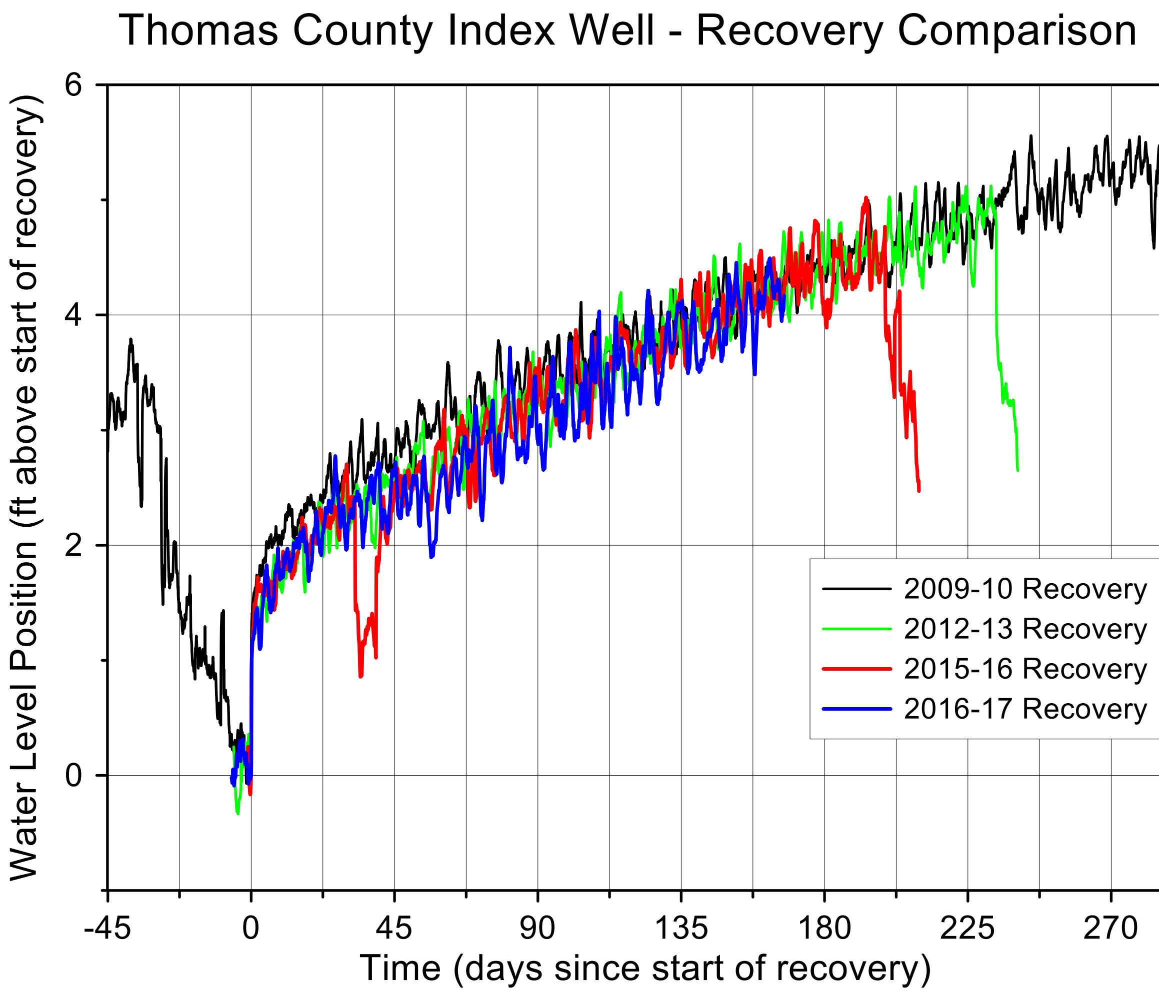

Figure 47—Water levels in the Thomas County index well for the 2009–2010, 2012–2013, 2015–2016, and 2016–2017 recovery periods. Recovery for the 2009–2010, 2012–2013, 2015–2016, and 2016–2017 recovery periods calculated from points A (2009–2010), B (2012–2013), C (2015–2016), and D (2016–2017) on fig. 32. Autumn pumping affected the recovery plots for 2012–2013, 2015–2016, and 2016–2017 for the first 90–100 days.

5. Relationships Among Water-Level Changes, Water Use, and Climatic Indices

5.1. Introduction

The measurement and interpretation of water-level changes at the index wells have provided an improved understanding of hydrologic responses at the local (section to township) scale in the HPA in western Kansas. The existing index wells also can serve as an index of the character of the year-to-year water-level changes measured in the annual well network in the western three GMDs and the western portion of GMD5. Understanding the relationships between water-level change at both local and GMD scales and water use (groundwater pumping) and changes in climatic conditions can be valuable for management purposes. This section describes results based on updated data and the continued advancements in this area.

The main driver of water-level changes 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, then the main factor controlling the annual pumping is the meteorological condition for a given year.

5.2. Climatic Indices

Climatic indices provide a measure of how precipitation-related weather conditions deviate from historic norms. Commonly used climatic indices for which data are readily available are the Palmer Drought Severity Index (PDSI), the Palmer Z Index, and the Standardized Precipitation Index (SPI) (Hayes, 2016; Heim, 2002; Logan et al., 2010; National Climatic Data Center, 2016). A brief description of these indices was given in a previous report (Butler et al., 2014). During 2014, the National Climatic Data Center (NCDC) transitioned "from its traditional climate divisional dataset to a new divisional dataset, known as nClimDiv, which is based on Global Historical Climatology Network-Daily (GHCN-D) observations using a 5-km gridded approach." In addition, the Center used "new methodologies to compute temperature, precipitation, and drought for the United States climate divisions." Further description of the new dataset can be found at http://www.ncdc.noaa.gov/news/transitioning-gridded-climate-divisional-dataset. The new dataset was used in graphs and correlations of climatic indices for this report.

5.3. Characterization of Climate Since Installation of the Three Original Index Wells

Except for a very small strip of southernmost GMD4, GMDs 4, 1, and 3 lie within Kansas climatic divisions 1 (northwest), 4 (west-central), and 7 (southwest Kansas), respectively. One each of the three original index wells was installed in Thomas, Scott, and Haskell counties in GMDs 4, 1, and 3 during 2007. These wells provide annual records for calendar years from 2008 to the present. Persistent climatic conditions can be represented by monthly PDSI values for each of the three climatic divisions that approximately coincide with the three GMDs; fig. 48 displays these conditions since the operation of the first three index wells, 2008–2016. Conditions changed from near normal in 2008 across the three western climatic divisions (coinciding with GMDs 4, 1, and 3) to wet in 2009. Wet conditions continued through the first part of 2010 in western Kansas, then changed to somewhat dry during the latter portion of 2010. In west-central Kansas, the climate became drier in 2011 until the latter part of the year, when more rainfall brought the climate to near normal during the winter of 2011–2012. Severe drought started in the summer of 2011 in the southwest and in the summer of 2012 in west-central and northwest Kansas. The long-term condition of drought continued until about mid-2014 in west-central and southwest Kansas but continued until early 2015 in northwest Kansas, although the trend was to less severe drought during 2014. After the drought, near normal to somewhat wet conditions prevailed through 2016 in northwest and west-central Kansas. The conditions in southwest Kansas during the latter part of 2014 were near normal but then transitioned to very wet during the latter half of 2015 and most of 2016.

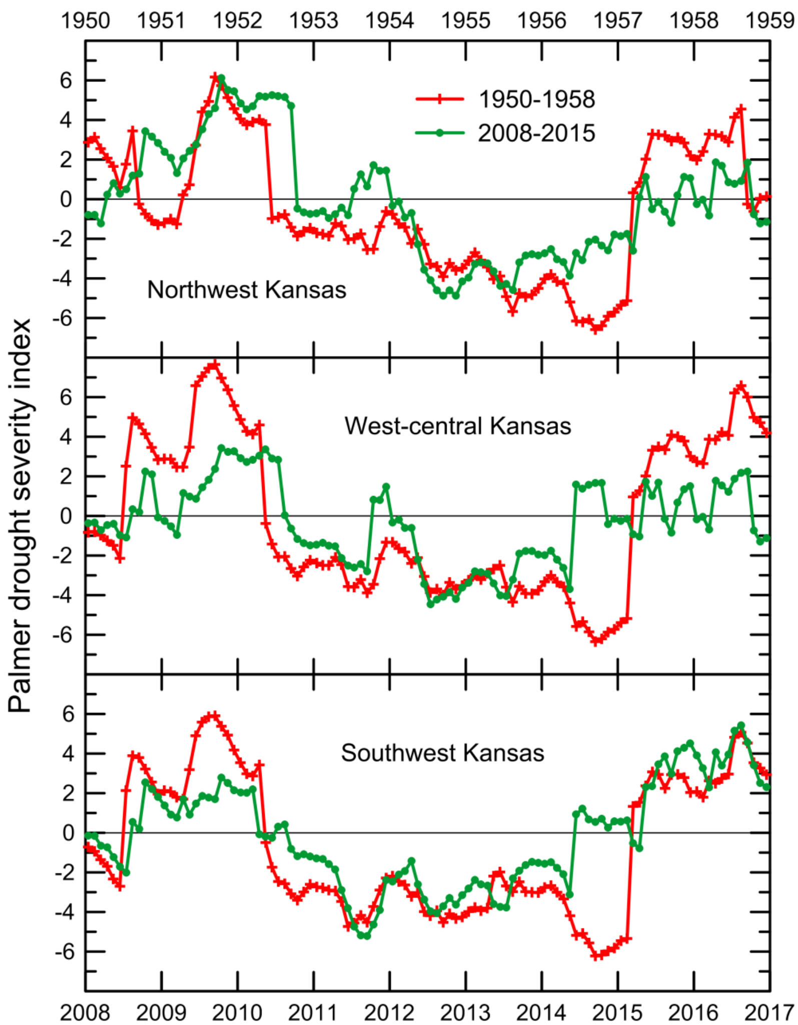

Figure 48—Comparison of monthly values of the Palmer Drought Severity Index (PDSI) for the three western climatic divisions of Kansas during 1950–1958 and 2008–2016. The monthly values are plotted as the middle of the month. Annual tick marks represent the beginning of a year.

Figure 48 also includes comparison of the monthly PDSI values during 1950 through 1958, which included the drought of the 1950s, with those for 2008 through 2016. The years of 1950 through early 1952 generally included predominantly wet conditions on either side of a shorter period with normal to somewhat dry climate. Drought conditions began in all three of the western climatic divisions in the summer of 1952 and generally grew worse until the particularly severe drought of 1956, with a brief respite to more normal climate from the end of 1953 to the early spring of 1954 in northwest and west-central Kansas. The climatic pattern for 2008 through early 2014 is similar to that for 1950 through early 1956. The drought in 2011 was somewhat comparable to that in 1953 for west-central and southwest Kansas; the drought of 2012 through early 2014 was fairly similar to that for 1954 through early 1956. The major difference between the 1950s and early 2010s drought is that climatic conditions became less dry to slightly wet after early 2014 in contrast to the severe drought of 1956; the change in 2014 was critical to reducing the amount of pumping needed for irrigation in that year in western Kansas in comparison to a repeat of 1956.

We have investigated the correlation of water-level changes in the GMDs with common climatic indices and found that the nine-month October SPI correlates well with annual water-level changes in all three of the western Kansas GMDs (Butler et al., 2015; Whittemore et al., 2016). Based on the nine-month October SPI, 2012 was the only year with a significant drought in northwest and west-central Kansas; its severity was between that of 1952 and 1956 in northwest Kansas and close to that of 1952 in west-central Kansas (fig. 49). The SPI indicates that drought occurred during both 2011 and 2012 in southwest Kansas; the drought of 2011 was severe and between the severity of 1952 and 1956. Conditions transitioned from the dry side of normal in 2013 to normal, the wet side of normal, and very wet in 2015 in northwest, west-central, and southwest Kansas, respectively, and then to the wet side of normal in all three regions in 2016.

5.4. Annual Winter Water-Level Measurements

Annual winter groundwater levels have been measured in a network of irrigation and other well types in western Kansas 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—www.kgs.ku.edu/Magellan/WaterLevels/index.html).

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 2016 ranged from less than a percent to several percent of the current total, depending on the county. For example, the numbers of unique points of groundwater diversion in Thomas, Scott, and Haskell counties in 2016 were 1,146, 1,355, and 1,686, respectively. The numbers of points of diversion that have been added after 1997 were 52, 21, and 0 for these three counties, respectively. Thus, for the period 1996–2016, the main driver for water-level changes in the HPA in western Kansas was the amount of pumping from each well.

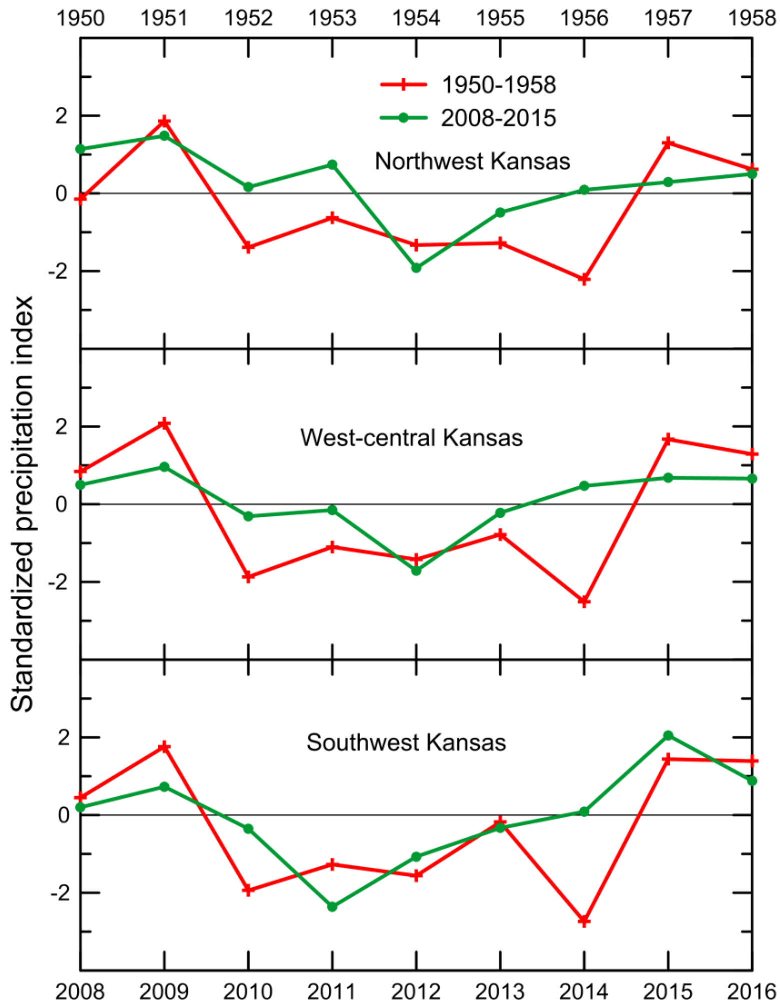

Figure 49—Comparison of the nine-month October SPI values for the three western climatic divisions of Kansas during 1950–1958 and 2008–2016. The nine-month October SPI correlates well with water-level changes in all three western GMDs (fig. 50).

