Kansas Geological Survey

High Plains Aquifer Index Well Program:
2015 Annual Report

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Drill Rig at Wallace County Index Well Site

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Acknowledgments

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Executive Summary

The index well program is directed at developing improved approaches for measuring and interpreting hydrologic responses at the local (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 for continuous monitoring of water levels 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 eight full recovery and pumping seasons and one ongoing 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 early spring of 2016, three new index wells were drilled in GMD1; telemetry equipment will be installed in these wells in June 2016.

This report provides a description of conditions as of late winter to early spring of 2016. The report consists of (a) an update of the hydrographs for the original three index wells, the new index wells (border wells, the Colby well, the Belpre well, and the five SD-6 LEMA wells), and additional wells (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 the original three index wells, the border wells, and the newer index wells; (c) a discussion of the installation of the three new index wells in GMD1; (d) a discussion of climatic indices and radar precipitation data and their relationship to annual water-level changes at the original three index wells and to water use in the vicinity of those wells; (e) a discussion of further development of the theoretical support for the linear annual water use versus annual water-level change relationship; and (f) a discussion of the results of chemical analyses of groundwater samples obtained from the SD-6 LEMA wells.

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

(1) Water-level data collected using a pressure transducer and data logger provide a near-continuous record of great practical value that can help in the assessment of the continued viability of the HPA as a source of water for large-scale irrigation.
(2) Interpretation of index well hydrographs 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) Under certain conditions, the annual water-level measurement network data, in conjunction with reliable water-use data, can be used to predict the near-term (fewer than 10 to 15 years) impact of management decisions using a new approach developed as part of this program.
(6) Additional measurements at nearby wells help establish the generality of the conclusions that can be obtained from interpretation of index well hydrographs.
(7) Local hydrogeologic variations and well construction need to be assessed and considered in the interpretation of well hydrographs for the most effective use of wells of opportunity.

The focus of project activities in 2016 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 three new index wells in GMD1; drilling of additional index wells at sites to be determined; further assessment of the relationships among climatic indices, radar precipitation data, annual water-level change, and water use; further exploration of the linear water use versus annual water-level change relationship; further interpretation of geochemical results of analyses of water samples from the vicinity of the index wells; continued assessment of the subsurface information that can be acquired from an analysis of the water-level response to changes in barometric pressure; 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 have resulted in large water-level declines in the Ogallala–High Plains aquifer (henceforth, High Plains aquifer or HPA) in Kansas that call into question the viability of the aquifer as a continuing resource for irrigated agriculture (Butler, Stotler, et al., 2013; Buchanan et al., 2015). The index well program (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 impact 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 project 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. The approach outlined by this study aims to provide more accurate and timely information at the subunit scale than is provided by the annual water-level measurement program. Furthermore, this study provides data that are valuable for the interpretation of the water-level change estimates from the annual measurement program and are the basis for the development of new methods for using the annual program measurements.

At the time of this report, monitoring data (hourly frequency) from eight full recovery and pumping seasons and one ongoing or completed, depending on location, recovery season have been obtained. With increasing data, the index well program has demonstrated the following:

(1) Water-level data collected using a pressure transducer and data logger provide a near-continuous record of great practical value that can help in the assessment of the continued viability of the HPA as a source of water for large-scale irrigation.

(2) Interpretation of index well hydrographs 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) Under certain conditions, the annual water-level measurement network data, in conjunction with reliable water-use data, can be used to evaluate the impact of management decisions using a new approach developed as part of this program.

(6) Additional measurements at nearby wells help establish the generality of the conclusions that can be obtained from interpretation of index well hydrographs.

(7) Local hydrogeologic variations and well construction need to be assessed and considered in the interpretation of well hydrographs for the most effective use of wells of opportunity.

In addition, the index well program has inspired the development of new methods that use the annual measurement program data to predict the effect of management decisions on the subunit and larger scale.

The index well network was enlarged in the early spring of 2016 by the drilling of three new wells in Lane, Wichita, and Wallace counties in GMD1. Note that the term "index well" is used here to designate a well at which monitoring is anticipated to continue for many years. There are additional wells, designated here as "expansion wells," at which monitoring is not likely to continue over the long term because of constraints imposed by well depth (i.e., water level is anticipated to drop below the bottom of the well screen) 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 to early spring of 2016. The report consists of (a) an update of the hydrographs for the original three index wells, the new index wells (border wells, the Colby well, the Belpre well, and the five SD-6 LEMA wells), and 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 the original three index wells, the border wells, and the newer index wells; (c) a discussion of the installation of the three new index wells in GMD1; (d) a discussion of climatic indices and radar precipitation data and their relationship to annual water-level changes at the original three index wells and to water use in the vicinity of those wells; (e) a discussion of further development of the theoretical support for the linear annual water use versus annual water-level change relationship; and (f) a discussion of the results of chemical analyses of groundwater samples obtained from the SD-6 LEMA wells.

2. Setting and Experimental Design

The foundation of this project consists of three transducer-equipped wells, designed and sited to function as HPA monitoring wells, installed 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 ongoing studies (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 expanded to also focus on the mechanisms that control changes in water level in the vicinity of each well. To establish the generality of the conclusions obtained from the index wells, the project was expanded to include "wells of opportunity" or "expansion wells" in the vicinity of the original three index wells:

1. Haskell County expansion—with the collaboration of the DWR, the project obtained access to water-level records from additional wells in the vicinity of the Haskell index well that are instrumented by the DWR; this provides an opportunity for more extensive comparisons over a relatively short distance (Section 3.2.8). However, the fact that the producing wells at the Haskell site may draw on and measure either or both of two separate aquifer units makes it more complicated than the commonly adopted view of the HPA as a single unconfined aquifer (see Butler, Stotler, et al., 2013).
2. Scott County expansion—early in 2012, with the assistance of GMD1, two additional expansion wells in the vicinity of the Scott County index well were equipped with transducers, and monitoring is continuing at one of these wells (Section 3.2.6). The commonly adopted view of the HPA as a single unconfined aquifer appears reasonable in the vicinity of the Scott County site.
3. Thomas County expansion—with the collaboration of the DWR and GMD4, six additional wells (two of which are annual program wells) were equipped with transducers. Continuous monitoring is ongoing at three of these additional wells (Section 3.2.7). The commonly adopted view of the HPA as a single unconfined aquifer appears reasonable in the vicinity of the Thomas County site.

Site characteristics are described and discussed in more detail in previous annual reports (Young et al., 2007, 2008; Buddemeier et al., 2010) but are briefly summarized below and in table 1. The three original index well sites are located, south to north, in Haskell, Scott, and Thomas counties.

The Haskell County site represents the most complex set of conditions. It is located over a relatively steeply sloping section of the bedrock surface underlying the High Plains aquifer and along a gradient in both water use and availability. Although the saturated thickness is large, the thickness of intervals that readily yield water is much less. As a result, well yields have decreased over time and, in the spring of 2012, a lawsuit was filed to curtail pumping by some junior water rights holders. In May 2013 and again in May 2014, two pumping wells were shut down by court order; that order is continuing to be in effect at the time of this report. It appears that a two-aquifer system exists: an unconfined upper aquifer zone that is nearly depleted and a thin but productive confined aquifer zone on top of bedrock with a thick clay layer separating the two. The index well was installed to sample only the lower confined aquifer zone near the site of a previous impairment complaint related to the current lawsuit; DWR has installed transducers in a number of nearby wells screened in one or both aquifer zones, and these wells have been used by this project in past years. The Haskell County site is in an area of greater saturated thickness than the other sites but with a much more rapid rate of water-level decline. The water use in the vicinity of the Haskell site is much greater than that at either the Scott or Thomas sites. Based on a detailed analysis of the Haskell index well hydrograph and the hydrographs of the additional DWR wells in that vicinity presented in the 2011 annual report (Butler et al., 2012) and a published journal article based on that report (Butler, Stotler, et al., 2013), it is doubtful that large-scale irrigation withdrawals from the High Plains aquifer near the Haskell County site can be sustained at the rate of pumping before the court-ordered shutdown of two wells beyond this decade.

The Scott and Thomas sites are both located in areas where the saturated thickness is generally 100 ft or less, with areas of less than 50 ft nearby. Although both areas have shown long-term declines in water level, detailed analyses of the index well hydrographs indicate inflow into these areas, at least temporarily, is greater than originally thought. The Scott County site is in GMD1, which is the location of a recently completed KGS modeling study as well as a project that uses analyses of drillers' logs to determine and map the intervals of the aquifer that readily yield water (Hydrostratigraphic Drilling Record Assessment [HyDRA] Project). The HyDRA project information is useful for relating aquifer lithology to well-response characteristics. The Thomas County site has been the subject of previous water budget analyses and is of additional interest because of 1) the presence of stream channels (the channel of the South Fork of the Solomon River runs east-west just north of the index well) that may influence recharge and 2) the proximity of the site to the edge of the productive portion of the HPA. The Thomas County site is also the location of a detailed assessment as part of the HyDRA project.