5.4.1. Water-Level Change in the Groundwater Management Districts

The mean annual year-to-year changes in winter water levels during 1996–2016 for the three western GMDs are displayed in fig. 50 based only on wells for which measurements were made during the winters of all years from 1996 to 2016. The values for 2016 were computed using the provisional data for the winter (January) 2017 measurements. The axes are the same in the plots for all three GMDs to illustrate the relative water-level changes. Mean water-level changes in GMDs 1 and 4 have fluctuated between +0.6 and -1.6 ft each year. The changes in GMD3 during this period were substantially greater (between +0.1 and -3.3 ft). Some similarity is evident in the patterns of the water-level changes for the three GMDs. The water-level changes for all the GMDs have a general downward trend, with the slope of the trend increasing from north to south.

The mean annual water-level changes in the three GMDs generally mimic the variations in the nine-month October SPI, also displayed in fig. 50. The annual water-level decline in northwest Kansas in 2016 was a little less than in 2015 and the SPI indicates that conditions were slightly wetter in 2016 than 2015.

In contrast, the annual water-level decline in GMD1 in 2016 was greater than in 2015, even though the climatic conditions as represented by the SPI were about the same for the two years. The water-level decline in GMD3 was a little greater in 2016 than in 2015, reflecting the change from very wet to the wet side of normal climatic conditions as indicated by the SPI.

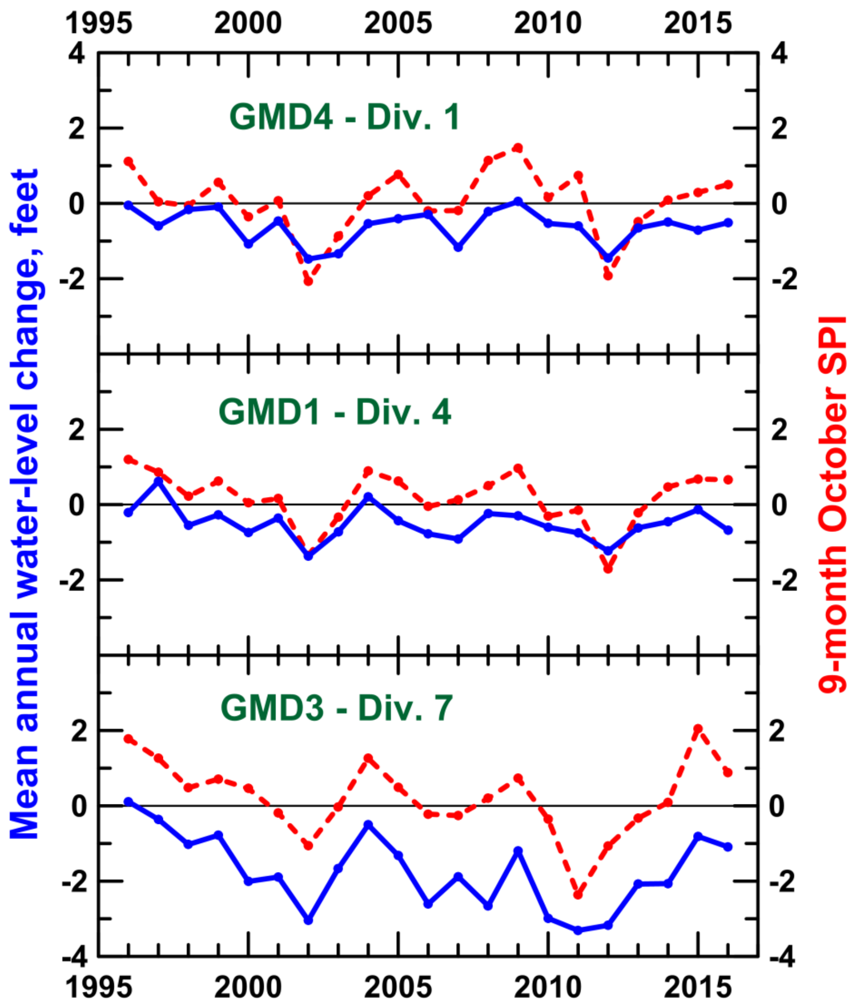

Figure 50—Mean annual water-level change in the HPA in GMDs 4, 1, and 3 and the nine-month October SPI for climatic divisions 1, 4, and 7, respectively, during 1996–2016. The water-level change for a particular year is the water-level difference between the following year and that year for continuously measured wells for 1996–2016 and between the 2017 provisional winter value and the 2016 value. The blue lines represent the water-level change and the red dashed lines the SPI. The ranges in the axes for water-level change and SPI are the same for all three graphs.

5.4.2. Water-Level Change in the Thomas, Scott, and Haskell Counties Index Wells

Winter water levels have been measured by steel tape in the original three index wells since January 2008 (see tables 4, 11, and 28). Figure 51 shows the annual year-to-year water-level changes for both the tape and transducer values for 2008–2016 (values not adjusted for barometric pressure changes) along with the mean water-level changes for the GMDs based on the network wells with continuous records for this period. The annual changes in the Scott index well have been within a relatively narrow range (between -0.2 and -1.5 ft; a total absolute range of 1.3 ft), whereas the changes have been appreciably larger at the Thomas index well (between +1.6 and -2.5 ft; a total absolute range of 4.1 ft), and even greater at the Haskell index well (between +4.1 and -10.2 ft; a total absolute range of 14.3 ft).

The range in the annual water-level declines for the Scott index well is only a little smaller than that for the mean annual water-level change for GMD1 during 2008–2016 (fig. 51). 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. The patterns in the annual water-level changes for the Thomas and Scott index wells are generally similar to the patterns for the mean annual changes for the GMDs. This indicates that these two wells are generally 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 variations in the index well water-level changes from 2013 to 2016 are substantially different from the nearly constant decline values for those three years for GMD3. This difference is mainly related to winter pumping period (late November to mid-December 2014) and variations in pumping in the area related to the court-ordered shutdown of nearby pumping wells in 2015 and 2016 (described in Section 3.2.2.1).

5.4.3. Water-Level Change in the Colby and Belpre Index and SC-8 Expansion Wells

This section discusses water-level changes at the Colby index well in Thomas County in GMD4, the SC-8 expansion well in Scott County in GMD1, and the Belpre index well in Edwards County in GMD5. All three of these wells have data records that extend back to before 1996. Last year's report (Butler, Whittemore, Reboulet, et al., 2016) describes the relevant history of the Colby well measurements, correction of an error in the water-level record, and water-level values measured in the winter of 2007 during which heavy snow occurred. Figure 52 displays the water-level changes for 1996–2016 for all three of these wells.

The range in water-level changes at the Colby well (1.80 ft, fig. 52) during 1996–2016 was substantially smaller than that for the Thomas County index well (fig. 51), whereas the range at the SC-8 well (5.56 ft, fig. 52) was much greater than that at the Scott County index well (fig. 51). The four years at the beginning of 1996–2015 and the latest year, 2016, were the only years during which substantial rises in water levels occurred at the SC-8 well. Appreciable declines occurred at the SC-8 well during 2000, 2002, 2006, and 2011; the decline in 2002 was substantially greater than for the other years. The greatest decline at the Scott County index well was in 2012, which was about the same as for the Colby well for that year; the decline in 2011 at the SC-8 well was greater than in 2012. The water-level declines were greater in 2016 than in 2015 for both the Thomas County and Colby index wells. In contrast, the water-level decline in the Scott County index well was greater in 2016 than in 2015 but the water level rose in 2016 in the SC-8 well (fig. 52).

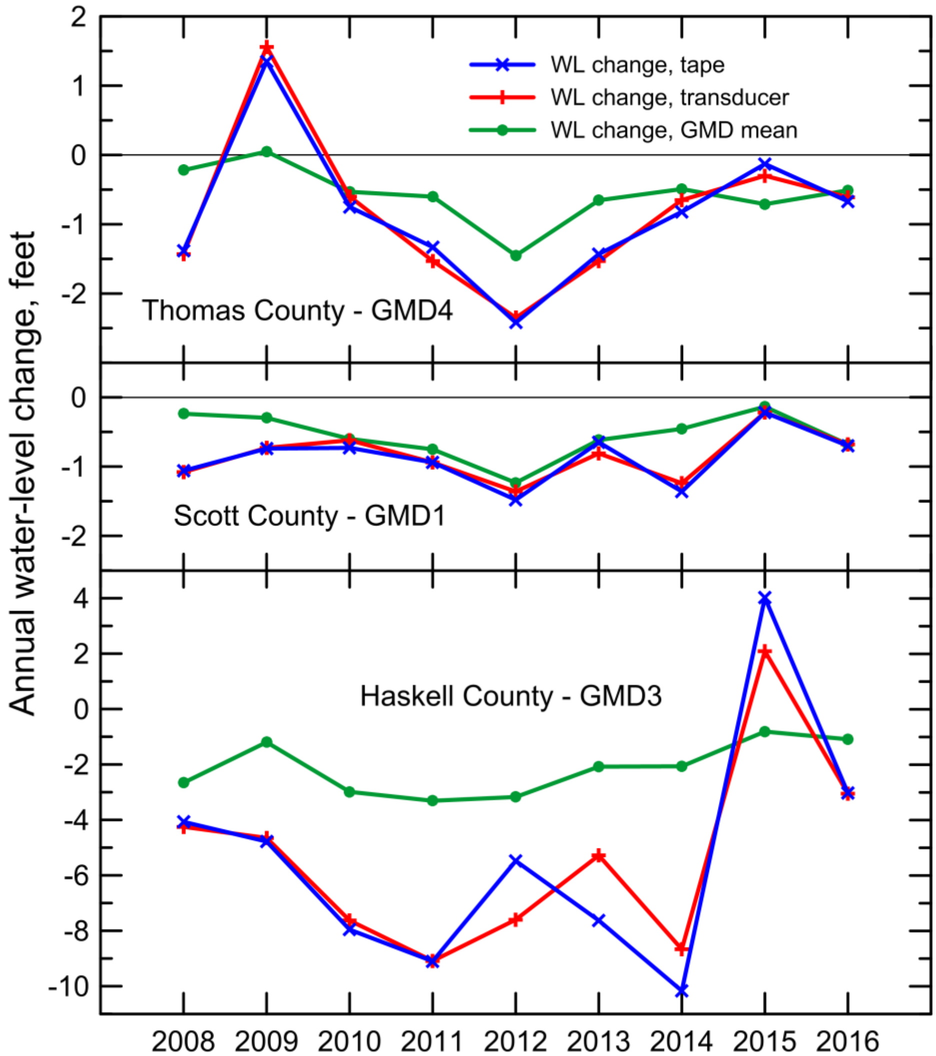

Figure 51—Annual winter water-level changes in the original three index wells and the mean annual changes in the three GMDs in western Kansas in which they are located. Note the different y-axis range for Haskell County versus that for Thomas and Scott counties; suspect 2012 tape measurement at the Haskell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

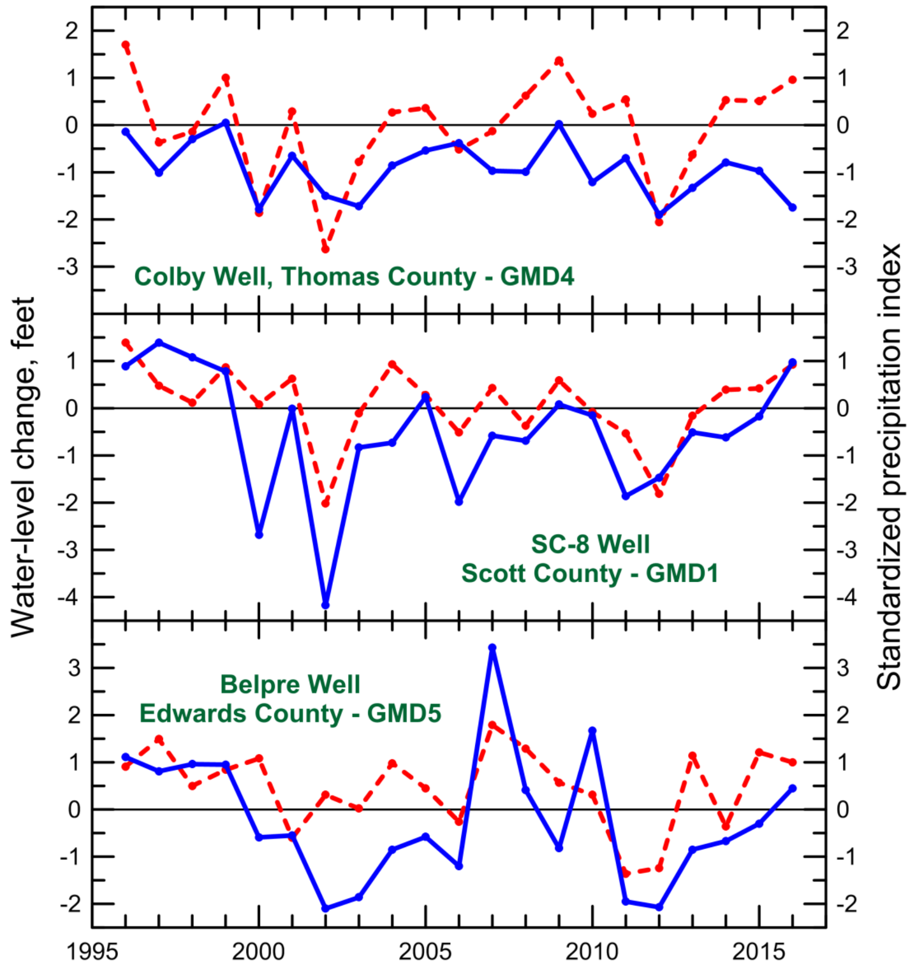

Figure 52—Annual water-level changes in the Colby index well, the SC-8 expansion well, and the Belpre index well 1996–2016, and the six-month September, nine-month September, and 12-month December SPI for these three wells, respectively. The blue lines and points represent the annual water-level change and the red dashed line is the SPI. The absolute range of the y-axes is the same for all three well graphs.

The water-level change was positive for 8 and negative for 13 of the 21 years of record for the Belpre well during 1996–2016 (fig. 52). The location is affected by surface precipitation recharge and stream-aquifer interactions to a much greater extent than the index wells in the western (Ogallala) part of the HPA. The substantial water-level variations reflect the differences caused by these factors during wet and dry years.

The annual water-level changes for these three wells generally mimic the pattern in the SPI shown in fig. 52, although the greater water-level decline for 2016 than 2015 at the Colby well did not fit well the increase in the climatic division SPI from 2015 to 2016. The SPI values used are those for which the optimum correlation exists between water-level change and SPI. The magnitude of the water-level changes relative to the SPI variation is greater for the Belpre well than for the Colby and SC-8 wells. This reflects the larger rainfall for a particular SPI value for south-central Kansas than for western Kansas, and the response of the water levels to the greater precipitation recharge to and stream-aquifer interactions in the HPA at the Belpre site.

5.5. Correlation of Annual Water-Level Change with Climatic Indices

5.5.1. Correlations for the Groundwater Management Districts

As shown in the last three years' index well reports (Butler et al., 2014, 2015; Butler, Whittemore, Reboulet, et al. 2016) and in Whittemore et al. (2016), the correlations between water-level change in the GMD areas and SPI for climatic divisions are high. The coefficients of determination (R^2) for 1996–2016 and 2005–2016 are listed in table 33; 1996–2016 represents the period that includes data from the first year (1997) that the KGS measured winter water levels with the DWR; 2005–2016 represents a period with less uncertainty in water-use data and also the beginning of radar precipitation data as described later in this report. The correlations in table 33 are all highly statistically significant. As indicated earlier, the final 2017 data for water-level changes for continuously measured wells in the GMDs are not yet available, so the provisional 2017 measurements were used for determining the correlations. The table has correlations for GMD4 that include the 2006 and 2007 water-level changes as individual values and as the mean for those years; as indicated in earlier reports, many water-level measurements in the winter of 2007 were delayed by heavy snow and the observations made later reflected additional water-level recovery. The correlations with the mean 2006–2007 value are higher than those with the two years considered separately.

Table 33—Coefficients of determination (R^2) for the correlation of mean annual water-level changes for continuously measured wells in GMDs 4, 1, and 3 with the nine-month October SPI for climatic divisions 1, 4, and 7 during 1996–2016 and 2005–2016.

Period	Water-Level Change Region – Climatic Division	R^2
1996–2016	GMD4 – Division 1	0.72[a]
1996–2016	GMD4, mean 2006, 2007 – Division 1	0.80[a]
2005–2016	GMD4 – Division 1	0.73[a]
2005–2016	GMD4, mean 2006, 2007 – Division 1	0.89[a]
1996–2016	GMD1 – Division 4	0.65[b]
2005–2016	GMD1 – Division 4	0.64[b]
1996–2016	GMD3 – Division 7	0.78[a]
2005–2016	GMD3 – Division 7	0.71[a]

[a] Significant at P = 0.001
[b] Significant at P = 0.01

5.5.2. Correlations for the Index Wells and SC-8 Expansion Well

Table 34 lists the coefficients of determination (R^2) for correlations between the nine-month SPI climatic index and annual water-level change (based on both tape and transducer measurements) for the Thomas, Scott, and Haskell counties index wells for 2008–2016. Last year's report (Butler, Whittemore, Reboulet, et al., 2016) included correlations for the 2008–2013, 2008–2014, and 2008–2015 periods for the Thomas, Scott, and Haskell counties wells. The water-level changes for 2014 and 2015 for the Scott County well appreciably diverged from the regression line; the 2014 value substantially below and the 2015 much above. Thus, the correlation based on average water-level change for 2014 and 2015 is also given for this index well in table 34. Last year's report (Butler, Whittemore, Reboulet, et al., 2016) describes the probable causes for the 2014 and 2015 divergences. Table 35 includes the coefficients of determination for the Colby and Belpre index wells and the SC-8 expansion well for 1996–2016 and 2005–2016. These correlations with the regional climatic index will be compared to those for the local indicator of climatic conditions (radar precipitation) around the index wells in the next section.

Table 34—Coefficients of determination (R^2) for the correlation of annual water-level changes at the Thomas, Scott, and Haskell counties index wells with the nine-month October SPI for climatic divisions for 2008–2016.

Index Well	Water-Level Type	Climatic Division	R^2
Thomas County	Tape	1	0.51[c]
Thomas County	Transducer	1	0.45[c]
Scott County	Tape	4	0.28
Scott County, mean 2014—2015	Tape	4	0.50[c]
Scott County	Transducer	4	0.27
Scott County, mean 2014—2015	Transducer	4	0.57[c]
Haskell County	Tape	7	0.57[b]
Haskell County, mean 2014—2015	Tape	7	0.68[b]
Haskell County	Transducer	7	0.72[a]
Haskell County, mean 2014—2015	Transducer	7	0.86[a]

[a] Significant at P = 0.01
[b] Significant at P = 0.02
[c] Significant at P = 0.05

Table 35—Coefficients of determination (R^2) for the correlation of annual water-level changes (tape measurements) at the Colby, SC-8, and Belpre wells with climatic division SPI values for 1996–2016 and 2005–2016.

Period	Expansion Well	Climatic Division	SPI Period	R^2
1996–2016	Colby well	1	6-month October	0.51[a]
2005–2016	Colby well	1	6-month October	0.45[c]
1996–2016	SC-8 well	4	9-month September	0.56[a]
2005–2016	SC-8 well	4	9-month September	0.60[b]
1996–2016	Belpre well	8	12-month December	0.41[b]
2005–2016	Belpre well	8	12-month December	0.52[b]

[a] Significant at P = 0.001
[b] Significant at P = 0.01
[c] Significant at P = 0.02

5.6. *Correlation of Annual Water-Level Change with Radar Precipitation*

Radar precipitation has been found to be a good indicator of climatic conditions driving pumping and water-level changes (Whittemore, Butler, and Wilson, 2015; Whittemore, Butler, Wilson, and Woods, 2015). The Advanced Hydrologic Prediction Service of the National Weather Service 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 compared to and 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 the index well report for 2014 (Butler et al., 2015).

Figure 53 shows an image for total annual precipitation during 2016 from this website. The data are displayed as a gridded field 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. Coverages for radar precipitation data available from the website begin for the year 2005. Figure 54 illustrates the normal precipitation for Kansas (derived from PRISM climate data for 1981–2010) for comparison to the 2016 precipitation.

Although the annual radar precipitation for Kansas in 2016 (fig. 53) displays the typical general increase in normal precipitation from west to east across Kansas (fig. 54), it also indicates the substantial spatial variation in precipitation within regions such as climatic divisions and GMD areas. For example, in 2016, areas of greater than normal precipitation (yellow and tan colors) are interspersed with areas of normal precipitation (green colors) in the region of the three western GMDs. We have found that the more detailed variation in precipitation available from radar data generally better represents the climatic conditions affecting water-level change (give higher correlations) than the much more widely spaced precipitation stations used in the SPI computation. In addition, the detailed radar precipitation around a well is more representative of the precipitation affecting pumping around the well than the divisional climatic index SPI. For this year's report, we downloaded monthly radar precipitation data for 2016 for the Kansas region to update our data set for 2008–2015 for use in correlations with water-level changes.

5.6.1. Correlations for the Groundwater Management Districts

In the 2014 index well report (Butler et al., 2015), we found that correlations between radar precipitation and annual water-level changes for the western three GMDs were comparable to those between SPI and water-level changes. Thus, we determined that radar precipitation is a good regional indicator of the climatic conditions driving pumping and water-level declines. We updated the correlations to 2016 by finding the monthly sum of spatial average precipitation for each of the areas of GMDs 1, 3, and 4 that give the optimum correlation with the average annual water-level change for those GMDs (fig. 55). As indicated earlier, the water-level data for 2017 for the GMD areas are provisional. The R^2 values range from 0.83 for GMD4 (using the mean water-level change and radar precipitation for 2006 and 2007 due to the heavy snowfall that delayed many of the January 2007 water-level measurements) to 0.70 for GMD1 and GMD3. These compare to R^2 values of 0.89, 0.64, and 0.71 for correlations between water-level change for GMDs 4, 1, and 3 and the nine-month October SPI for climatic divisions 1, 4, and 7, respectively (table 33). Figure 55 shows that 2016 was a little wetter than normal for precipitation for the GMDs 1 and 4 areas but was substantially wetter than normal (although not as wet as 2015) for the GMD3 area. Thus, the 2016 value exerts a greater influence on the regression between water-level change and radar precipitation for GMD3 than for GMDs 1 and 4.

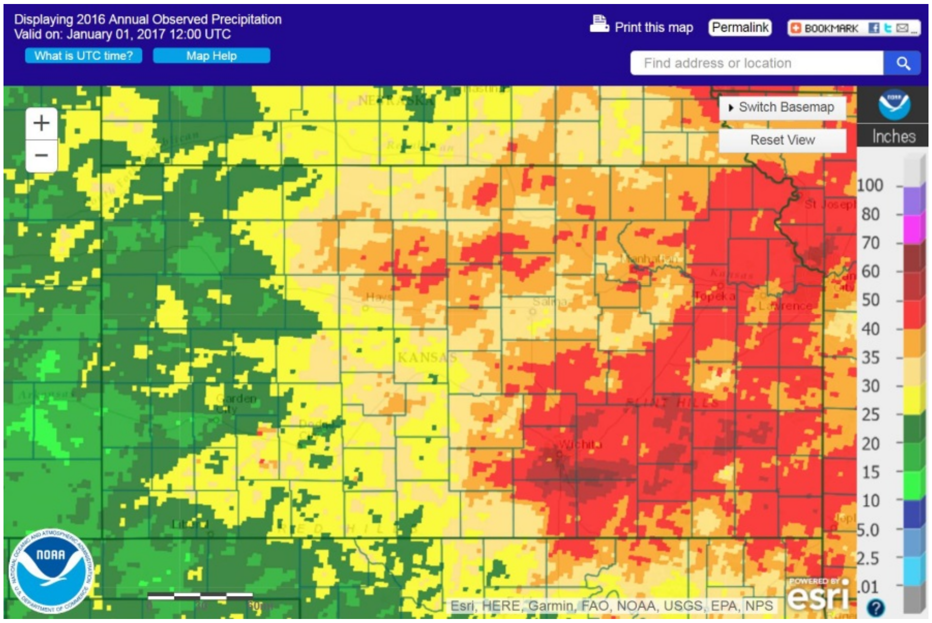

Figure 53—Total 2016 radar precipitation for Kansas. County lines and the state boundary are displayed.

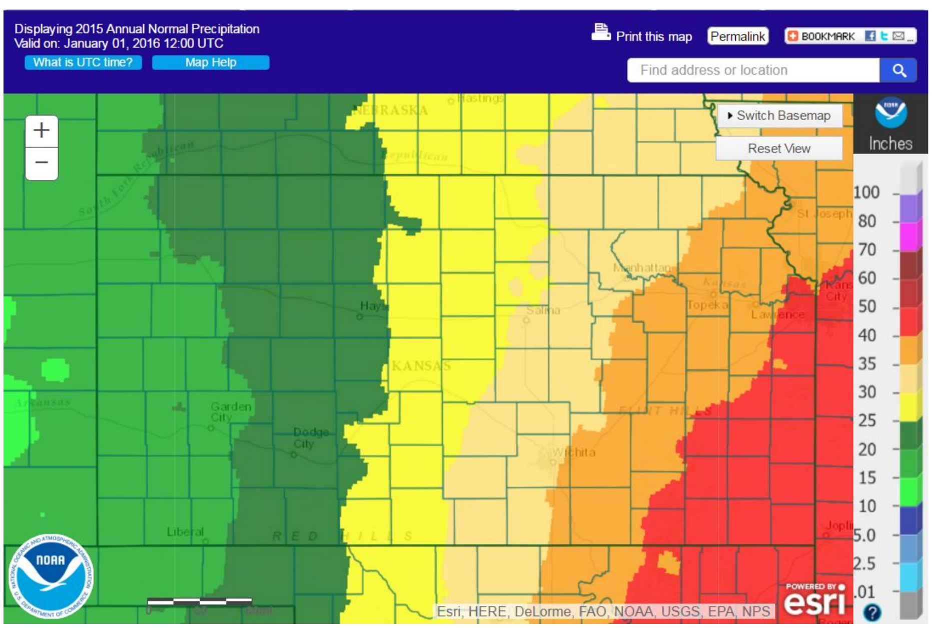

Figure 54—Normal annual precipitation for Kansas based on PRISM data for 1981–2010. The image is the same area as in fig. 52 for comparison purposes.

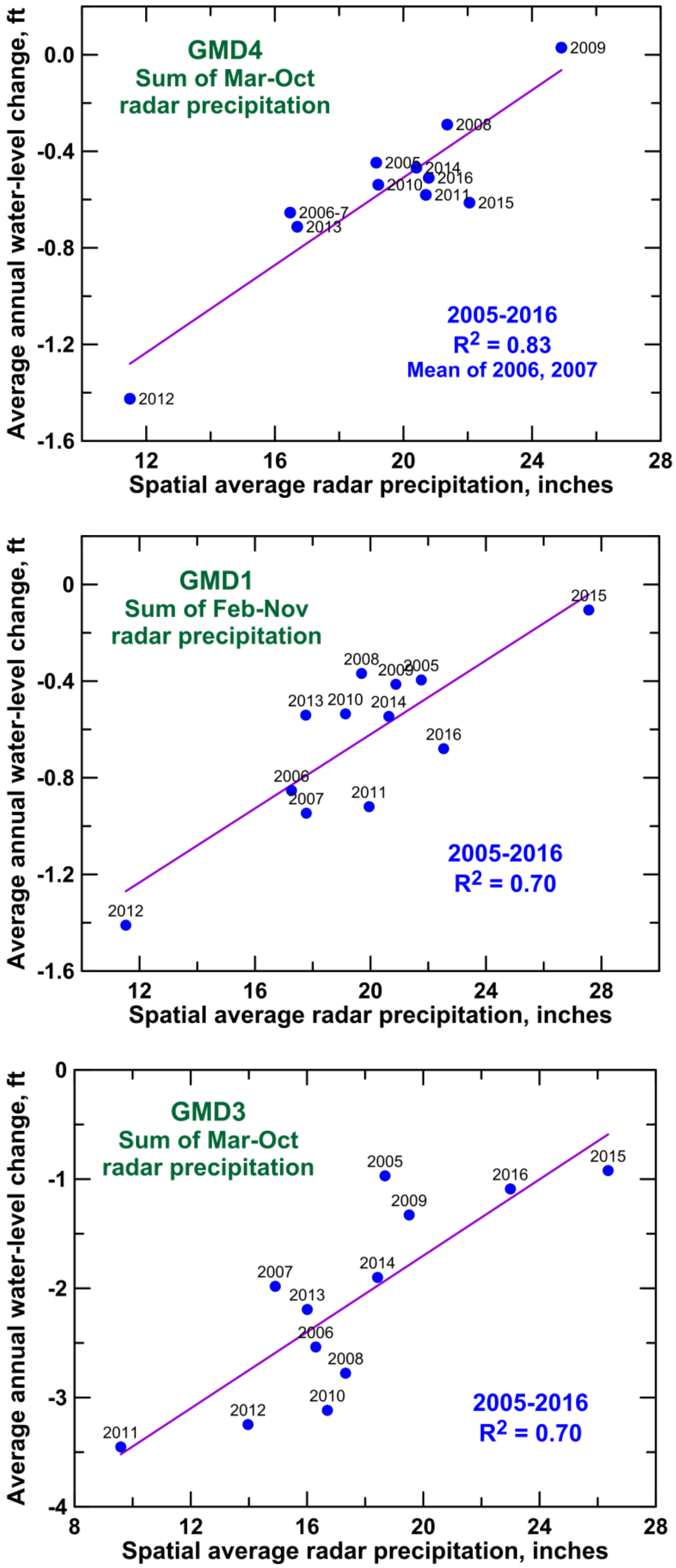

Figure 55—Correlation of mean annual winter water-level change during 2005–2016 for the three western Kansas GMDs with monthly sums of radar precipitation data for GMD areas.