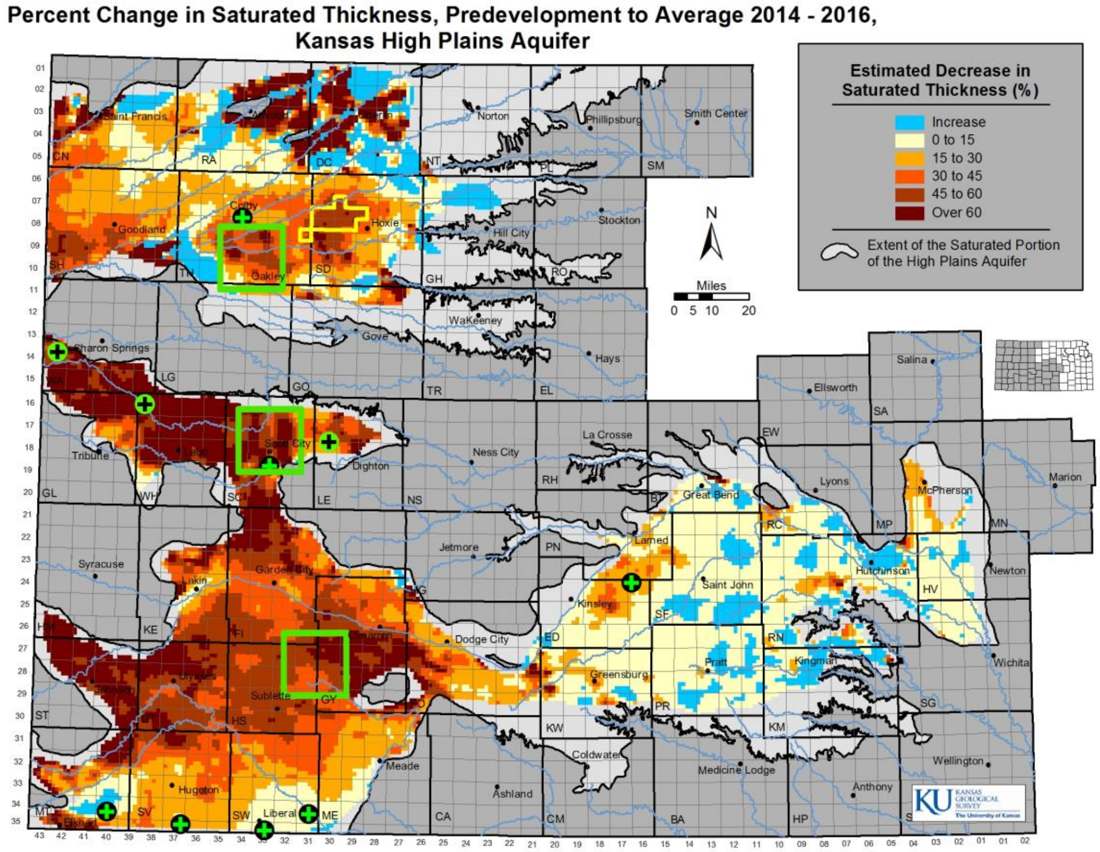


Figure 1—The Kansas portion of the High Plains aquifer, with aquifer and county boundaries shown. Each colored pixel represents one section (1 mi^2), coded for the degree of groundwater depletion from the beginning of large-scale development to the average of conditions in 2014–2016. The green boxes 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 location of the new GMD1 index wells installed in early spring of 2016. Additional wells (expansion wells) are monitored within each of the green boxes.

Table 1—Characteristics of the original three index well sites.

Site	2016 WL elev. (ft)[a]	2016 Saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2014 Water Use (ac-ft)		
					1-mi circle	2-mi circle	5-mi circle
Haskell	2,539.3	134.5	433	420–430	1,363	7,816	43,706
Scott	2,828.1	84.0	223	215–225	1,095	3,461	16,800
Thomas	2,967.8	64.3	284	274–284	1,245	3,016	13,818

[a] 2016 annual tape water-level measurements from WIZARD database (http://www.kgs.ku.edu/Magellan/WaterLevels/index.html)

3. Overview of Index Well Sites and Monitoring Data

3.1. *Original Index Wells*

This section provides a brief overview of the hydrographs from the three original index wells. With more than eight and a half years of hourly measurements, our understanding of water-level responses and trends at all three sites has improved significantly. All three index well hydrographs indicate that, although pumping occurs sporadically throughout the year, the major drawdown in water levels occurs during the pumping season in the summer when the aquifer is stressed significantly for an extended period of time. 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 during the recovery period at all three index wells, and full recovery has not been observed at any of the 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 impact 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). Note that all of the original index wells were added to the annual water-level measurement network and, since January 2008, have been measured as part of the annual program.

As shown in Section 4 of this report, the continuous water-level records from a network of index wells can provide the appropriate context for interpretation of year-to-year changes in annual water-level measurements and assessing future prospects for the aquifer in the vicinity of the index wells. The demonstrated value of continuous monitoring at the original three index wells led to a significant expansion of the index well network beginning in 2012. That expansion and the data obtained from the new network wells are described in Section 3.2.

The hydrographs from the original three index wells can be viewed in real time on the KGS website (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml); real-time viewing of the hydrographs from the Scott and Thomas County index wells is also possible through the GMD1 (www.gmd1.org) and GMD4 (www.gmd4.org) websites, respectively.

3.1.1. Haskell County

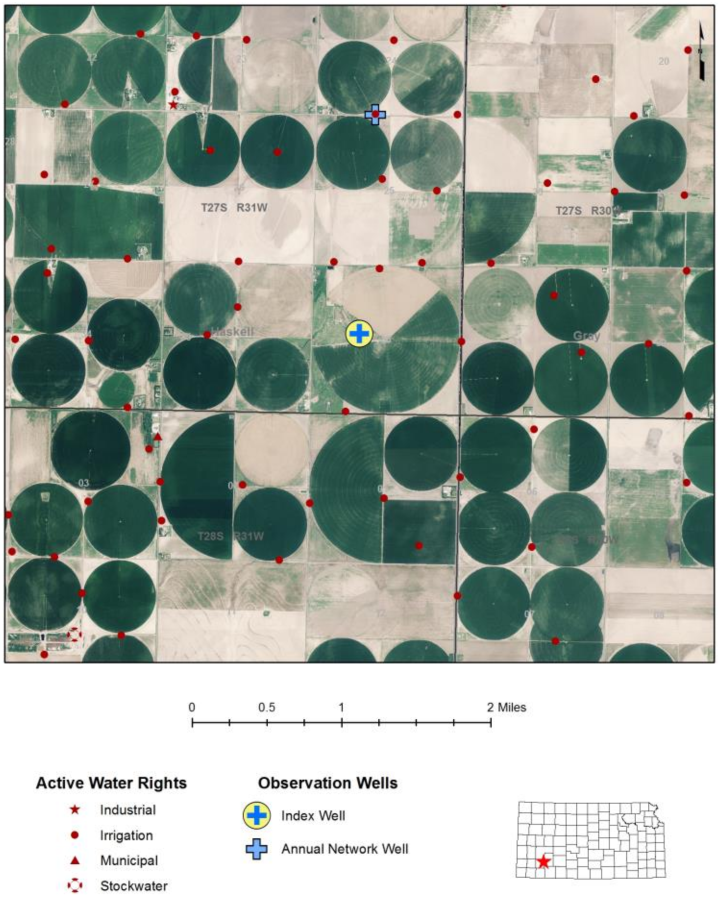


Figure 2—Haskell County site, showing the index well, an additional annual network well, and the nearby points of diversion. Pumping wells that are monitored by DWR are not marked and observation wells monitored by DWR are not shown.

The Haskell County site is the most extensively monitored of the three sites because of its location within an area of concentrated DWR monitoring. Figure 2 is an aerial overview of the Haskell County site at a scale that shows the index well, an additional nearby annual network well, and the location of wells with active water rights.

3.1.1.1. *Hydrograph and General Observations*

Figure 3 shows the complete hydrograph for the Haskell index well, table 2 summarizes its general characteristics, and table 3 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 2014–2015 recovery started on August 28, 2014, the last date of pumping for the 2014 irrigation season that had a major impact on the index well, and ended March 10, 2015. Other than an 18-day pumping period that lasted from November 28 to December 15, 2014, only a minor amount of pumping took place during the 2014–2015 recovery. The 2015 pumping season started earlier in the vicinity of the Haskell site than at the Scott and Thomas sites, with a break from April 14 to June 4. 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. The 2015–2016 recovery season began on August 12, 2015, and continued with only a minor amount of pumping until February 15, 2016.

Until 2013, the minimum recorded water-level elevation at the Haskell index well declined each year. However, the minimum 2013 and 2014 water-level elevations were 3.2 ft and 2.0 ft, respectively, higher than that in 2012. That pattern continued in 2015 as the minimum 2015 water-level elevation was 6.7 ft higher than that in 2014 and 8.7 ft higher than that in 2012. The most likely explanation is the cessation of pumping early in the 2013 and 2014 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). Water use for 2015 will be available later in 2016 and, as a result of the court decision, is expected to be among the lowest during the monitoring period. In 2014, water use within the 2-mi radius surrounding the index well was 7,816 ac-ft, the lowest use year during the monitoring period, and 1,276 ac-ft below the average for the period (9,092 ac-ft). The 2014 water use was applied on fewer irrigated acres than all but one year during the monitoring period, resulting in slightly below average water use per acre irrigated during the monitoring period (table 2). In 2015, the index well recorded a year-to-year decline in the maximum recovered water level of 2.0 ft (estimated value because of sensor failure in 2014), the smallest decline observed during the monitoring period. Given that the 2016 water use is expected to be well below average for the monitoring period, the expectation is that the decline in the maximum recovered water level in 2016 will be close to the smallest observed during the monitoring period.