5.6.2. Correlations for the Index Wells and SC-8 Expansion Well

For correlations of radar precipitation data with annual water-level changes at the index wells, we selected precipitation data for the nearest grid point to each of the index well locations and for the spatial average of the nine grid points centered on each of the index wells. We found the optimum correlations based on a similar procedure as for the GMD areas—varying sums of the number of months and the particular span of those months.

In last year's report (Butler, Whittemore, Reboulet, et al., 2016), we found that the spatial mean for the nine grid points centered on the index well gave either higher or about the same correlation with annual water-level change as the nearest grid point. In addition, the nine-point approach is thought to be less susceptible to anomalies that might occur for one grid point. The area represented by the nine radar data points is approximately a square a little more than 7.7 mi on a side (nearly 60 sq mi). In this report, we only show graphs for correlations with nine-point means of radar precipitation for the transducer measurements, although we report the correlation values in table 36 for both tape and transducer measurements.

Annual water-level change and radar precipitation for 2008–2016 around the Thomas County index well are well correlated with the April–September sum of precipitation (fig. 56). The R^2 values for both the tape and transducer water-level changes (table 36) are substantially greater for the correlation with radar precipitation than with the SPI values for the climatic division in which the well is located (table 34). Figure 56 also displays the correlation between water-level change and the January–November sum of radar precipitation for the Scott County index well. Last year's report (Butler, Whittemore, Reboulet, et al., 2016) describes the probable reason for the divergence of the 2014 and 2015 values from the regression line. The R^2 values for both the tape and transducer water-level changes (table 36) are substantially greater for the correlation with radar precipitation than with the SPI values for the climatic division in which the well is located (table 34). The annual water-level changes (both tape and transducer) at the Haskell County index well are well correlated with the January–December sum of monthly radar precipitation at the well location for 2008–2016 (fig. 56 and table 36). Reasons for the deviations in the 2014 and 2015 points are described in last year's report (Butler, Whittemore, Reboulet, et al., 2016). The R^2 values for the tape and transducer water-level changes are comparable with those for the correlation of water-level change and climatic division SPI (table 34).

The correlations between annual water-level change and radar precipitation around the Colby and Belpre index wells and the SC-8 expansion well are all statistically significant at a P level of 0.02 or smaller (table 34, fig. 57). The R^2 values for the correlations with radar precipitation are greater than those with divisional SPI (table 34) for the Colby and Belpre wells but a little less than with the divisional SPI for the SC-8 well.

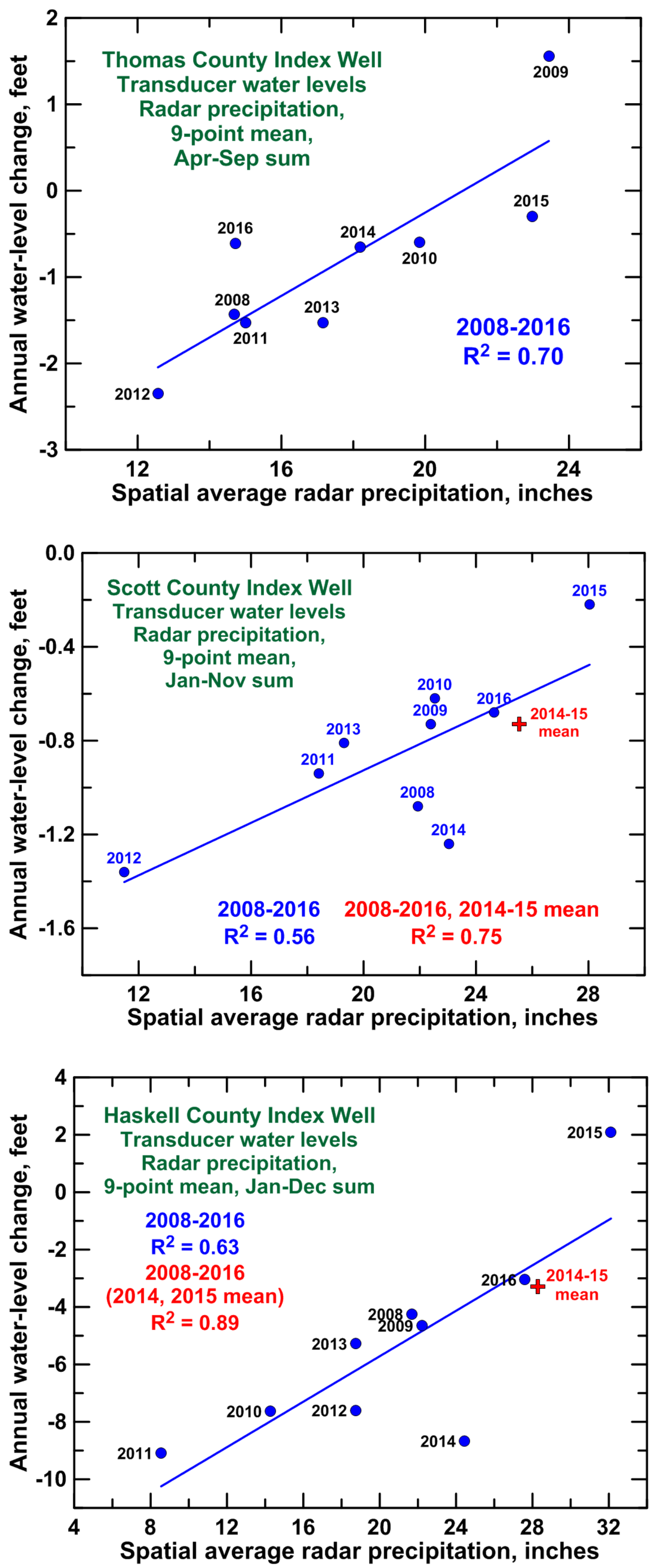

Figure 56—Correlation of annual winter water-level change during 2008–2016 for the Thomas, Scott, and Haskell counties index wells with monthly sums of radar precipitation around the wells.

Table 36—Coefficient of determination (R^2 values) for the optimum correlation of annual water-level change with the sum of monthly radar precipitation for the spatial mean of the nine grid points centered on an index or expansion well for 2005–2016.

Index or Expansion Well	Monthly Sum of Precipitation	Type of Water-Level Measurement	
		Tape	Transducer
Thomas County	April–December	0.73[a]	0.70[a]
Scott County	January–November	0.50[c]	0.56[b]
Scott County, mean 2014–2015	January–November	0.62[b]	0.75[a]
Haskell County	January–December	0.54[b]	0.63[b]
Haskell County, mean 2014–2015	January–December	0.89[a]	0.89[a]
Colby Well	March–December	0.54[b]	
SC-8 Well	January–September	0.54[b]	
Belpre Well	March–December	0.68[a]	

[a] Significant at P = 0.001
[b] Significant at P = 0.01
[c] Significant at P = 0.02

5.7. Correlation of Annual Water Use with Water-Level Change

5.7.1. Correlations for the Groundwater Management Districts

Correlations between average annual changes in winter water levels (continuous network wells) and total groundwater use in the three western GMDs (1, 3, and 4) and GMD5 in south-central Kansas for 2005–2015 (fig. 58) are all statistically significant at the P = 0.01 level or smaller (table 37). The graphs in fig. 58 include a dashed horizontal line for the intersection of the zero water-level change with the regression line, and a dashed vertical line from this intersection to the x-axis for water use. The pumping reduction needed for stable water levels (zero water-level change—henceforth, stable water use) is visually represented as the difference between this vertical line and the dashed vertical line representing the average water use during 2005–2015. Based on the regression equations for these correlations and the approach of Butler, Whittemore, Wilson, et al. (2016) for interpreting the water balance from the equations, the percentage reduction in the average pumping in the GMDs needed to bring the HPA to stable water levels (water-level change equal to zero), ranges from 27% for GMDs 1 and 4 to 34% for GMD3 (table 37). The pumping reduction needed for GMD5 based on 2005–2015 data is much smaller—2.5%. The average water use for the GMDs for 2005–2015 expressed as inches of water applied over the GMD area ranges from 1.61 in for GMD4 up to 4.31 in for GMD3 (table 37). The stable water use (equivalent to the net inflow of water to each GMD area) ranges from 1.17 in for GMD4 to 2.85 in for GMD3.

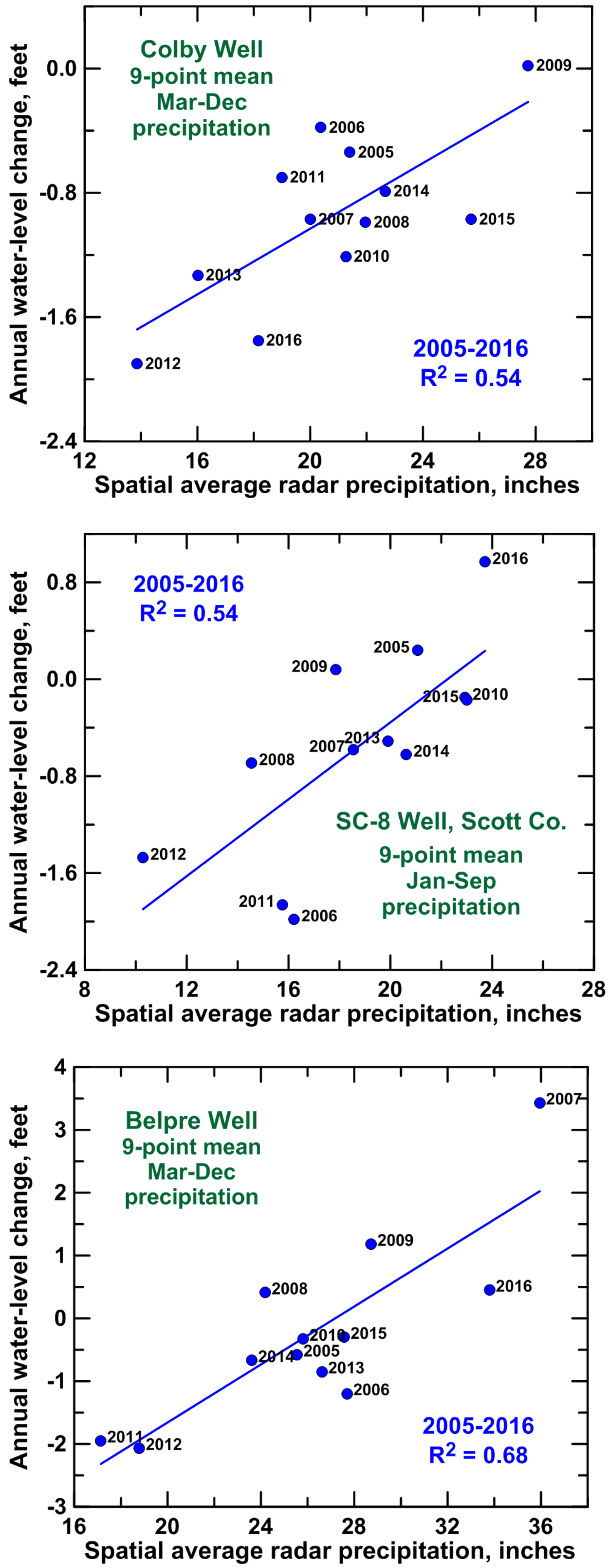

Figure 57—Correlation of annual winter water-level change during 2005–2016 for the Colby, SC-8, and Belpre wells with monthly sums of radar precipitation around the wells.

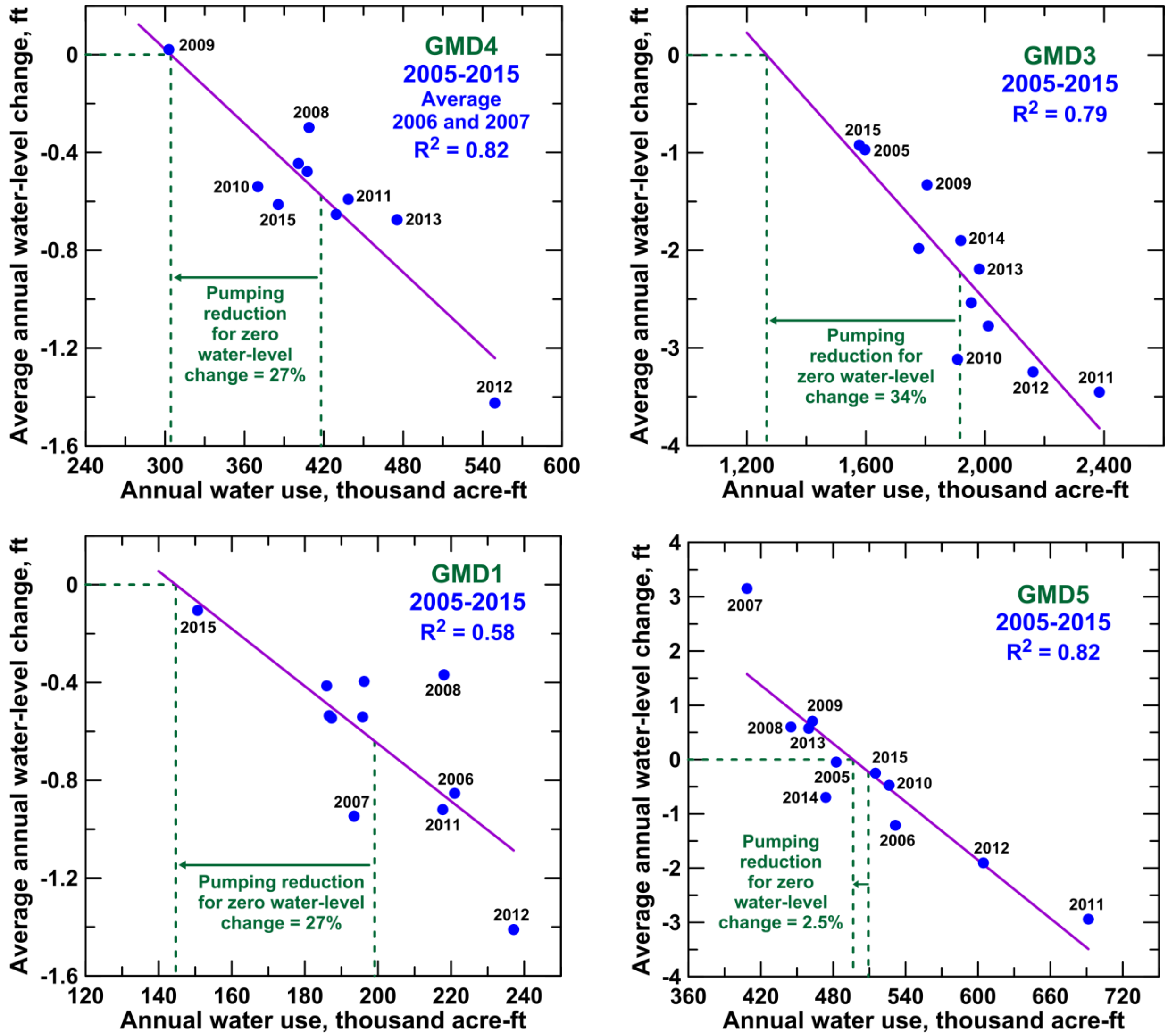

Figure 58—Correlation of average annual winter water-level change with annual water use for GMDs 1, 3, 4, and 5 during 2005–2015.

Table 37—Coefficients of determination (R^2) and information derived from the regression equations for the correlation of average annual water-level changes with groundwater use for the three western GMDs and GMD5 for 2005–2015.

GMDs, 2005–2015	GMD1	GMD3	GMD4	GMD5
R^2	0.58[b]	0.79[a]	0.82[a]	0.82[a]
Pumping reduction for stable water levels, %	27.3	33.9	27.2	2.49
Average water use/area, in	2.04	4.31	1.61	2.44
Stable water use (net inflow), in	1.48	2.85	1.17	2.38
Specific yield	0.073	0.055	0.063	0.022

[a] Significant at P = 0.001
[b] Significant at P = 0.01

5.7.2. Correlations for the Index Wells and SC-8 Expansion Well

Highly statistically significant correlations exist between annual water-level change and annual water use in the vicinity of the Thomas and Scott counties index wells for 2008–2015 (figs. 59 and 60). A statistically significant correlation was found between water-level change and water use for tape measurements for a 1 mi radius water use for the Haskell County well for 2008–2012 before changes in pumping in the area around the well become inconsistent due to winter pumping and the shutdown of selected wells related to impairment complaint proceedings. However, based on examination of water-level change and water-use relationships in this report, the significant correlation for the Haskell well for 2008–2012 is thought to be partially due to the spurious nature of the 2012 tape water-level measurement. The R^2 value for the regression between water-level change and transducer measurements for 2008–2012 at the Haskell well is not significant (fig. 61).

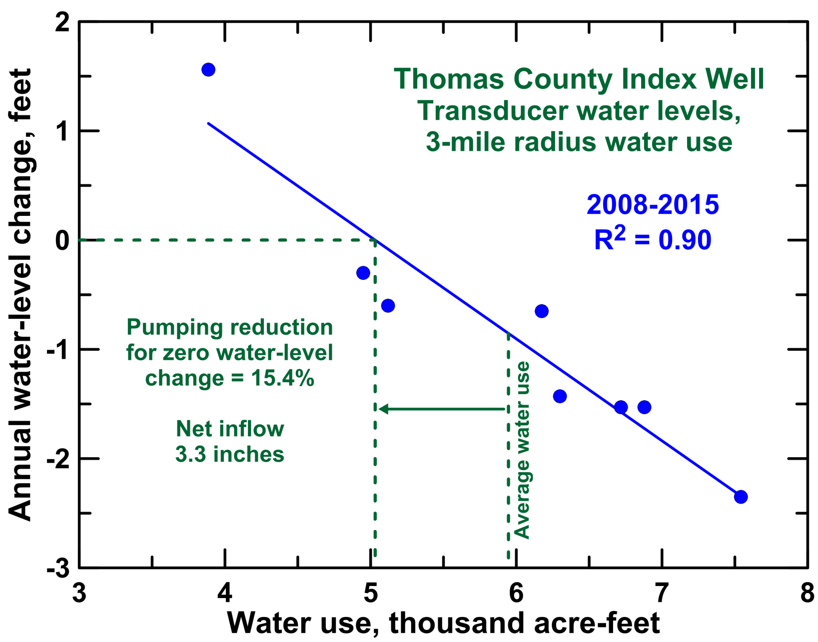

Figure 59—Correlation of annual water-level change based on transducer measurements in the Thomas County index well with annual water use within a 3 mi radius around the well during 2008–2015.

The R^2 values for the correlations between water-level change and water use for 3–5 mi radii circles around the Thomas index well are greater than for water use within 1–2 mi radii (table 38), although all are statistically significant at the P = 0.01 level or smaller. The plot for the 3 mi radius is shown in fig. 59 along with lines that visually represent the pumping at zero water-level change and the average pumping used in determining the pumping reduction needed to achieve stable water levels. The pumping reduction needed for stable water levels decreases from about 25% for the 1 mi radius for water use to the range of 15–20% for the larger radii (table 38). The overall range of 15–25% is smaller than the 27% for all of GMD4 (table 37). The average water use decreases from the 6.4 in applied within the 1 mi radius to 3.1 in for the 5 mi radius of water use. This range in average use is substantially greater than the 1.6 in for all of GMD4. The stable water use (net inflow) also consistently decreases from a high of about 4.8 in within a

1 mi radius to 2.5 in for a 5 mi radius, all of which are greater amounts than the 1.2 in for GMD4. These values indicate that the area of the Thomas well is a more prolific portion of GMD4 than average 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 approximately 1–2 mi to the north and south of the Thomas well. The specific yield calculated from the regression equations is greatest for the 1 mi radius (0.15), decreases to approximately 0.07 for a 2 mi radius, and then is about 0.06 for the 3–5 mi radii of water use, which is comparable to the specific yield of 0.063 for GMD4.

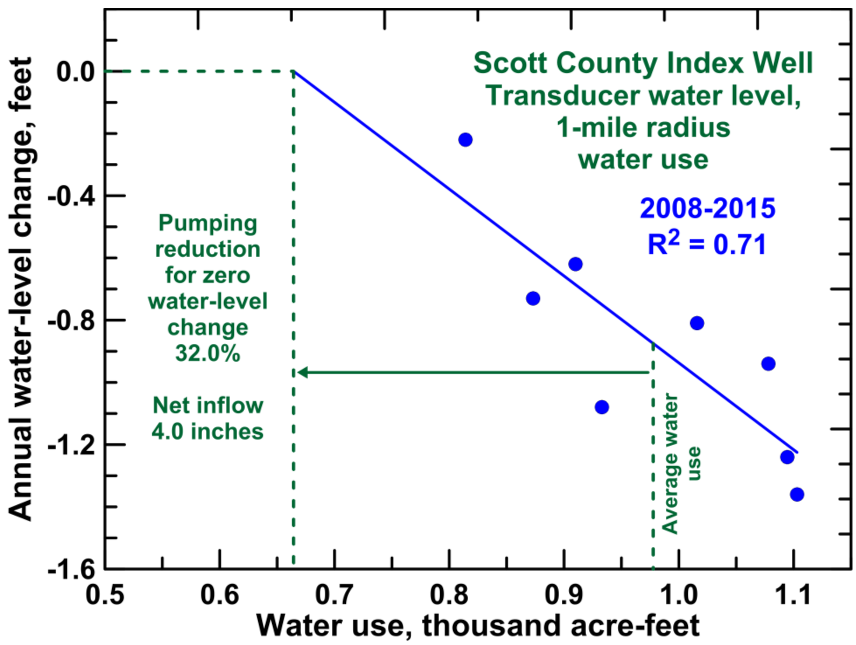

Figure 60—Correlation of annual water-level change based on transducer measurements in the Scott County index well with annual water use within a 1 mi radius around the well during 2008–2015.

The correlations for the Scott County index well for 2008–2015 are statistically significant at the P = 0.05 level or lower for radii of water use except for the 3 mi radius (P values just slightly higher than 0.05). The highest R^2 is for the 1 mi radius of water use and transducer water-level data (fig. 60); the figure also includes dashed lines that visually represent the pumping reduction needed to bring the HPA in the area around the well to stable water levels based on the 2008–2015 data. The pumping reduction is about 32% for the 1 mi radius of water use, and, unlike the Thomas well area, is somewhat higher (32–38%) for 2, 4, and 5 mi radii, for which the R^2 values are statistically significant (P <0.05) (table 38). The pumping reduction range is higher than the 27% for the whole of GMD1 (table 37). The average water use decreases from 5.8 in applied within the 1 mi radius to 4.0 in for the 5 mi radius of water use, values substantially greater than the 2.0 in for all of GMD1. Although the average water use of 5.8 in within a 1 mi radius of the Scott well is less than the 6.4 in within the same radius around the Thomas well, the use densities within each of the larger radii circles around the Scott well are larger than for the Thomas well. The stable water use (net inflow) for the Scott well also consistently decreases from a high of about 4.0 in within a 1 mi radius to 2.7 in for a 5 mi radius, again, values appreciably greater than for GMD1 but within the range for the Thomas well. The specific yield calculated from the regression equations is greatest for the 1 and 2 mi radii (0.17–0.18) and decreases to approximately 0.12 for a 5 mi radius (for radii with statistically significant correlations); these values are all about double the specific yield for GMD1. Although the specific yield values within the 1 mi radius for both the Scott and Thomas counties wells are close to each other, the values for the larger radii circles around the Scott well are about twice those for the Thomas well.

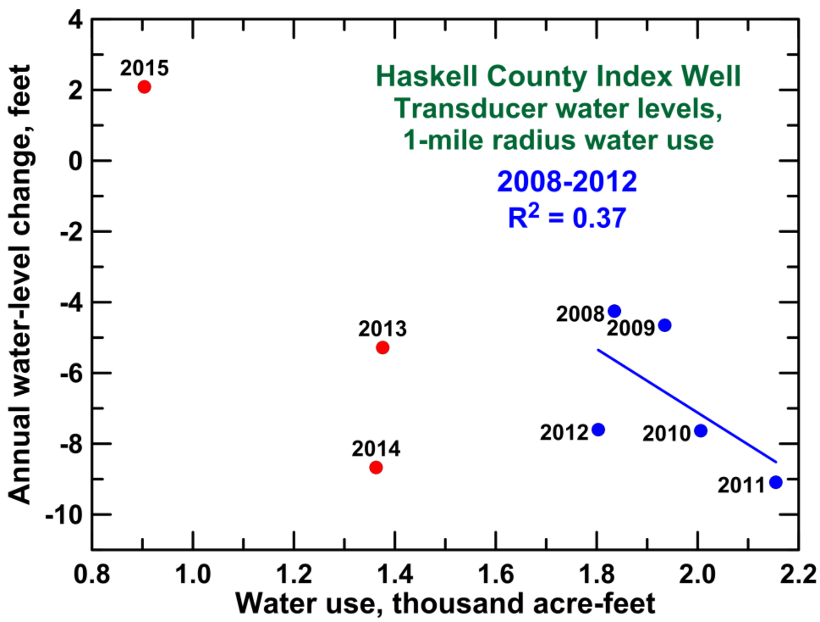

Figure 61—Correlation of annual water-level change based on transducer measurements in the Haskell County index well with annual water use within a 1 mi radius around the well during 2008–2015.

The water use around the Haskell County index well for 2013–2015 is substantially lower than for 2008–2012. The lower use is related to both the court-ordered shutdown of nearby pumping wells described in Section 3.2.2.1 as well as to the greater than average 2008–2015 precipitation that occurred in 2015 and 2016 (see fig. 56). As indicated earlier in this section, the regression for water-level change versus water use is not statistically significant; thus, no computations of reductions required to reach stable water levels were included in table 38 for this well.

Highly statistically significant correlations exist between annual water-level change and annual water use in the vicinity of the Colby and Belpre index wells and the SC-8 expansion well during 2005–2015 (table 39). The graphs for the optimum correlations (those with the highest R^2 for a particular radius of water use) for each well are shown in fig. 62.

The water-level change versus water use regression is only statistically significant for the 1 mi radius of water use around the Colby index well. All or very close to all of the groundwater use within the 3 mi radius of the Thomas, Scott, and Haskell counties, SC-8, and Belpre wells is for irrigation. In contrast, substantial water is pumped for municipal use in the vicinity of the Colby well; the average municipal and irrigation uses are 35% and 65%, respectively, of the total water use within the 1 mi radius circle of the well during 2005–2015. Although the correlation for water-level change and total water use within a 1 mi radius is significant at the P = 0.01 level, the R^2 for the correlation with irrigation water use is only 0.15, whereas the R^2 for municipal use is 0.61. The large range in the municipal use (49 acre-ft in the wet year 2009 to 395 acre-ft in the drought of 2012) in comparison to the small range in irrigation use (288 acre-ft in 2010 to 388 acre-ft in 2013) during 2005–2015 explains these results. This indicates that the municipal water use is also seasonal as is usual for irrigation use to give the significant correlation for total use. The relatively small range in irrigation use, coupled with variability related to other factors than precipitation, result in an insignificant correlation. The R^2 values for correlations with larger radii of irrigation water use around the Colby well increase to about 0.3 by the 3 mi radius and remain at about 0.3 through the 5 mi radius, which is still not statistically significant. This suggests that the timing of the seasonal municipal use may not always coincide closely with that of the irrigation use such that the effects on water-level change could vary somewhat.