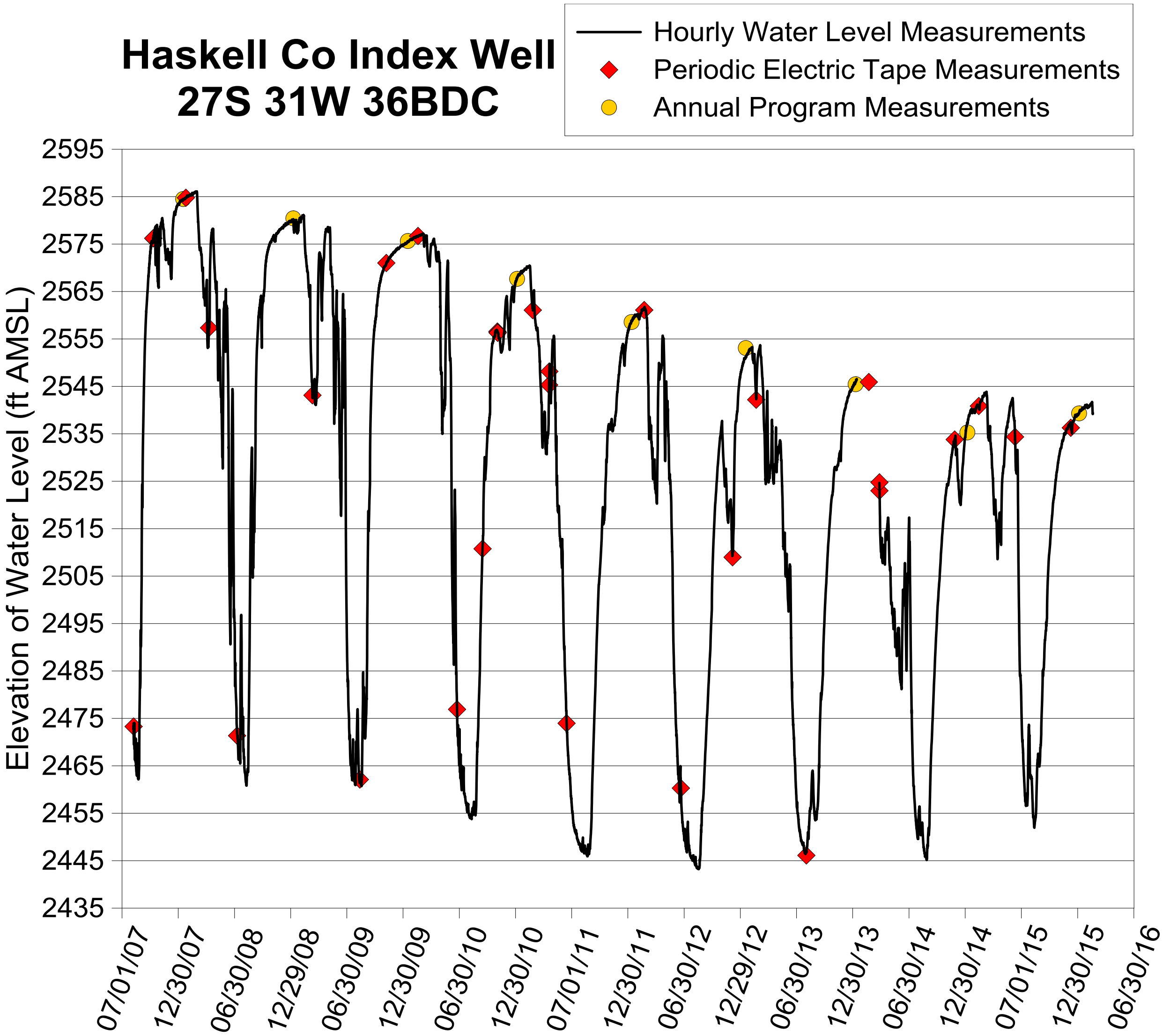


Figure 3—Haskell County index well hydrograph—total data run to 2/18/16. A water-level elevation of 2,445 ft corresponds to a depth to water of 392.85 ft below land surface (lsf); the top of the screen is 420 ft below lsf (elevation of 2,417.85 ft) and the bottom of the aquifer is 433 ft below lsf (elevation 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 result of sensor failure (see text).

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

		2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Minimum Water-Level Elevation	Feet	2,462.1	2,460.8	2,460.7	2,453.8	2,445.9	2,443.2	2,446.4	2,445.2	2,451.9
	Date	8/23/07	8/8/08	8/16/09	8/9/10	8/21/11	8/16/12	7/29/13	8/27/14	8/12/15
Maximum Observed Recovery Elevation	Feet	NA	2,586.1	2,581.1	2,577.2	2,570.4	2,561.7	2,553.6	2,545.9[b]	2,543.9
	Date	NA	2/28/08	2/9/09	3/5/10	2/13/11	2/23/12	3/4/13	2/20/14[b]	3/8/15
Apparent Recovery	Feet	NA	124.0	120.3	116.5	116.6	115.8	110.4	99.5[b]	98.7
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-5.0	-3.9	-6.8	-8.7	-8.1	-7.7	-2.0
Recovery Season	Start	NA	8/24/07	8/13/08	8/18/09	8/24/10	8/29/11	8/18/12	7/29/13	8/28/14
	End	NA	2/28/08	2/10/09	3/6/10	2/15/11	2/23/12	3/4/13	2/20/14[b]	3/10/15
	Length (Days)	NA	189.2	181.0	200.2	174.9	178.8	197.9	203.0[b]	193.3
Pumping During Recovery Season	Days	NA	41.5	20.0	5.2	25.8[a]	28.9	36.3	35.0	32.6
Length of Pumping Season	Days	NA	166.1	188.5	171.0	193.7	173.4	150.0	149.6[b]	160.5
2-mi Radius Water Use	Irrigated Acres	6,475	7,755	6,259	6,114	6,107	5,714	6,751	5,822	NA
	Total Use (ac-ft)	8,764.0	9,931.7	8,720.4	8,972.7	10,560.4	9,706.3	8,265.0	7,816.2	NA
	Irrigation Use Only (ac-ft)	8,762.1	9,929.8	8,718.3	8,970.0	10,556.8	9,703.0	8,251.9	7,800.3	NA
	Use per Irrigated Acre (ft)	1.35	1.28	1.39	1.47	1.73	1.70	1.22	1.34	NA

[a] Overall, the recovery was not smooth, indicating some pumping in the area for much of the recovery period. Number based on hours of water-level decline during the recovery period.

[b] 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.

3.1.1.2. *Measurement Comparisons*

Table 3—Annual water-level measurement[a] comparison with transducer measurements, Haskell County index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/15/2008	2,584.48	NA	Steel tape
	2,584.44[c]	NA	Transducer
1/7/2009	2,580.41	-4.07 (-5.0)	Steel tape
	2,580.19[c]	-4.25	Transducer
	2,580.10[d]	NA	Transducer
1/14/2010	2,575.63	-4.78 (-3.9)	Steel tape
	2,575.54[c]	-4.65	Transducer
	2,574.51[d]	-5.59	Transducer
1/4/2011	2,567.67	-7.96 (-6.8)	Steel tape
	2,567.91[c]	-7.63	Transducer
	2,567.94[d]	-6.57	Transducer
1/11/2012	2,558.57	-9.1 (-8.7)	Steel tape
	2,558.82[c]	-9.09	Transducer
	2,558.75[d]	-9.19	Transducer
1/16/2013	2,553.09[e]	-5.48[e] (-8.1)	Steel tape
	2,551.22[c]	-7.60	Transducer
	2,550.99[d]	-7.76	Transducer
1/8/2014	2,545.46	-7.63[e] (-7.7)	Steel tape
	2,545.94[c,f]	-5.28	Transducer
	NA	NA	
1/6/2015	2,535.29[g]	-10.17[g] (NA)	Steel tape
	2,537.27[c,g]	-8.67[g]	Transducer
	2,537.34[d,g]	-13.65[g]	Transducer
1/4/2016	2,539.31	+4.02 (NA)	Steel tape
	2,539.36[c]	+2.09	Transducer
	2,538.96[d]	+1.62	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, not corrected for barometric pressure.

[d] Average of values over time interval 0800–1600, corrected for barometric pressure using the KGS barometric pressure correction program (Bohling et al., 2011).

[e] Suspect 2013 annual measurement value.

[f] Data taken from 2-hour telemetry data, sensor not downloadable after 8/1/13 because of sensor failure.

[g] Measurement affected by 18-day pumping period ending on 12/15/14.

3.1.2. Scott County

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

Figure 4 is an aerial overview of the Scott County site at a scale that shows the index well, an additional nearby annual program well, and the location of wells with active water rights. The remaining GMD1 expansion well, which is discussed in Section 3.2, is located approximately nine miles due south of the Scott County index well.

3.1.2.1. *Hydrograph and General Observations*

Figure 5a shows the complete hydrograph for the Scott index well, table 4 summarizes its general characteristics, and table 5 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 3.9 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 2014–2015 recovery started on September 4, 2014. There was little pumping during the recovery period; pumping for the 2015 irrigation season started on March 9, 2015. Pumping continued until April 24, 2015, and then largely ceased until early July. This break in pumping was likely due to planting of summer crops and late spring and early summer rains. After a sudden drop of more than 0.7 ft within 24 hours on July 4, pumping appeared to continue, except for a four-day period in late July, at all wells in the vicinity until September 16. There was little pumping during the 2015–16 recovery period, which continued until March 4, 2016.

As a result of the sensor failure at the Haskell County index well on January 12, 2014, the transducer was replaced at the Scott County index well on March 27, 2014. However, transducer measurements during the 2014 recovery period and much of 2015 (fig. 5b) were noisier than previous years. A close examination of the measurements revealed that the gage pressure transducer appeared to be acting as an absolute pressure sensor (i.e., the vent tube was clogged). The 100 psig transducer and cable were removed from the well on June 26, 2015, (A on fig. 5b) to assess whether either were responsible for the increased noise; a temporary 20 psia transducer was installed on a steel cable. The manufacturer evaluated the transducer cable and its vent tube but found no problems. We tested the 100 psig transducer in the lab and found no problems. On July 22, 2015, (B on fig. 5b), we reinstalled the 100 psig transducer and cable. However, we found that the problem was not fixed and the data were noisier than before. We therefore decided to replace both the transducer and the cable. On October 20, 2015, (C on fig. 5b), a new 30 psig transducer and cable were installed in the well. Data acquired after the installation show that the transducer noise has been greatly reduced.

We also re-evaluated the 0.29 ft change in the transducer position applied to data collected after the February 22, 2012, download. We generally noted a very gradual change in the transducer position (<0.3 ft) between August 21, 2007 and June 26, 2015, (when the transducer was removed as described above). Because of this, we re-calculated the water-level elevations using the average transducer position over this entire time period. Figure 5a and table 4 have been updated to reflect this change. Cable stretch and cable slippage appear to be the most likely explanations for the gradual change.

Each year, the minimum recorded water-level elevation has declined from the previous year at the Scott County index well. The lowest water level observed was in 2015; the minimum 2015 water-level elevation was 0.3 ft lower than in 2014 (the smallest single-year decline during the monitoring period) and 6.7 ft lower than in 2008 (the first year for which a value was recorded). The maximum recovered water level has also declined every year since the onset of monitoring. The lowest maximum recovered water level was in 2015 and was 1.0 ft below that of 2014 and 6.5 ft below that of 2008 (average annual decline of 0.8 ft/yr). Given that the 2016 maximum water-level elevation appears to be within 0.5 ft of that in 2015, the expectation is that the minimum water-level elevation in 2016 will not be much less than that of 2015. Water-use data for 2015 will be available later in 2016. Water use within the 2-mi radius surrounding the index well in 2014 (3,468 ac-ft) was 59 ac-ft above the average for the monitoring period (3,409 ac-ft).