Table 38—Coefficients of determination (R^2) and information derived from the regression equations for the correlation of annual water-level changes with groundwater use for the Thomas and Scott counties index wells for 2008–2015. Tape and trans. (transducer) refer to the water-level measurement type. All R^2 values are statistically significant at P = 0.05 or lower except those for the 3 mi radius around the Scott County well.

Index well or parameter	1 mi radius, tape	1 mi radius, trans.	2 mi radius, tape	2 mi radius, trans.	3 mi radius, tape	3 mi radius, trans.	4 mi radius, tape	4 mi radius, trans.	5 mi radius, tape	5 mi radius, trans.
Thomas County well										
R^2	0.72[b]	0.70[b]	0.81[b]	0.80[b]	0.91[a]	0.90[a]	0.89[a]	0.89[a]	0.91[a]	0.91[a]
Pumping reduction for stable water levels, %	25.8	24.5	17.6	16.5	16.4	15.4	19.0	17.7	19.9	18.6
Average water use per area, in	6.37	6.37	4.31	4.31	3.94	3.94	3.44	3.44	3.13	3.13
Stable water use (net inflow), in	4.72	4.81	3.55	3.60	3.29	3.34	2.79	2.83	2.51	2.55
Specific yield	0.159	0.152	0.073	0.070	0.063	0.059	0.063	0.060	0.060	0.057
Scott County well										
R^2	0.65[c]	0.71[b]	0.58[d]	0.67[c]	0.50[d]	0.49[e]	0.63[c]	0.67[c]	0.63[c]	0.65[c]
Pumping reduction for stable water levels, %	30.9	32.0	37.6	37.8	43.7	46.1	34.4	36.1	31.2	33.4
Average water use per area, in	5.84	5.84	5.02	5.02	5.58	5.58	4.49	4.49	4.04	4.04
Stable water use (net inflow), in	4.03	3.97	3.13	3.12	3.14	3.01	2.94	2.87	2.78	2.69
Specific yield	0.167	0.178	0.175	0.180	0.226	0.245	0.143	0.154	0.117	0.128

[a] Significant at P = 0.001
[b] Significant at P = 0.01
[c] Significant at P = 0.02
[d] Significant at P = 0.05
[e] Significant at P = 0.1

Table 39—Coefficients of determination (R^2) and information derived from the regression equations for the correlation of annual water-level changes with groundwater use for the Colby, SC-8, and Belpre wells for 2005–2015. The R^2 and parameters are not shown for other than the 1 mi radius for the Colby well because the regressions are statistically insignificant. Values are also included for 2011–2015 for the 1 mi radius for the SC-8 well.

Index well or parameter	1 mi radius	1 mi radius 2011–2015	2 mi radius	3 mi radius	4 mi radius	5 mi radius
Colby expansion well						
R^2	0.64[b]		0.01	0.13	0.21	0.26
Pumping reduction for stable water levels, %	57.8					
Average water use per area, in	3.04					
Stable water use (net inflow), in	1.28					
Specific yield	0.165					
SC-8 expansion well						
R^2	0.68[b]	0.87[a]	0.42[c]	0.59[b]	0.66[b]	0.46[c]
Pumping reduction for stable water levels, %	31.0	47.5	32.1	19.7	15.4	17.0
Average water use per area, in	4.83	4.83	3.34	3.11	2.68	2.73
Stable water use (net inflow), in	3.33	2.54	2.27	2.50	2.27	2.26
Specific yield	0.178	0.177	0.128	0.073	0.049	0.055
Belpre expansion well						
R^2	0.70[b]		0.74[a]	0.67[b]	0.66[b]	0.66[b]
Pumping reduction for stable water levels, %	4.67		5.23	4.66	4.46	4.44
Average water use per area, in	4.38		3.46	3.88	4.00	3.94
Stable water use (net inflow), in	4.18		3.28	3.70	3.82	3.77
Specific yield	0.064		0.057	0.057	0.056	0.055

[a] Significant at P = 0.001
[b] Significant at P = 0.01
[c] Significant at P = 0.05

The percent reduction required to attain stable water levels (58%) within the 1 mi radius circle of water use at the Colby well based on 2005–2015 data is appreciably greater than for the 1 mi radius for the Thomas County index well (table 38) and also GMD4 (table 37), even though the water-use per area is about half that at the Thomas well (but about twice that of GMD4). The stable water use (1.3 in) for the Colby well is close to that for GMD4 (1.2 in) but much less than that for the 1 mi circle around the Thomas well (4.7–4.8 in). The specific yield for the Colby well is about the same as for the 1 mi radius for the Thomas well, both of which are a little more than twice the specific yield for all of GMD4.

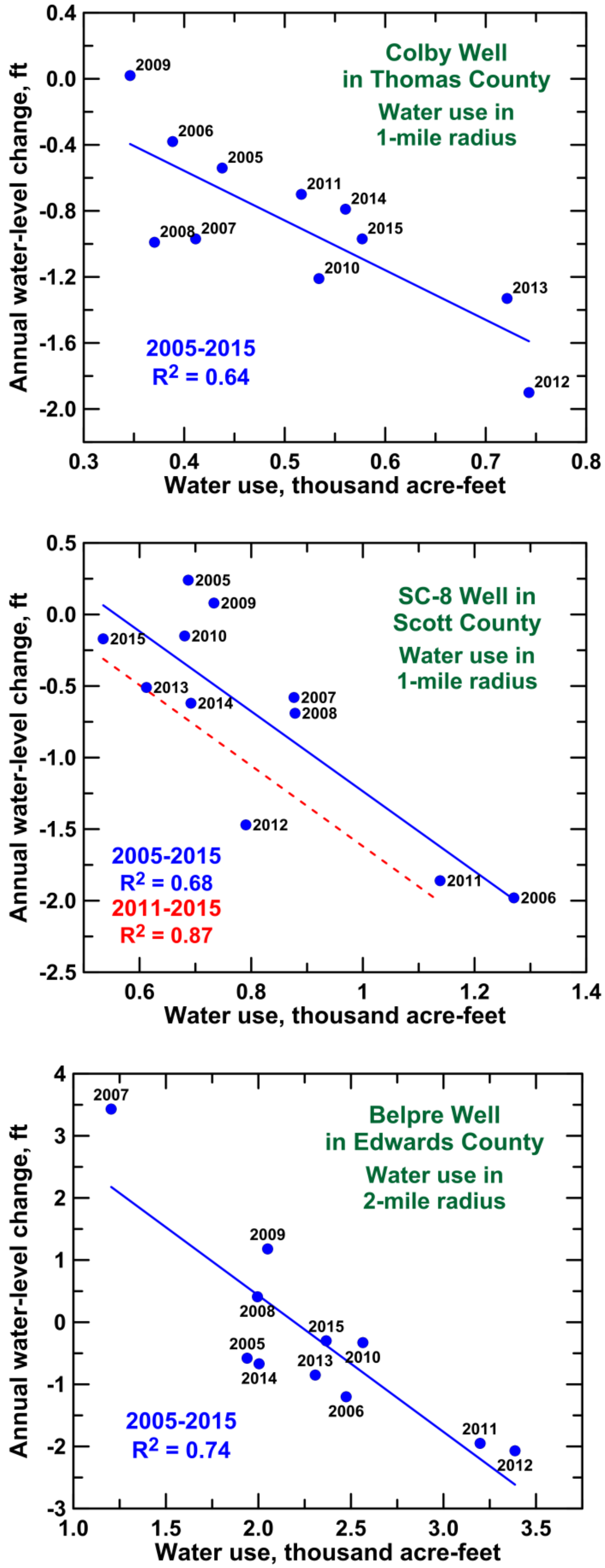

Figure 62—Correlation of annual water-level change in the Colby, SC-8, and Belpre wells with annual water use within a 1 or 2 mi radius around the wells during 2005–2015.

The correlations of water-level change with water use are statistically significant for all 1 to 5 mi radii circles around the SC-8 expansion well (table 39). The highest R^2 is for the 1 mi radius (fig. 62). The pumping reduction to attain stable water levels (31%, table 39) for the 1 mi radius of water use for the SC-8 well is close to the same as for the 1 mi circle for the Scott County index well (31%, table 38), and is a little more than the 27% for all of GMD1 (table 37). The density of water use around the SC-8 well decreases from 4.8 in for the 1 mi circle to 2.7 in for the 4 and 5 mi circles of water use; these values are roughly an inch less than the values at corresponding radii around the Scott County well. The stable water use at the SC-8 well decreases from 3.3 in for the 1 mi radius to 2.3 in for the 4 and 5 mi radii of water use, values approximately 0.5–0.8 in less than for the corresponding radii of water use for the Scott County well but substantially greater than the 1.5 in for all of GMD4. The specific yields for the 1 mi radius around the SC-8 and Scott wells are approximately the same and a little more than twice the specific yield for GMD1. For larger radii around the wells, the specific yield for the SC-8 well decreases to about that of GMD1 for radii of 3 mi and greater, whereas the specific yield for the Scott well is in the range of roughly twice to three times that of GMD1.

The points for 2011–2015 on the plot for the 1 mi radius of water use for well SC-8 in fig. 62 are all shifted to lower water-level change and water-use values than those for 2005–2010. The regression line for the 2011–2015 data (shown as the dashed red line) is parallel to that for the entire period of 2005–2015 (solid blue line). The R^2 for 2011–2015 (0.87) is higher than that for the entire period. Stable water use and specific yield values are also listed in a separate column in table 39 for the 1 mi radius for the SC-8 well. The pumping reduction to attain stable water levels (47%) for 2011–2015 is substantially greater and the stable water use (2.5 in) appreciably less than the values for 2005–2015. The specific yield for both the 2011–2015 and 2005–2015 periods is the same. The results for 2011–2015 suggest that the water-level declines after 2010 might have reduced the inflow to the HPA around the well enough to significantly reduce the stable water use. Another possibility is that the reported water use prior to 2011 may have been greater than actual (Butler, Whittemore, Reboulet, et al., 2016). However, no similar shift in pre-2011 points relative to 2011–2015 points exists for the water-level change versus 1 mi radius water use graph for the Scott County index well.

The water-level change versus water use regressions for 2005–2015 are highly statistically significant for all 1 to 5 mi radii circles around the Belpre index well (table 39). The 2 mi radius circle gives the highest R^2 (fig. 62). Although the density of water use around the Belpre well (3.5–4.4 in, table 39) is in the same general range as for water use at the Thomas and Scott counties (table 38) and Colby and SC-8 (table 39) wells in western Kansas, the pumping reduction needed to attain stable water levels around the Belpre well (4.4%–5.2%) is much smaller. This is caused by the higher aquifer recharge related to greater precipitation, shallower water table, and stream-aquifer interactions in the region of the Belpre well in comparison to the Ogallala portion of the HPA. The pumping reduction for the Belpre well is twice that required for all of GMD5 (table 37). The average water use per area for the 1 mi to 5 mi circles around the Belpre well ranges from about 40% to 80% greater than the average water use in GMD5. The range in the specific yield for the Belpre well decreases slightly from 0.064 for the 1 mi radius to 0.055 for the 5 mi radius of water use, values 2–3 times the specific yield for GMD5. Although the Belpre specific yield for the 1 mi radius is only a third to a half those for the Thomas and Scott counties (table 38) and Colby and SC-8 (table 39) wells in western Kansas, at the 5 mi radius the values for the Thomas County and SC-8 wells are similar to that for the Belpre well.

5.8. Correlation of Annual Water Use with Radar Precipitation

The last two years' index well reports (Butler et al., 2015; Butler, Whittemore, Reboulet, et al., 2016) showed the high correlations between annual groundwater water use and radar precipitation (within selected areas around the index wells) for the Thomas and Scott counties index wells. The February–October sum of radar precipitation was used for the correlations for last year's report to compare to correlations with the nine-month October SPI computed for the index well location, although correlations using the January–December (annual) sum of radar precipitation were also examined to determine the change in the correlations with a different monthly sum. Updates of the correlations for 2008–2015 are listed in table 40 based on the optimum R^2 obtained by varying the range and number of months for which the radar precipitation was summed as well as comparing the results for the nearest point and the spatial mean of the nine-point block of radar precipitation values around the well (the nearest radar point was only compared to the nine-point mean for the 1 and 2 mi radii). For 2008–2015, additional areas (3 mi and 4 mi radii) for water use around all except the Haskell County index well were included to more fully determine the effect of the water use area on the correlation than for only the 1, 2, and 5 mi radii used previously.

The correlations are highly statistically significant for at least two or more radii of water use for all of the six wells listed in table 40. The highest R^2 value (0.92), for the Thomas County index well, is for the 2 mi radius circle of water use and the nearest point of April–August radar precipitation (fig. 63), although the nine-point mean of March–October precipitation for the 3 mi radius gave nearly the same R^2. The R^2 values generally increase with increasing radii around the Scott County well; the highest correlation (R^2 = 0.85) is for the 5 mi radius and the April–September sum of precipitation (fig. 63). As the radius increases around the Scott well, the amount of municipal pumping included in the area increases, although it is still a minor percentage relative to the irrigation use. The 2012–2015 water use within the 1 mi radius around the Haskell County index well was affected by non-typical variations in pumping and an impairment complaint as explained earlier in this report. Thus, the regression line for the 1 mi radius shown in fig. 63 and listed in table 40 is only for 2008–2012; points for 2013–2015 are shown as separate symbols to display the deviation from the regression line for 2008–2012. For larger radii of water use, the substantial local pumping effects on the correlation become smaller such that the 2 and 5 mi radii circle use correlations are highly significant.

The correlations of total water use and radar precipitation around the Colby well are low, although significant at the P = 0.05 level, for the 1 and 2 mi radii (table 40), possibly as a result of the somewhat different timing of municipal and irrigation water use during each year near the well as described previously. At the greater distance of 3 or more miles around the well, the municipal use becomes a relatively small component of the total water use, such that the irrigation use dominates and the correlation with total use becomes highly significant (R^2 = 0.87 for the 5 mi radius and March–October sum of precipitation, fig. 64). The optimum correlations between radar precipitation and irrigation water use at the Colby well for the 1 and 2 mi radii (R^2 = 0.39 and 0.40, respectively) are about the same as for municipal water use. The highest R^2 values for precipitation versus irrigation water use at the 3, 4, and 5 mile radii (0.96, 0.90, and 0.90, respectively) are greater than for total water use.