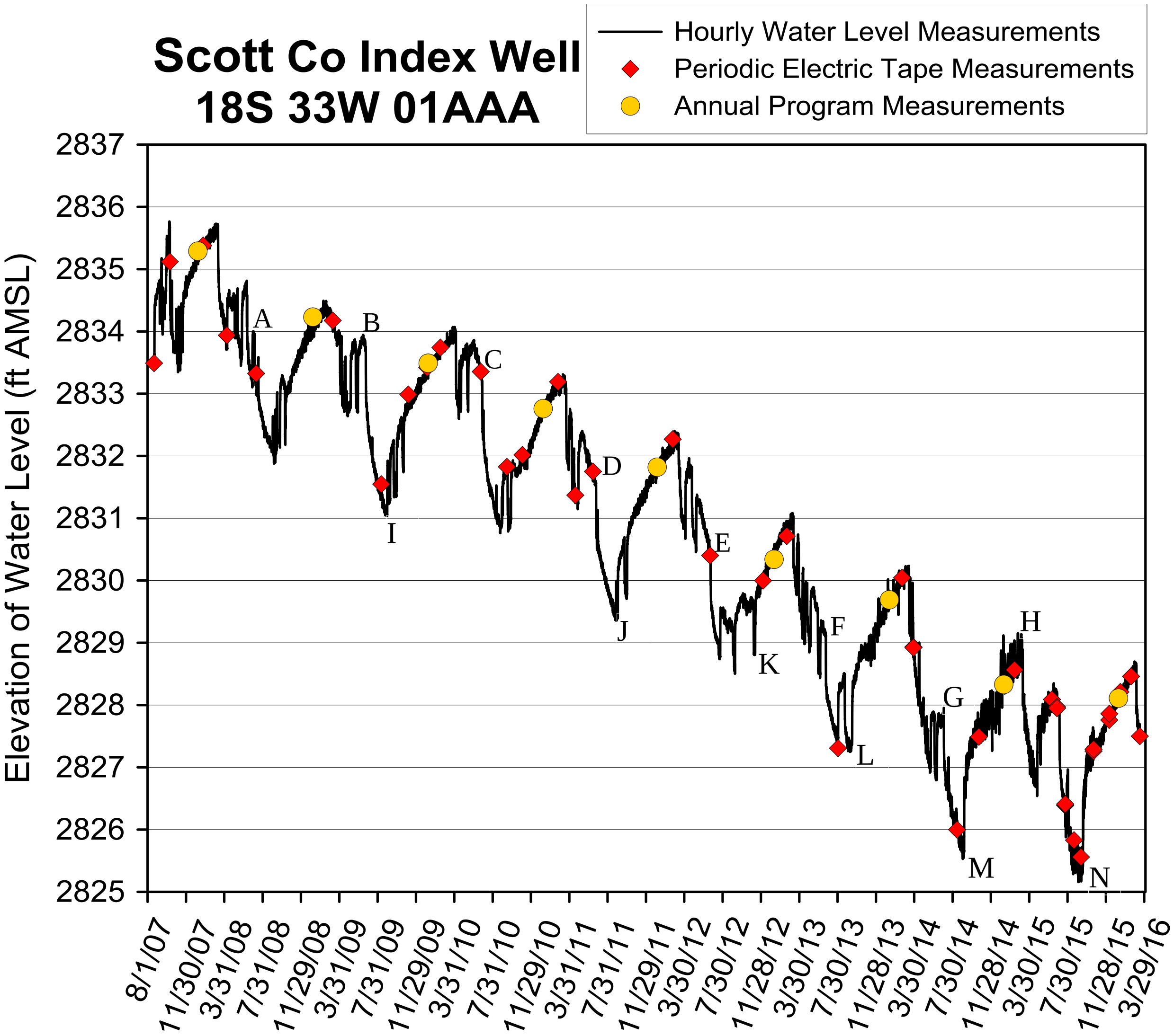


Figure 5a—Scott County index well hydrograph—total data run to 3/15/16. A water-level elevation of 2,829 ft corresponds to a depth to water of 138.15 ft below land surface (lsf); the top of the screen is 215 ft below lsf (elevation of 2,752.15 ft) and the bottom of the aquifer is 223 ft below lsf (elevation of 2,744.15 ft). The screen terminates 2 ft below the bottom of the aquifer. A–N defined in text (Section 4.2). Transducer data adjusted for change in position as described in text.

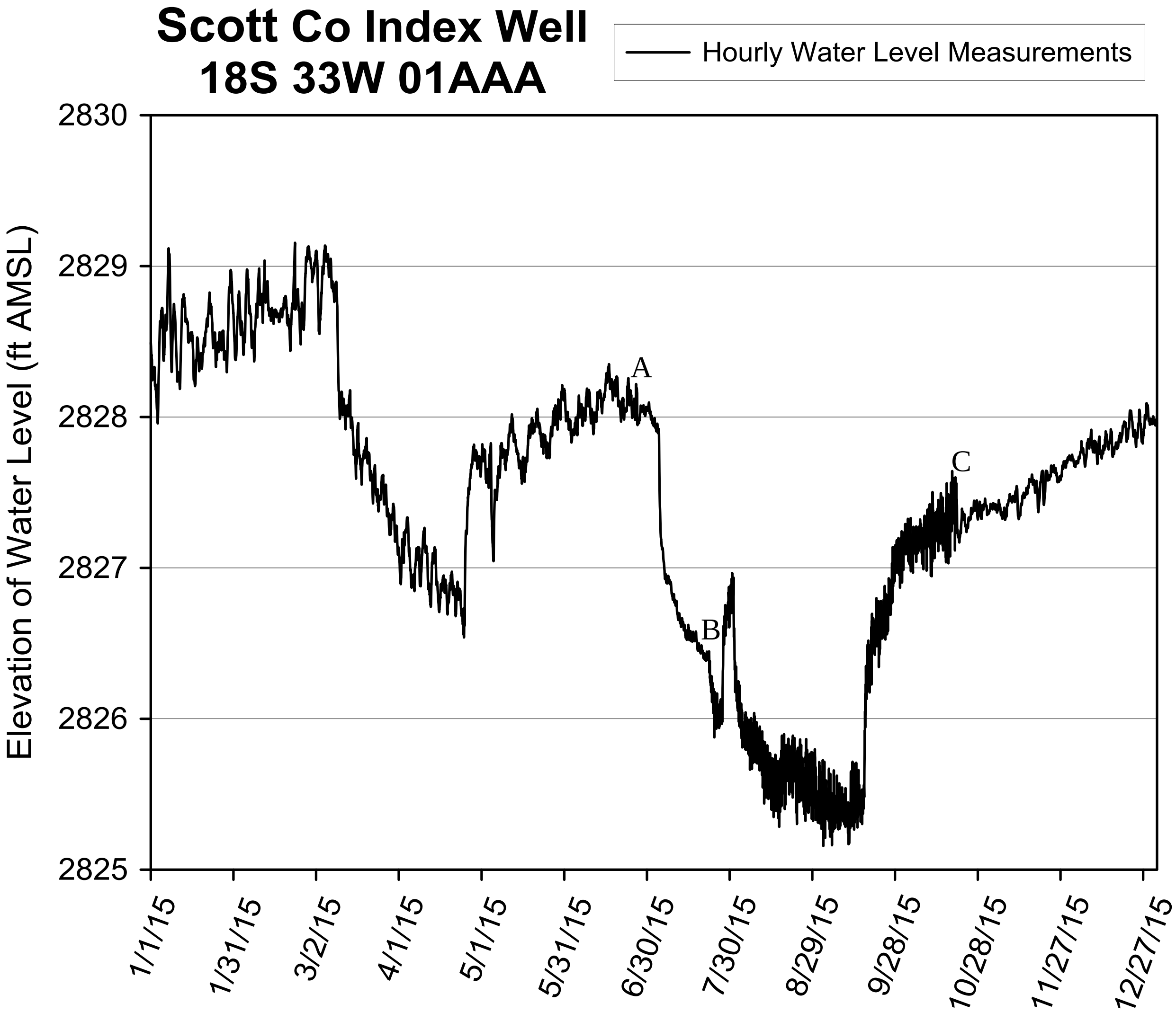


Figure 5b—Scott County index well 2015 hydrograph. A-C defined in text.

Table 4—General characteristics of the Scott County index well hydrograph and local water-use data.

		2007	2008	2009	2010	2011	2012	2013	2014	2015
Minimum Water-Level Elevation	Feet	< 2,833.4	2,831.9	2,831.0	2,830.8	2,829.4	2,828.5	2,827.3	2,825.5	2,825.2
	Date	11/5/07	9/5/08	8/30/09	8/24/10	8/29/11	9/7/12	9/7/13	8/31/14	9/2/15
Maximum Observed Recovery Elevation	Feet	NA	2,835.7	2,834.5	2,834.1	2,833.3	2,832.4	2,831.1	2,830.2	2,829.2
	Date	NA	3/4/08	2/9/09	3/16/10	3/11/11	2/28/12	3/9/13	3/13/14	2/22/15
Apparent Recovery	Feet	NA	> 2.3	2.6	3.1	2.5	3.0	2.6	2.9	3.7
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-1.2	-0.4	-0.8	-0.9	-1.3	-0.9	-1.0
Recovery Season	Start	NA	< 8/21/07	9/13/08	8/30/09	8/29/10	9/1/11	9/7/12	9/14/13	9/4/14
	End	NA	3/11/08	4/2/09	4/5/10	3/17/11	3/12/12	3/11/13	3/13/14	3/9/15
	Length (Days)	NA	> 203	201.3	217.8	200.2	192.8	185.2	180.3	185.3
Pumping During Recovery Season	Length (Days)	NA	> 48.2	13.7	21.0	12.8	8.7	5	8.6	0[a]
Length of Pumping Season	Days	NA	182.3	150.0	145.7	168.1	186.4	186.7	175.1	191.2
2-mi Radius Water Use	Irrigated Acres	4132	3,950	3,923	3,665	4,078	3,734	3,857	3,649	NA
	Total Use (ac-ft)	3,175.1	4,059.0	2,955.5	3,035.9	3,595.6	3,760.8	3,228.2	3,460.7	NA
	Irrigation Use Only (ac-ft)	3,095.8	4,014.3	2,955.5	3,017.9	3,580.6	3,747.7	3,212.0	3,443.2	NA
	Use per Irrigated Acre (ft)	0.75	1.02	0.75	0.82	0.88	1.00	0.83	0.94	NA

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

3.1.2.2. *Measurement Comparisons*

Table 5—Annual water-level measurement[a] comparison with transducer measurements, Scott County index well.

Date	**WL Elevation (ft)**	**Indicated Annual WL Change (ft)[b]**	**Method**
1/7/2008	2,835.29	NA	Steel tape
	2,835.13[c]	NA	Transducer
1/6/2009	2,834.23	-1.06 (-1.24)	Steel tape
	2,834.05[c]	-1.08	Transducer
1/7/2010	2,833.49	-0.74 (-0.42)	Steel tape
	2,833.32[c]	-0.73	Transducer
	2,833.37[d]	NA	Transducer
1/7/2011	2,832.76	-0.73 (-0.73)	Steel tape
	2,832.70[c]	-0.62	Transducer
	2,832.71[d]	-0.66	Transducer
1/4/2012	2,831.82	-0.94 (-0.91)	Steel tape
	2,831.76[c]	-0.94	Transducer
	2,831.79[d]	-0.92	Transducer
1/9/2013	2,830.34	-1.48 (-1.32)	Steel tape
	2,830.40[c]	-1.36	Transducer
	2,830.45[d]	-1.34	Transducer
1/10/2014	2,829.69	-0.65 (-0.84)	Steel tape
	2,829.59[c]	-0.81	Transducer
	2,829.55[d]	-0.90	Transducer
1/8/2015	2,828.33	-1.36 (-1.08)	Steel tape
	2,828.35[c]	-1.24	Transducer
	2,828.25[d]	-1.30	Transducer
1/7/2016	2828.11	-0.22 (NA)	Steel tape
	2828.13[c]	-0.22	Transducer
	2828.11[d]	-0.14	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] 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, not corrected for barometric pressure.

[d] Average of values over time interval 0800–1600, corrected for barometric pressure using the KGS barometric pressure correction program.

3.1.3. Thomas County

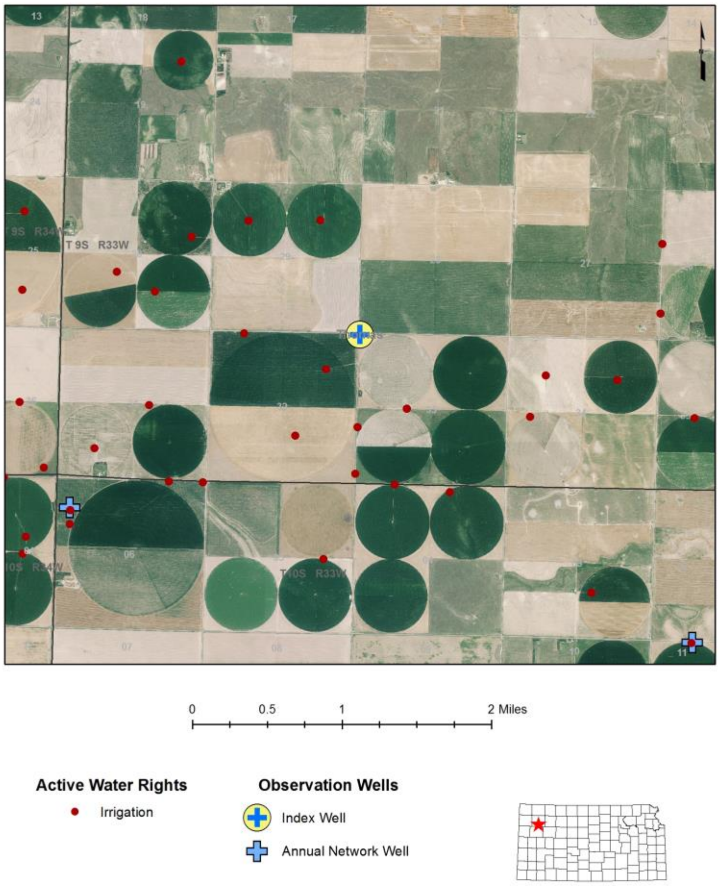


Figure 6—Thomas County site, showing the index well, an additional annual program well, and nearby points of diversion.

Figure 6 is an aerial overview of the Thomas County site at a scale that shows the index well, an additional annual program well, 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 3.2.7.

3.1.3.1. *Hydrograph and General Observations*

Figure 7 shows the complete hydrograph for the Thomas County index well, table 6 summarizes its general characteristics, and table 7 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 2014–2015 recovery was the second longest observed during the monitoring period at the Thomas well, beginning on August 24, 2014, and ending on June 24, 2015, only 1.4 days shorter than the longest observed recovery (2009–2010). The 2015 pumping season began on June 24. Other than two shutdowns of a few days in July, sustained pumping essentially continued until the end of the pumping season on September 11, 2015. Beyond a one-week pumping period from October 14 to 21, there has been little pumping during the 2015–2016 recovery period, which was still continuing at the time of this report (March 15, 2016). Note that as a result of the sensor failure at the Haskell County index well on January 12, 2014, the sensor was replaced at the Thomas County index well on March 27, 2014.

Unlike the Haskell index well (until the court-ordered shutdowns of two nearby irrigation wells in 2013 and 2014) and the Scott index well, the minimum recorded water-level elevation at the Thomas index well has not declined every year. The minimum observed water-level elevation in 2015, which was the second lowest recorded over the monitoring period, was 0.1 ft above that of 2014 and 6.8 ft below that of 2010 (the highest recorded minimum water-level elevation during the monitoring period). Water-use data for 2015 will be available later in 2016. In 2014, water use within the 2-mi radius surrounding the index well (3,016 ac-ft) was the fourth highest during the monitoring period and 104 ac-ft above the average for the period (2,912 ac-ft). The 2014 water use was applied on the smallest number of irrigated acres during the monitoring period and just slightly below (98 acres) the average irrigated acres over the monitoring period (3,014 ac); the water use per acre irrigated was the fourth highest for the period (table 6). The maximum observed water level in 2015 was 0.3 ft below that of 2014 and 6.4 ft below that of 2010 (the highest maximum observed water level during the monitoring period). Given that the 2015 minimum water level (recorded on September 11) was slightly above the 2014 minimum recorded water-level elevation, the expectation is that the maximum observed water level at the end of the 2015–2016 recovery will be within a few tenths of a foot of that of 2014.

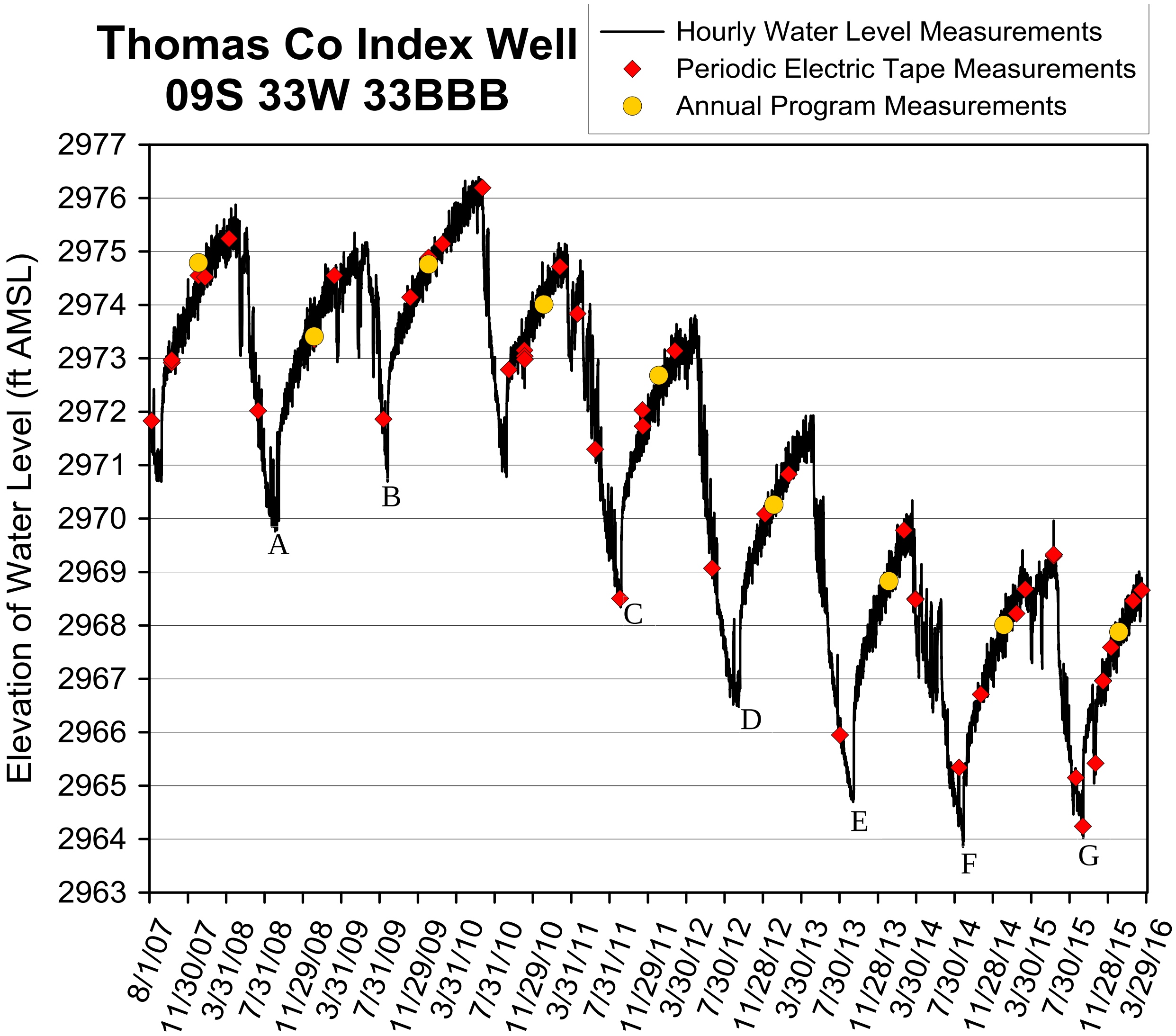


Figure 7—Thomas County index well hydrograph—total data run to 3/15/16. A water-level elevation of 2,968 ft corresponds to a depth to water of 219.56 ft below land surface (lsf); the top of the screen is 274 ft below lsf (elevation of 2,913.56 ft), and the bottom of the aquifer is 284 ft below lsf (elevation of 2,903.56 ft). The screen terminates at the bottom of the aquifer. A–G defined in text (Section 4.2).