The correlations of water use and radar precipitation around the SC-8 well are also low for the 1 and 2 mi radii even though all the water use in these circles is for irrigation. Although the 3 mi to 5 mi radii around the SC-8 well include an increasing, although relatively small, amount of municipal use compared to irrigation pumping, the R^2 increases to 0.64 for both the 4 (fig. 64) and 5 mi radii of water use and February–September precipitation sum. The reason for the low correlation for the 1 and 2 mi radii for the SC-8 well could be related to the smaller irrigation water use around the well in comparison with the other wells (except the Colby well), such that variations in annual use by individual farmers based on year-to-year changes in irrigation practices could introduce more uncertainty into the use and precipitation correlation. The correlations for the Belpre well are highly statistically significant for all of the 1 to 5 mi radii of water use; the highest R^2 (0.87) is for the 5 mi radius and February–October precipitation sum (fig. 64). This suggests relatively consistent irrigation use in time and space across the area around the well relative to climatic conditions.

The monthly sums of precipitation giving the optimum correlation for water use and radar precipitation for the six wells listed in table 40 range from as low as a 5-month span for the Thomas County well (2 mi radius of water use) to an annual span for the 1 to 5 mi radii for the Haskell County well. All of the monthly sums giving the highest R^2 values for the six wells encompass the common period of irrigation water use from spring through the summer. However, the fact that the optimum correlations often start in February and end in October indicates that pre-irrigation to add to soil moisture and late season irrigation are important enough to affect the correlations. The optimum of annual precipitation for the Haskell well suggests that winter irrigation may also be important enough to affect the results, which is in keeping with the frequently observed late fall pumping periods in the vicinity of the Haskell index well (fig. 13).

Table 40—Optimum coefficient of determination (R^2) for correlations of annual total groundwater use around the Thomas, Scott, and Haskell counties and Colby and Belpre index and SC-8 expansion wells with the sum of monthly radar precipitation centered on the well. Data periods are 2008–2015 for the county index wells except for 2008–2012 for the 1 mi radius for the Haskell County well, and 2005–2015 for the Colby, SC-8, and Belpre wells.

Index or expansion well	Period	Water use radius, mi	Radar point block	Precipitation month sum	R^2
Thomas County well	2008–2015	1	9-point mean	Mar–Oct	0.79[b]
	2008–2015	2	Nearest point	Apr–Aug	0.92[a]
	2008–2015	3	9-point mean	Mar–Oct	0.91[a]
	2008–2015	4	9-point mean	Mar–Oct	0.87[a]
	2008–2015	5	9-point mean	Mar–Oct	0.88[a]
Scott County well	2008–2015	1	Nearest point	Mar–Nov	0.58[d]
	2008–2015	2	Nearest point	Mar–Aug	0.63[c]
	2008–2015	3	9-point mean	Feb–Sep	0.62[d]
	2008–2015	4	9-point mean	Feb–Sep	0.74[b]
	2008–2015	5	9-point mean	Apr–Sep	0.85[b]
Haskell County well	2008–2012	1	Nearest point	Jan–Dec	0.72[e]
	2008–2015	2	Nearest point	Jan–Dec	0.71[b]
	2008–2015	5	9-point mean	Jan–Dec	0.77[b]
Colby well	2005–2015	1	9-point mean	Mar–Dec	0.42[d]
	2005–2015	2	9-point mean	Apr–Sep	0.40[d]
	2005–2015	3	9-point mean	May–Sep	0.75[a]
	2005–2015	4	9-point mean	Apr–Sep	0.84[a]
	2005–2015	5	9-point mean	Mar–Oct	0.87[a]
SC-8 well	2005–2015	1	Nearest point	Feb–Sep	0.28[e]
	2005–2015	2	Nearest point	Feb–Sep	0.29[e]
	2005–2015	3	9-point mean	Feb–Sep	0.51[c]
	2005–2015	4	9-point mean	Feb–Sep	0.64[b]
	2005–2015	5	9-point mean	Feb–Sep	0.64[b]
Belpre well	2005–2015	1	Nearest point	Feb–Oct	0.76[a]
	2005–2015	2	9-point mean	Jan–Oct	0.80[a]
	2005–2015	3	9-point mean	Jan–Oct	0.86[a]
	2005–2015	4	9-point mean	Feb–Oct	0.85[a]
	2005–2015	5	9-point mean	Feb–Oct	0.87[a]

[a] Significant at P = 0.001
[b] Significant at P = 0.01
[c] Significant at P = 0.02
[d] Significant at P = 0.05
[e] Significant at P = 0.1

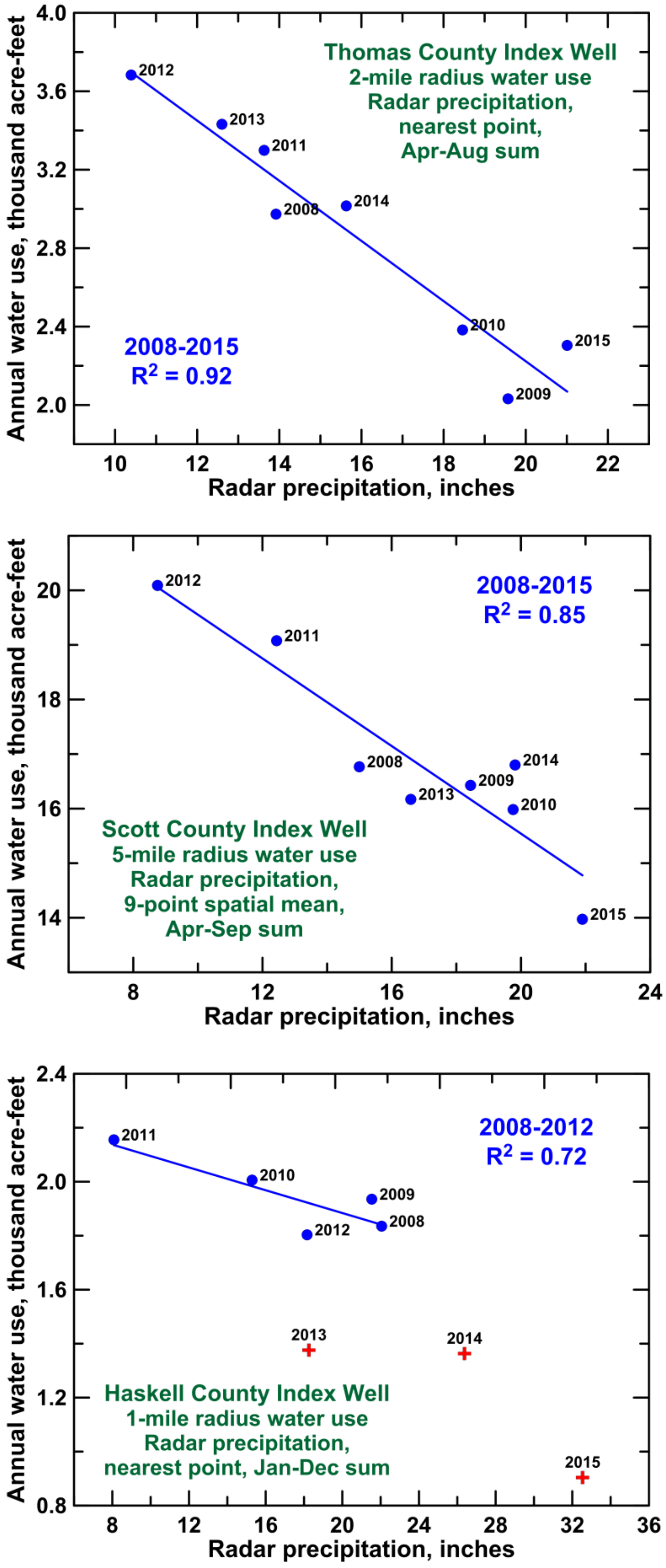

Figure 63—Correlation of annual total groundwater use with radar precipitation at the Thomas, Scott, and Haskell counties index wells for 2008–2015.

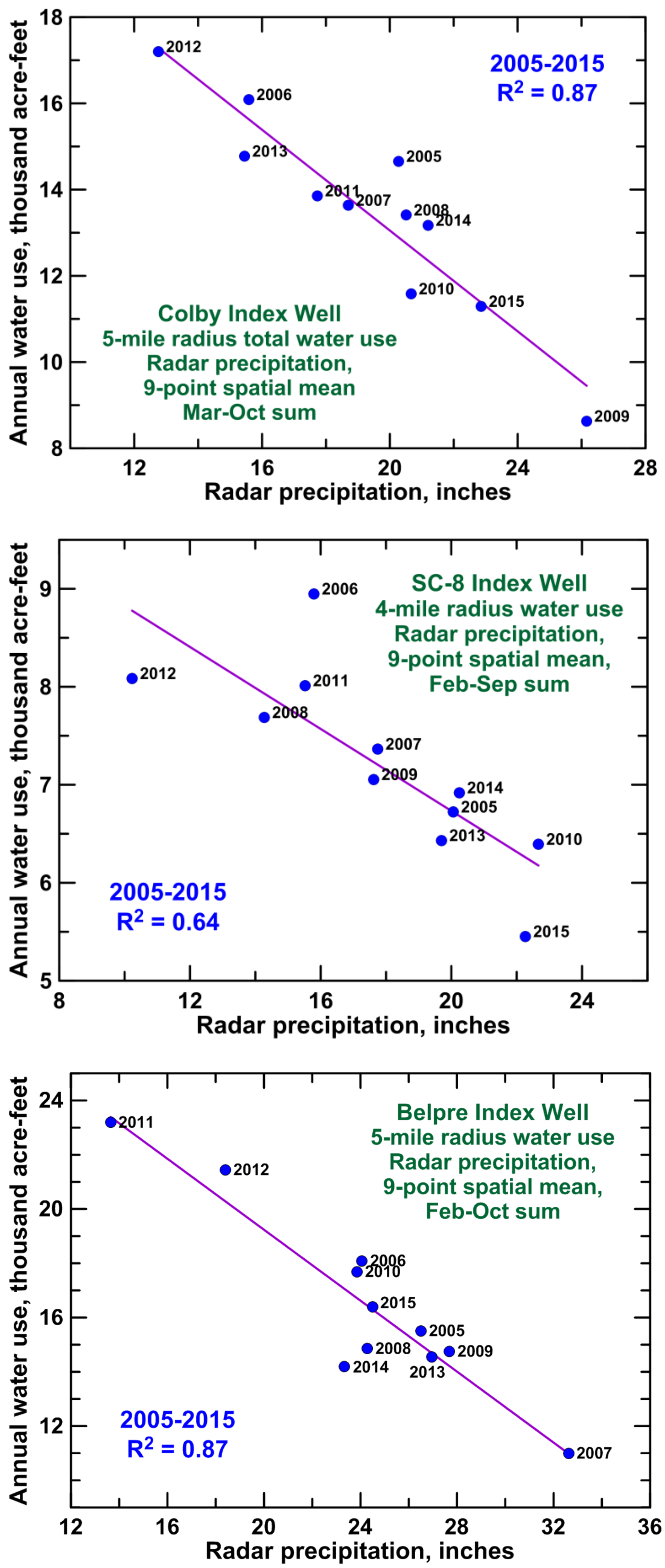

Figure 64—Correlation of annual total groundwater use with radar precipitation at the Colby, SC-8, and Belpre wells for 2005–2015.

6. Summary of 2016 Accomplishments and Plans for 2017

6.1. 2016 Accomplishments

- Continued collection and processing of data. Telemetered data from the original three index wells have continued to be served on the web, and downloads have been used for analysis and presentations. Data collection and analysis from the Thomas and Scott expansion wells have continued.
- Continued collection and processing of data from the index wells along the Kansas-Oklahoma border (border wells). Telemetered data from two wells at the Hugoton site and two wells at the Liberal site continued to be served on the web. Downloads from all wells have been used for analysis and presentations.
- Continued collection and processing of data from the two index wells (Colby and Belpre) added to the network in 2014. Telemetered data from these wells is now served on the web. Downloads from the wells have been used for analysis and presentations.
- Continued collection and processing of data from the five monitoring wells in the Sheridan-6 LEMA added to the network in 2014. Sensors are being manually downloaded quarterly. Downloads from the wells have been used for analysis and presentations. Telemetry equipment was installed in one of these wells (Seegmiller index well) in 2016.
- Assessed the hydrographs from the DWR monitoring wells in the vicinity of the Haskell index well.
- Installed sensors and telemetry equipment and initiated monitoring at the three new index wells drilled in GMD1 in the spring of 2016.
- Drilled one new index well southwest of Goodland in GMD4; sensor and telemetry equipment will be installed in the spring of 2017.
- Installed sensor and telemetry equipment and initiated monitoring at an existing well on the Willis Water Technology Farm in southern Finney County.
- Installed sensors and initiated monitoring at the five new GMD1 expansion wells; monitoring is expected to begin at a sixth well in the spring of 2016.
- Continued detailed analysis of hydrographs at all three original index well sites.
- Continued assessment of the information that can be acquired from an analysis of the water-level response to changes in barometric pressure.
- Continued comparison of transducer data with the results of the annual water-level network measurements.
- Continued analysis of climatic indices and their relationship to annual water-level changes measured at the index well and across the western three GMDs.
- Continued an analysis of the utility of 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 in the three western GMDs.

- Assessed relationship between annual water-level change and annual water use at the Thomas, Scott, and Haskell counties and Colby and Belpre index and SC-8 expansion wells and compared to the relationships for the GMDs.
- Continued integration of program data into the digital Kansas High Plains Aquifer Atlas (Fross et al., 2012).
- Gave presentations about the index well program to KWO, DWR, and GMD personnel, among others.

6.2. *Planned Activities, 2017*

- Continue monitoring and processing water-level data from the three original index wells and the expansion wells in their vicinity, the border index wells, the Colby and Belpre index wells, the Sheridan-6 index wells, the new GMD1 index wells, the Willis Water Technology Farm index well, and the five new GMD1 expansion wells.
- Continue detailed analysis of hydrographs from the three original index wells and the expansion wells in their vicinity, the border index wells, the Colby and Belpre index wells, the Sheridan-6 index wells, the new GMD1 index wells, and the Willis Water Technology Farm index well.
- Install sensor and telemetry equipment and initiate monitoring at the new index well drilled in GMD4 in the late fall of 2016.
- Install sensor and initiate monitoring at the sixth new GMD1 expansion well.
- Assess recovery and pumping for 2016 and 2017 periods.
- Install sensor and telemetry equipment and initiate monitoring at an existing well northwest of Garden City in GMD3.
- Continue to seek new wells to add to the network.
- Continue interpretation of geochemical results to assess age(s) and source(s) of groundwater in the vicinity of each index well.
- If possible, collect and analyze water samples from irrigation wells in the vicinity of all of the index wells.
- Continue progression toward improving end-user capabilities for broader implementation of the index well program.
- 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 at the index and expansion wells and compare to relationships for the GMDs.
- Integrate information from drillers' logs in the vicinity of the Thomas and Scott index wells into interpretation of water-level responses in those areas.