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

		2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Minimum Water-Level Elevation	Feet	2,970.7	2,969.8	2,970.7	2,970.8	2,968.3	2,966.5	2,964.7	2,963.9	2964.0
	Date	9/7/07	9/2/08	8/25/09	9/6/10	9/4/11	9/13/12	9/11/13	8/26/14	9/11/15
Maximum Observed Recovery Elevation	Feet	NA	2,975.9	2,975.4	2,976.4	2,975.2	2,973.8	2,971.9	2,970.3	2970.0
	Date	NA	4/30/08	5/12/09	6/10/10	2/20/11	4/27/12	4/29/13 and 5/7/13	3/17/14	6/9/15
Apparent Recovery	Feet	NA	5.2	5.6	5.7	4.4	5.5	5.4	5.6	6.1
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-0.5	+1.0	-1.2	-1.4	-1.9	-1.6	-0.3
Recovery Season	Start	NA	9/8/07	9/8/08	8/26/09	9/6/10	9/6/11	9/17/12	9/13/13	8/28/14
	End	NA	5/12/08	6/24/09	6/24/10	3/17/11	5/4/12	5/9/13	3/24/14	6/24/15
	Length (Days)	NA	247.2	289.5	301.4	191.4	241.3	233.7	191.9	300.0
Pumping During Recovery Season	Length (Days)	NA	5.0	17.0	2.2	18.4	14.0	0[a]	7.6	9.7
Length of Pumping Season	Days	NA	118.5	63.2	74.6	173.8	135.8	127.0	156.1	79.5
2-mi Radius Water Use	Irrigated Acres	2,983	3,016	2,958	3,009	3,109	3,070	3,054	2,916	NA
	Total (ac-ft)	2,868.87	2,825.21	1,917.17	2,256.13	3,298.83	3,683.24	3,432.01	3,016	NA
	Use per Irrigated Acre (ft)	0.96	0.94	0.65	0.75	1.06	1.20	1.12	1.03	NA

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

3.1.3.2. *Measurement Comparisons*

Table 7—Annual water-level measurement[a] comparison with transducer measurements, Thomas County index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/3/2008	2,974.67	NA	Steel tape
	2,974.61[c]	NA	Transducer
1/4/2009	2,973.29	-1.38 (-0.53)	Steel tape
	2,973.18[c]	-1.43	Transducer
	2,973.59[d]	NA	Transducer
1/2/2010	2,974.64	+1.35 (+1.05)	Steel tape
	2,974.74[c]	+1.56	Transducer
	2,974.65[d]	+1.06	Transducer
1/3/2011	2,973.89	-0.75 (-1.24)	Steel tape
	2,974.14[c]	-0.60	Transducer
	2,974.15[d]	-0.50	Transducer
1/3/2012	2,972.56	-1.33 (-1.40)	Steel tape
	2,972.61[c]	-1.53	Transducer
	2,972.36[d]	-1.79	Transducer
1/2/2013	2,970.14	-2.42 (-1.87)	Steel tape
	2,970.26[c]	-2.35	Transducer
	2,970.31[d]	-2.05	Transducer
1/2/2014	2,968.71	-1.43 (-1.64)	Steel tape
	2,968.73[c]	-1.53	Transducer
	2,968.86[d]	-1.45	Transducer
1/2/2015	2,967.89	-0.82 (-0.38)	Steel tape
	2,968.08[c]	-0.65	Transducer
	2,967.95[d]	-0.91	Transducer
1/2/2016	2,967.76	-0.13 (NA)	Steel tape
	2,967.78[c]	-0.30	Transducer
	2,967.75[d]	-0.20	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, not corrected for barometric pressure.

[d] Average of values over time interval 0800–1600, corrected for barometric pressure using KGS barometric correction program.

3.2. New Index Wells and the Expansion Well Network

3.2.1. Border Index Wells

In the spring of 2012, we identified wells in four well nests that were originally installed by the USGS (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 are 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.

On August 1–2, 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. On February 20, 2014, a barometer was added at the Rolla site. That barometer was removed on December 8, 2015, because it appeared to be malfunctioning. The Hugoton site barometer was turned off by USGS personnel when they removed KGS transducers from the wells at that site in November 2015. A barometer was added to the Cimarron site in December 2015.

Table 8 summarizes site characteristics and information about all monitored wells. In this section, we provide a brief overview and interpretation of the hydrographs from each of these wells.

Table 8—Characteristics of the border index wells.

Site	2016 WL elev. (ft)[a]	2016 Saturated thickness (ft)	Bedrock depth (estimated ft below land surface)[b]	Screened interval (ft below land surface)[b]	2014 Water Use (ac-ft)		
					1-mi circle	2-mi circle	5-mi circle
Cimarron 210	2,474.42	290.42	345	200–210	73	73	9,470
Liberal 160[c]	2,691.40[d]	446.40	576	140–160	4.11	1,318[e]	34,459[e,f]
Liberal 436	2,660.19	415.19	576	426–436			
Hugoton 313[c]	2,920.98[d]	455.98	635	303–313	1,055	3,539	42,494[e]
Hugoton 495	2,918.51	453.51	635	485–495			
Rolla 366	3,187.65	211.65	399	356–366	199	1,296	10,792

[a] 2015 annual tape water-level measurements from WIZARD database.
[b] Measurements from table 2 in McMahon (2001).
[c] Not an annually measured index well but an additional sensor and telemetry equipped well.
[d] 2016 water-level measurements from hand measurements taken 2/17/2016.
[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 ac-ft [5-mi circle]).
[f] Includes 6,797 ac-ft of non-irrigation water for city of Liberal.

3.2.1.1. *Cimarron Site*

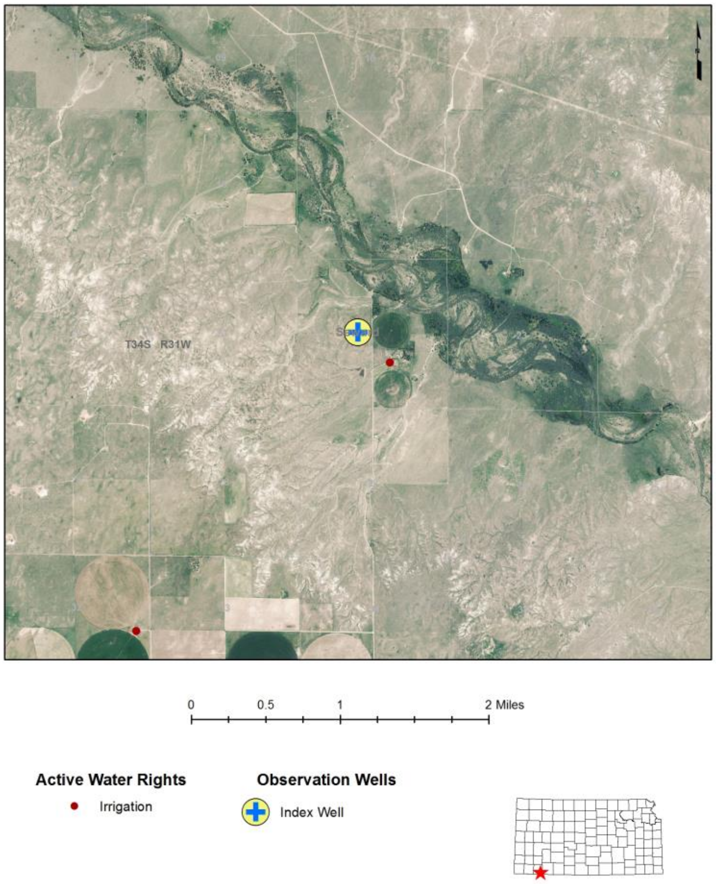


Figure 8—Aerial view of Cimarron index well site and nearby points of diversion.

Figure 8 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 instrumented (henceforth, Cimarron 210 or Cimarron index well).

3.2.1.1.1. Hydrograph and General Observations

Figure 9 shows the complete hydrograph for the Cimarron index well, table 9 summarizes its general characteristics, and table 10 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 2014–2015 recovery began on August 21, 2014, and ended on May 24, 2015. Other than extended periods of pumping in April to early May, there was little pumping during the recovery period. During the 2015 pumping season (May 24–October 21), the water level was affected by sporadic pumping at the nearby irrigation well (e.g., the abrupt decline at A on fig. 9) and by more regional pumping effects (e.g., the gradual decline during period B on fig. 9). The 2015–2016 recovery season was continuing at the time of the download used for this report (February 17, 2016). There is an abrupt break in slope of the 2015–2016 recovery in early January 2016. The mechanism producing this break has yet to be determined but it likely related to regional pumping activity. Water-use data for 2015 will be available later in 2016. In 2014, water use within the 2-mi radius surrounding the index well was 73 ac-ft, the lowest water use at any of the index wells. The 2014 water use was applied on 70 acres, resulting in water use per acre irrigated of 1.0 ft (table 9).

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 given in McMahon (2001, table 2) using recent elevation measurements (85 ft added to McMahon [2001] elevations). After the 1999 pumping season, the water level at Cimarron 210 recovered to an elevation of approximately 2,476 ft. In early 2016, the water level appears to be recovering to near 2,474.5 ft, a loss of about 1.5 ft in 16 years.

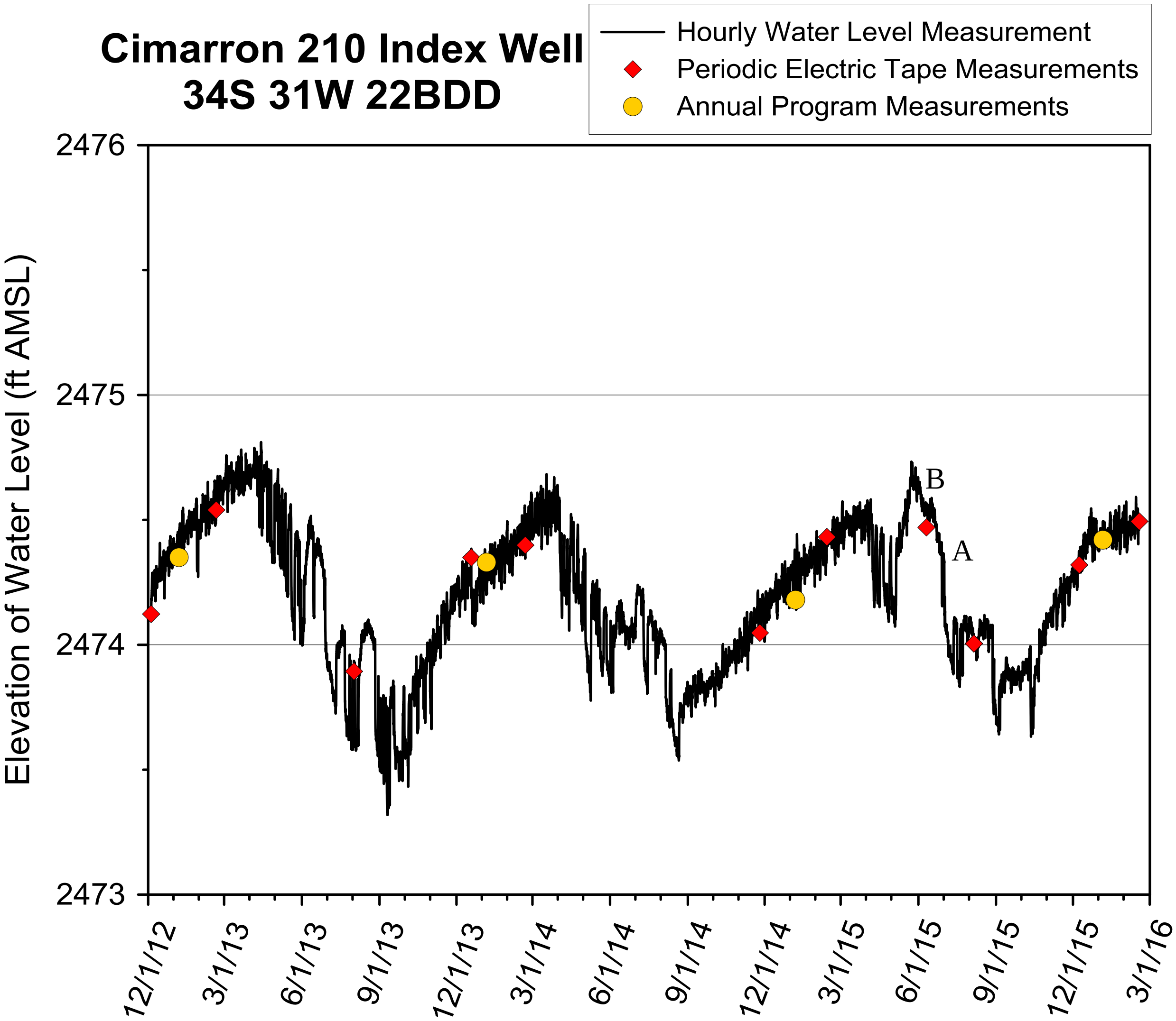


Figure 9—Cimarron 210 index well hydrograph—total data run to 2/17/16. A water-level elevation of 2,474 ft corresponds to a depth to water of 55.0 ft below land surface (lsf); the top of the 10-ft screen is 200 ft below lsf (elevation of 2,329 ft), and the bottom of the aquifer is 345 ft below lsf (elevation of 2,184 ft). A and B defined in text.

Table 9—General characteristics of the Cimarron 210 index well hydrograph and local water-use data.

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

[a] 2012 Irrigated Acres—70, Total—81 ac-ft, Use per Irrigated Acre—1.16 ft

3.2.1.1.2. Measurement Comparisons

Table 10—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
	2,474.40[d]	NA	Transducer
1/5/2014	2,474.33	-0.02 (-0.13)	Steel tape
	2,474.21[c]	-0.20	Transducer
	2,474.28[d]	-0.12	Transducer
1/6/2015	2,474.18	-0.15 (+0.06)	Steel tape
	2,474.24[c]	+0.03	Transducer
	2,474.27[d]	-0.01	Transducer
1/5/2016	2,474.42	+0.24 (NA)	Steel tape
	2,474.34[c]	+0.10	Transducer
	2,474.40[d]	+0.13	Transducer

[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, not corrected for barometric pressure.

[d] Average of values over time interval 0800–1600, corrected for barometric pressure using KGS barometric correction program.

3.2.1.2. *Liberal Site*

Figure 10—Aerial view of Liberal index well site, an additional annual program well, and 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 10 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 initially instrumented (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 also instrumented (henceforth, Liberal 160 or Liberal 160 index well). The fields in the immediate vicinity of the site appear to be dryland farmed.

3.2.1.2.1. Hydrograph and General Observations

Figure 11 shows the hydrographs for the two Liberal index wells, table 11 summarizes the general characteristics of the Liberal 436 hydrograph, and table 12 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. The hydraulic conditions in the screened interval at the Liberal 160 well will be explored further in 2016.

Interpretation of the 2015 data from the two Liberal wells is difficult because of a series of problems that arose beginning in August 2014. As described in the previous year's report (Butler et al., 2015), 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. 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 Figure 11 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 Figure 11), the KGS transducer was removed from Liberal 160 by USGS personnel and replaced with another transducer. The values recorded by that transducer are plotted and are considerably noisier than the previously acquired data. These data were later adjusted but the adjusted values are not plotted because of uncertainty about the justification for the adjustments. Similarly, on June 10, 2015 (E on Figure 11), the KGS transducer was removed from Liberal 436 by USGS personnel and replaced with another transducer. The values recorded by that transducer are plotted and are considerably noisier than the previously acquired data. These data were later adjusted but the adjusted values are not plotted because of uncertainty about the justification for the adjustments. Note the form of the hydrograph during 2015 is considerably different from the previous years, as is the timing of the minimum water level. Given that the quality of the data obtained at the Liberal wells appears to have suffered as a result of the removal of the KGS sensors and measurements are being adjusted in a manner not consistent with KGS practices, the decision was made to reinstall the KGS transducers. The transducers were reinstalled in both wells on May 12, 2016. The data from the KGS transducers will be the focus of future reports.

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 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 2016 at Liberal 436 is recovering to near 2,660 ft, a loss of about 23 ft in 16 years (1.5 ft/yr), which is consistent with the 25-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 2016 at Liberal 160 is recovering to an elevation of approximately 2,691.5 ft, a loss of about 14.5 ft in 16 years (less than 1 ft/yr).

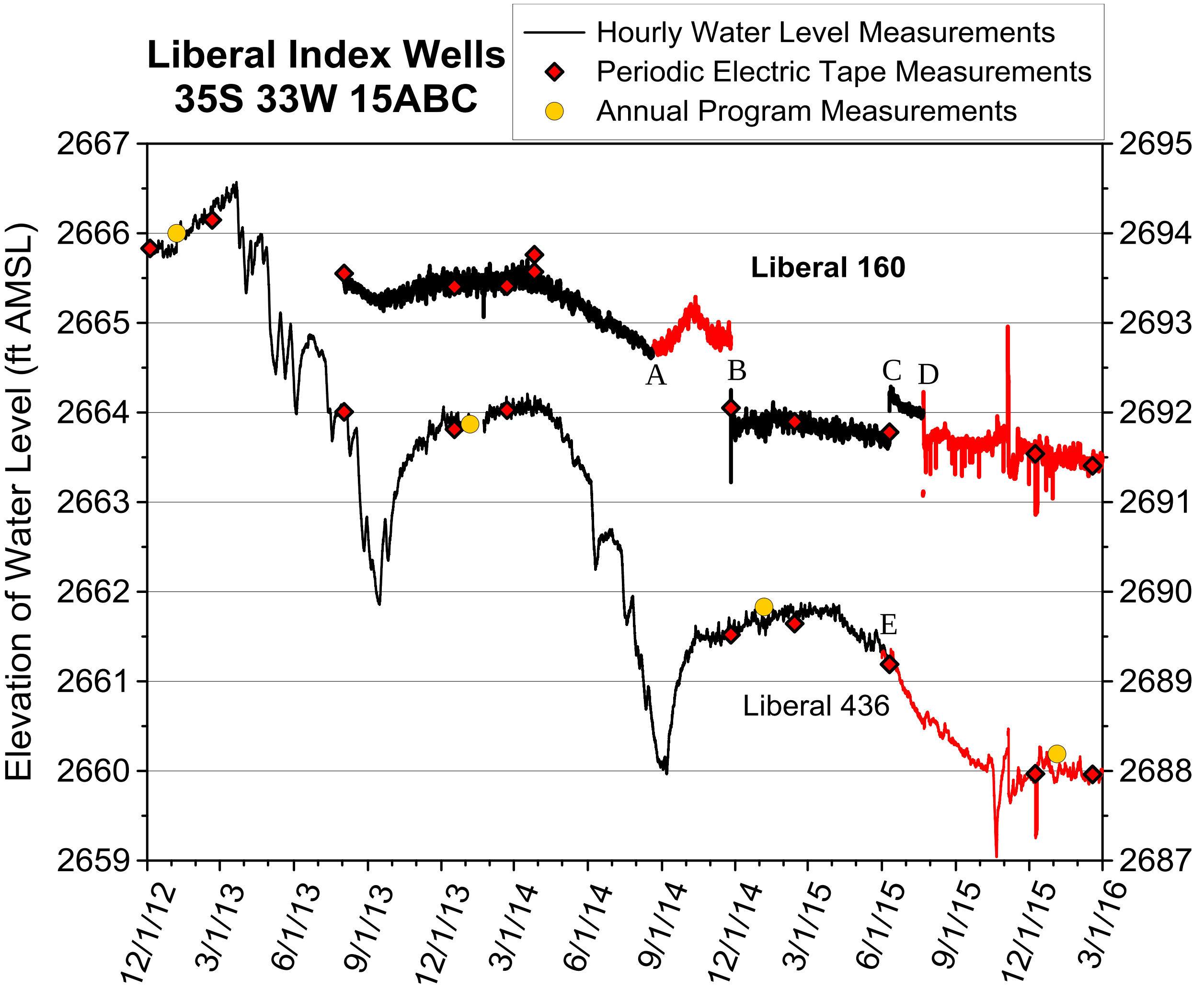


Figure 11—Hydrographs of Liberal index wells—total data run to 3/22/16. The Liberal 436 plot corresponds to the left y-axis; a water-level elevation of 2,664.0 ft corresponds to a depth to water of 157.0 ft below land surface (lsf); the top of the 10-ft screen is 426 ft below lsf (elevation of 2,395 ft). The Liberal 160 plot corresponds to the right y-axis; a water-level elevation of 2,694.0 ft corresponds to a depth to water of 127.0 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 the 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.