6.3. Outstanding Issues

Major unresolved issues include the following:

- The source and areal extent of the inflow, which is greater than that expected from estimates of precipitation recharge, in the vicinity of the Thomas County index well.
- Possibility of similar inflow occurring in the vicinity of the SD-6 and Colby index wells in GMD4, as well as at other index wells in western Kansas for which water-level change and water use relationships are significant.
- Conditions in the HPA at the Scott County site; understanding is still incomplete but similar inflow may also be occurring in that vicinity.
- Relationship between the Dakota aquifer and the HPA in southwestern Kansas.

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8. Appendix A: WWC-5 Forms for New GMD3 and GMD4 Index Wells

8.1. New GMD3 Index Well

Willis Technology Farm Index Well – fraction entry is incorrect – should be NW¼, NW¼, NE¼

WATER WELL RECORD **Form WWC-5** 1212864 Division of Water Resources App. No. 34371 Well ID

☑ Original Record ☐ Correction ☐ Change in Well Use

1 LOCATION OF WATER WELL: County: Finney | Fraction: SE¼ SW¼ SW¼ NE¼ | Section Number: 20 | Township Number: T 26 S | Range Number: R 33 ☐ E ☑ W

2 WELL OWNER: Last Name: First:
Business: T & O LLC
Address: 300 N Lincoln Ave
Address:
City: Liberal State: KS ZIP: 67901

Street or Rural Address where well is located (if unknown, distance and direction from nearest town or intersection): If at owner's address, check here: ☐
At intersection of Plymell rd & Highway 83: S on highway 83 for 2 miles to TV rd; W 4 miles to sandhill rd; S 1/3 mi to field rd.

3 LOCATE WELL WITH "X" IN SECTION BOX: N, W, E, S; NW, NE (X), SW, SE; |----------1 mile---------|

4 DEPTH OF COMPLETED WELL: 532 ft.
Depth(s) Groundwater Encountered: 1) 299 ft. 2) .... ft. 3) .... ft., or 4) ☐ Dry Well
WELL'S STATIC WATER LEVEL: 299 ft.
☑ below land surface, measured on (mo-day-yr) 5/22/2014
☐ above land surface, measured on (mo-day-yr)..........
Pump test data: Well water was 347 ft. after 4 hours pumping 522 gpm
Well water was .... ft. after .... hours pumping .... gpm
Estimated Yield: 522 gpm
Bore Hole Diameter: 24 in. to 532 ft. and .... in. to .... ft.

5 Latitude: 37.77380 (decimal degrees)
Longitude: 100.951107 (decimal degrees)
Datum: ☐ WGS 84 ☐ NAD 83 ☑ NAD 27
Source for Latitude/Longitude:
☐ GPS (unit make/model: ....) (WAAS enabled? ☐ Yes ☐ No)
☐ Land Survey ☐ Topographic Map
☐ Online Mapper: ....

6 Elevation: 2939 ft. ☑ Ground Level ☐ TOC
Source: ☐ Land Survey ☑ GPS ☐ Topographic Map
☐ Other ....

7 WELL WATER TO BE USED AS:
1. Domestic: ☐ Household ☐ Lawn & Garden ☐ Livestock
2. ☑ Irrigation
3. ☐ Feedlot
4. ☐ Industrial
5. ☐ Public Water Supply: well ID ....
6. ☐ Dewatering: how many wells? ....
7. ☐ Aquifer Recharge: well ID ....
8. ☐ Monitoring: well ID ....
9. Environmental Remediation: well ID .... ☐ Air Sparge ☐ Soil Vapor Extraction ☐ Recovery ☐ Injection
10. ☐ Oil Field Water Supply: lease ....
11. Test Hole: well ID .... ☐ Cased ☐ Uncased ☐ Geotechnical
12. Geothermal: how many bores? .... a) Closed Loop ☐ Horizontal ☐ Vertical b) Open Loop ☐ Surface Discharge ☐ Inj. of Water
13. ☐ Other (specify): ....

Was a chemical/bacteriological sample submitted to KDHE? ☐ Yes ☑ No If yes, date sample was submitted: ....
Water well disinfected? ☑ Yes ☐ No

8 TYPE OF CASING USED: ☑ Steel ☐ PVC ☐ Other .... CASING JOINTS: ☐ Glued ☐ Clamped ☑ Welded ☐ Threaded
Casing diameter 16 in. to 532 ft., Diameter .... in. to .... ft., Diameter .... in. to .... ft.
Casing height above land surface 12 in. Weight 42.09 lbs./ft. Wall thickness or gauge No. .250
TYPE OF SCREEN OR PERFORATION MATERIAL:
☑ Steel ☐ Stainless Steel ☐ Fiberglass ☐ PVC ☐ Other (Specify) ....
☐ Brass ☐ Galvanized Steel ☐ Concrete tile ☐ None used (open hole)
SCREEN OR PERFORATION OPENINGS ARE:
☐ Continuous Slot ☑ Mill Slot ☐ Gauze Wrapped ☐ Torch Cut ☐ Drilled Holes ☐ Other (Specify) ....
☐ Louvered Shutter ☐ Key Punched ☐ Wire Wrapped ☐ Saw Cut ☐ None (Open Hole)
SCREEN-PERFORATED INTERVALS: From 262 ft. to 482 ft., From .... ft. to .... ft., From .... ft. to .... ft.
GRAVEL PACK INTERVALS: From 20 ft. to 448 ft., From 448 ft. to 532 ft., From .... ft. to .... ft.

9 GROUT MATERIAL: ☐ Neat cement ☐ Cement grout ☑ Bentonite ☐ Other ....
Grout Intervals: From 0 ft. to 20 ft., From .... ft. to .... ft., From .... ft. to .... ft.
Nearest source of possible contamination:
☐ Septic Tank ☐ Lateral Lines ☐ Pit Privy ☐ Livestock Pens ☐ Insecticide Storage
☐ Sewer Lines ☐ Cess Pool ☐ Sewage Lagoon ☐ Fuel Storage ☐ Abandoned Water Well
☐ Watertight Sewer Lines ☐ Seepage Pit ☐ Feedyard ☐ Fertilizer Storage ☐ Oil Well/Gas Well
☐ Other (Specify) ....
Direction from well? .... Distance from well? .... ft.

10 FROM	TO	LITHOLOGIC LOG	FROM	TO	LITHO. LOG (cont.) or PLUGGING INTERVALS
0	3	top soil	326	352	fine to med sand
3	51	tan sticky clay	352	438	tan sticky clay, few sugars and streaks
51	126	medium coarse sand, little gravel	438	482	very fine sugar sand, clay streaks
126	238	fine to coarse sand, clay streaks	482	501	tight tan sticky clay, brown and clack rock
238	262	black shale	501	512	tan sticky clay
262	274	black sand fine to med, black shale streak	512	540	grey shale
274	281	fine to med sand, clay streaks	**Notes:**		
281	302	fine to coarse sand, clay streaks			
302	326	tan sticky clay			

11 CONTRACTOR'S OR LANDOWNER'S CERTIFICATION: This water well was ☑ constructed, ☐ reconstructed, or ☐ plugged under my jurisdiction and was completed on (mo-day-year) 5/20/2014 and this record is true to the best of my knowledge and belief. Kansas Water Well Contractor's License No. 145 This Water Well Record was completed on (mo-day-year) 7/2/2014 under the business name of Hydro Resources Mid Continent, Inc.

Send one copy to WATER WELL OWNER and retain one for your records. Fee of $5.00 for each constructed well.
KS Department of Health and Environment, Bureau of Water, Geology Section, 1000 SW Jackson St., Suite 420, Topeka, Kansas 66612-1367. Telephone 785-296-3565.
Visit us at http://www.kdheks.gov/waterwell/index.html KSA 82a-1212

8.2. *New GMD4 Index Well*

Sherman County Index Well

WATER WELL RECORD Form WWC-5

☑ Original Record ☐ Correction ☐ Change in Well Use

Division of Water Resources App. No. ____

Well ID: SH Co Index

1 LOCATION OF WATER WELL: County: Sherman

Fraction: NE ¼ NE ¼ NE ¼ SE ¼ | Section Number: 1 | Township Number: T 10 S | Range Number: R 41 ☐ E ☑ W

2 WELL OWNER: Last Name: First:
Business: University of Kansas
Address: 1246 W Campus Rd, Room 20
Address:
City: Lawrence State: Ks ZIP: 66045

Street or Rural Address where well is located (if unknown, distance and direction from nearest town or intersection): If at owner's address, check here: ☐
At road 57 and Highway 27 in Sherman County: west on road 57 for 6 miles to Road 13. South 1.5 miles to drill location on the

3 LOCATE WELL WITH "X" IN SECTION BOX:
N
-- NW -- | -- NE --
W | X E
-- SW -- | -- SE --
S
|--------1 mile--------|

4 DEPTH OF COMPLETED WELL: 335 ft.
Depth(s) Groundwater Encountered: 1) 170 ft. 2) .... ft. 3) .... ft., or 4) ☐ Dry Well
WELL'S STATIC WATER LEVEL: 170 ft.
☑ below land surface, measured on (mo-day-yr) 12/6/2016
☐ above land surface, measured on (mo-day-yr) ....
Pump test data: Well water was .... ft. after .... hours pumping .... gpm
Well water was .... ft. after .... hours pumping .... gpm
Estimated Yield: .... gpm
Bore Hole Diameter: 9.875 in. to 335 ft. and .... in. to .... ft.

5 Latitude: 39.212321 (decimal degrees)
Longitude: 101.838546 (decimal degrees)
Datum: ☐ WGS 84 ☐ NAD 83 ☑ NAD 27
Source for Latitude/Longitude:
☐ GPS (unit make/model: ....) (WAAS enabled? ☐ Yes ☐ No)
☐ Land Survey ☐ Topographic Map
☐ Online Mapper: ....

6 Elevation: 3794 ft. ☑ Ground Level ☐ TOC
Source: ☐ Land Survey ☑ GPS ☐ Topographic Map ☐ Other ....

7 WELL WATER TO BE USED AS:
1. Domestic: ☐ Household ☐ Lawn & Garden ☐ Livestock
2. ☐ Irrigation
3. ☐ Feedlot
4. ☐ Industrial
5. ☐ Public Water Supply: well ID ....
6. ☐ Dewatering: how many wells? ....
7. ☐ Aquifer Recharge: well ID ....
8. ☑ Monitoring: well ID SH Co Index Well
9. Environmental Remediation: well ID .... ☐ Air Sparge ☐ Soil Vapor Extraction ☐ Recovery ☐ Injection
10. ☐ Oil Field Water Supply: lease ....
11. Test Hole: well ID .... ☐ Cased ☐ Uncased ☐ Geotechnical
12. Geothermal: how many bores? .... a) Closed Loop ☐ Horizontal ☐ Vertical b) Open Loop ☐ Surface Discharge ☐ Inj. of Water
13. ☐ Other (specify): ....

Was a chemical/bacteriological sample submitted to KDHE? ☐ Yes ☑ No If yes, date sample was submitted: ....
Water well disinfected? ☑ Yes ☐ No

8 TYPE OF CASING USED: ☐ Steel ☑ PVC ☐ Other .... CASING JOINTS: ☐ Glued ☐ Clamped ☐ Welded ☑ Threaded
Casing diameter 2.5 in. to 335 ft., Diameter .... in. to .... ft., Diameter .... in. to .... ft.
Casing height above land surface 2 in. Weight 1.45 lbs./ft. Wall thickness or gauge No. 0.276
TYPE OF SCREEN OR PERFORATION MATERIAL:
☐ Steel ☐ Stainless Steel ☐ Fiberglass ☑ PVC ☐ Other (Specify) ....
☐ Brass ☐ Galvanized Steel ☐ Concrete tile ☐ None used (open hole)
SCREEN OR PERFORATION OPENINGS ARE:
☐ Continuous Slot ☑ Mill Slot ☐ Gauze Wrapped ☐ Torch Cut ☐ Drilled Holes ☐ Other (Specify) ....
☐ Louvered Shutter ☐ Key Punched ☐ Wire Wrapped ☐ Saw Cut ☐ None (Open Hole)
SCREEN-PERFORATED INTERVALS: From 310 ft. to 320 ft., From .... ft. to .... ft., From .... ft. to .... ft.
GRAVEL PACK INTERVALS: From 300 ft. to 330 ft., From .... ft. to .... ft., From .... ft. to .... ft.

9 GROUT MATERIAL: ☐ Neat cement ☐ Cement grout ☑ Bentonite ☐ Other ....
Grout Intervals: From 0 ft. to 20 ft., From .... ft. to .... ft., From .... ft. to .... ft.
Nearest source of possible contamination:
☐ Septic Tank ☐ Lateral Lines ☐ Pit Privy ☐ Livestock Pens ☐ Insecticide Storage
☐ Sewer Lines ☐ Cess Pool ☐ Sewage Lagoon ☐ Fuel Storage ☐ Abandoned Water Well
☐ Watertight Sewer Lines ☐ Seepage Pit ☐ Feedyard ☐ Fertilizer Storage ☐ Oil Well/Gas Well
☐ Other (Specify) ....
Direction from well? .... Distance from well? .... ft.

10 FROM	TO	LITHOLOGIC LOG	FROM	TO	LITHO. LOG (cont.) or PLUGGING INTERVALS
0	2	surface			
2	50	brown clay, few sands			
50	100	sand fine to med coarse small gravel som			
100	155	sand fine to med coarse small rock, clay n			
155	205	brown sandy clay			
205	280	brown clay, few sands			
280	300	brown sandy clay	Notes:		
300	323	sand fine to med clay mix			
323	335	ochre			

11 CONTRACTOR'S OR LANDOWNER'S CERTIFICATION: This water well was ☑ constructed, ☐ reconstructed, or ☐ plugged under my jurisdiction and was completed on (mo-day-year) 12/16/2016 and this record is true to the best of my knowledge and belief. Kansas Water Well Contractor's License No. 145 This Water Well Record was completed on (mo-day-year) 2/15/2017 under the business name of Hydro Resources Mid Continent, Inc.

Send one copy to WATER WELL OWNER and retain one for your records. Fee of $5.00 for each constructed well.
KS Department of Health and Environment, Bureau of Water, Geology Section, 1000 SW Jackson St., Suite 420, Topeka, Kansas 66612-1367. Telephone 785-296-3565.
Visit us at http://www.kdheks.gov/waterwell/index.html KSA 82a-1212