Table 11—General characteristics of the Liberal 436 index well hydrograph and local water-use data.

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

[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.

3.2.1.2.2. Measurement Comparisons

Table 12—Annual water-level measurement[a] comparison with transducer measurements[e], 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
	2,665.97[d]	NA	Transducer
1/5/2014	2,663.87	-2.13 (-2.4)	Steel tape
	2,663.87[c]	-2.01	Transducer
	2,663.90[d]	-2.07	Transducer
1/5/2015	2,661.83	-2.04 (-2.3)	Steel tape
	2,661.67[c]	-2.2	Transducer
	2,661.68[d]	-2.22	Transducer
1/4/2016	2,660.19	-1.64 (NA)	Steel tape
	2,660.26[e]	-1.41[e]	Transducer
	2,660.39[d,e]	-1.29[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, not corrected for barometric pressure.

[d] Average of values over time interval 0800–1600, corrected for barometric pressure using KGS barometric correction program.

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

3.2.1.3. *Hugoton Site*

Figure 12—Aerial view of Hugoton index well site, an additional annual program well, and nearby points of diversion.

Figure 12 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 initially instrumented (henceforth, Hugoton 495 or Hugoton 495 index well). On August 1, 2013, the third deepest well, screened at 303–313 ft below lsf, was also 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 well could not be instrumented. As in 2013, the 2014 water use in the vicinity of the Hugoton site (2-mi radius) was the second highest of all the index wells (the Haskell site had the highest 2014 water use).

3.2.1.3.1. Hydrograph and General Observations

Figure 13 shows the hydrographs for the two Hugoton index wells, table 13 summarizes the general characteristics of the Hugoton 495 hydrograph, and table 14 compares the manual and transducer measurements from Hugoton 495. The large rapid drops and rises following 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 pumping season began on March 12 with a seven-day pumping period. Pumping began again on April 2 and continued until April 26. There was little further pumping until widespread pumping in the area began on June 19; that pumping continued until September 22. 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 (74 ft of drawdown at peak of 2015 pumping season) indicate that interval is more heavily stressed, while the elevation difference indicates the pumping induces downward flow from the shallower interval. Other than a few days of pumping in late September and mid-October, there was little pumping during the 2015–2016 recovery, which continued until February 26, 2016.

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 12, 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 prior to the sensors being 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). Following 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. The data from the KGS transducers will be the focus of future reports 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 from McMahon (2001, table 2) using recent elevation measurements (subtracted 12 ft from McMahon [2001] elevations). During the two pumping seasons in which McMahon (2001) reports measurement, the same relative pattern was observed as in 2013–2015 (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 2016 at both wells are recovering to near 2,920 ft, a loss of about 50 ft in 16 years (more than 3 ft/yr); the 2016 water level in the closest annual measurement program well (T. 34 S., R. 37 W., 35 AAD 01) rose 13 ft over the 2015 measurement so the 2016 measurement appears questionable.

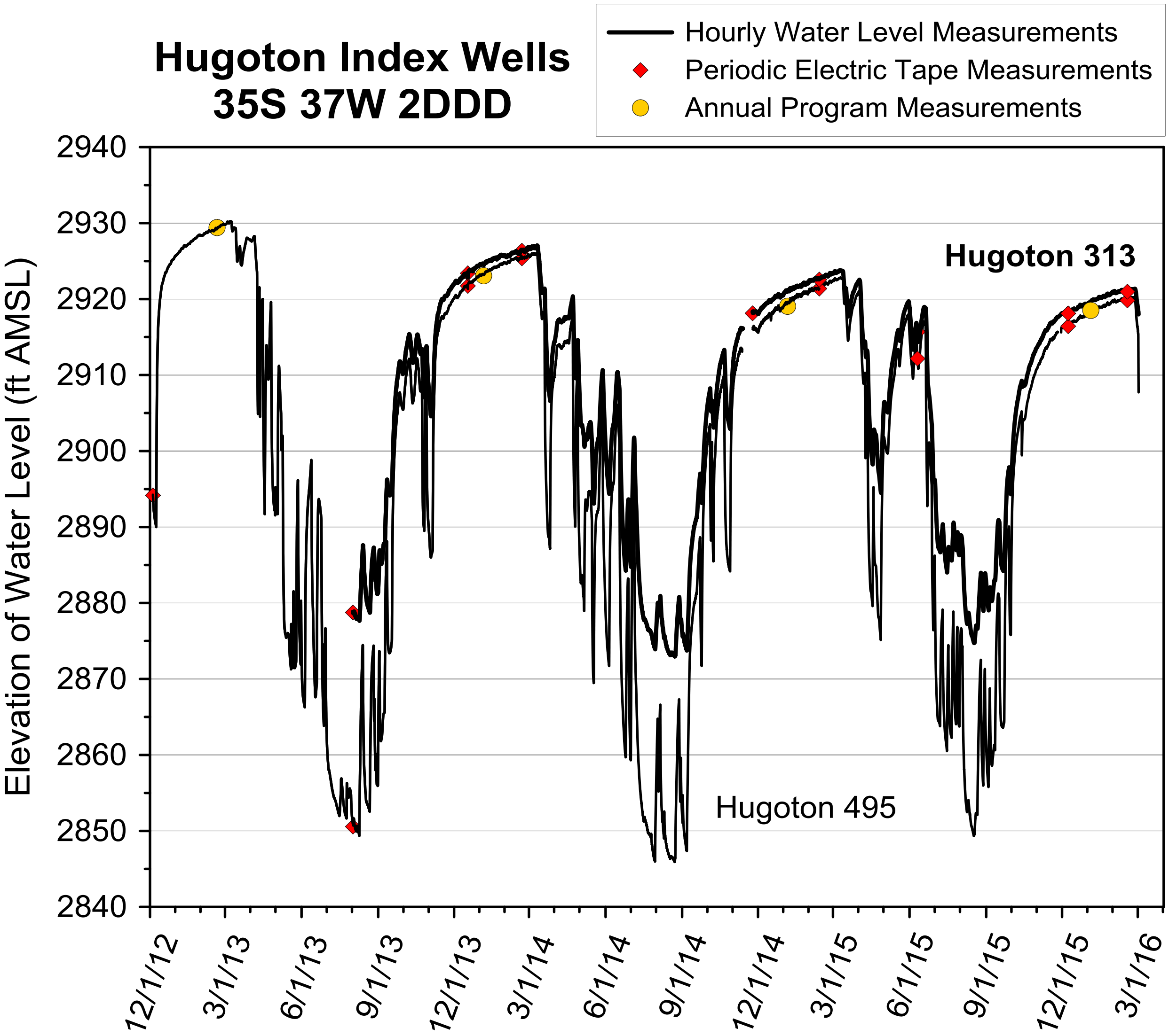


Figure 13—Hydrographs of Hugoton index wells—total data run to 3/1/16. A water-level elevation of 2,930.0 ft corresponds to a depth to water of 170.0 ft below land surface (lsf). For the Hugoton 495 well, the top of the 10-ft screen is 485 ft below lsf (elevation of 2,615 ft). For the Hugoton 313 well, 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 13—General characteristics of the Hugoton 495 index well hydrograph and local water-use data.

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

[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.

3.2.1.3.2. Measurement Comparisons

Table 14—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
	2,929.34[e]	NA	Transducer
1/5/2014	2,923.07	NA (-4.1)	Steel tape
	2,923.18[c]	-3.19	Transducer
	2,923.27[e]	NA	Transducer
1/5/2015	2,919.05	-4.02 (-3.3)	Steel tape
	2,919.55[c]	-3.63	Transducer
	2,919.47[e]	-3.80	Transducer
1/4/2016	2,918.51	-0.54 (NA)	Steel Tape
	2,918.24[c,f]	-1.31	Transducer
	2,918.18[e,f]	-1.29	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, not corrected for barometric pressure.

[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] Average of values over time interval 0800–1600, corrected for barometric pressure using KGS barometric correction program.

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

3.2.1.4. *Rolla Site*

Figure 14—Aerial view of Rolla index well site, two additional annual program wells, and nearby points of diversion.

Figure 14 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 instrumented (henceforth, Rolla 366 or Rolla index well).

3.2.1.4.1. Hydrograph and General Observations

Figure 15 shows the hydrograph for the Rolla index well, table 15 summarizes its general characteristics, and table 16 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 and 2015 annual program measurements appear to be questionable; the 2016 annual program measurement is consistent with the hourly transducer measurements.

The 2014–2015 recovery began on September 20, 2014, and ended on April 20, 2015. Other than small regional pumping influences in the early spring of 2015, there was little pumping during the recovery period. The 2015 pumping season began with a nearly one-month period of sustained pumping (April 20 to May 18) after which there was more than a month (May 18 to June 23) of little to no pumping. A nearby well began pumping on June 23 and continued, save for a few brief shutdowns in August, until September 21. The 2015–2016 recovery season was continuing at the time of the February 17, 2016, download used for this report; there has been little pumping during recovery.

Water-use data for 2015 will be available later in 2016. The reported 2014 use (1,295.9 ac-ft for a 2-mile radius centered on the index well) was 258 ac-ft less than in 2013, which is surprising given the much greater drawdown observed in 2014 at the Rolla index well (minimum water-level elevation in 2014 was 1.2 ft below that of 2013; maximum observed recovery in 2015 was 1.2 ft below that of 2013). The water use for 2015 appears to have been less than that in 2014 as the minimum water-level elevation in 2015 was just 0.2 ft below that of 2014.

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 from McMahon (2001, table 2) using recent elevation measurements (14 ft added to McMahon [2001] 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 2016 is recovering to near 3,188.0 ft, a loss of about 9.0 ft in 16 years (0.6 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 8.6 ft over this same time period.

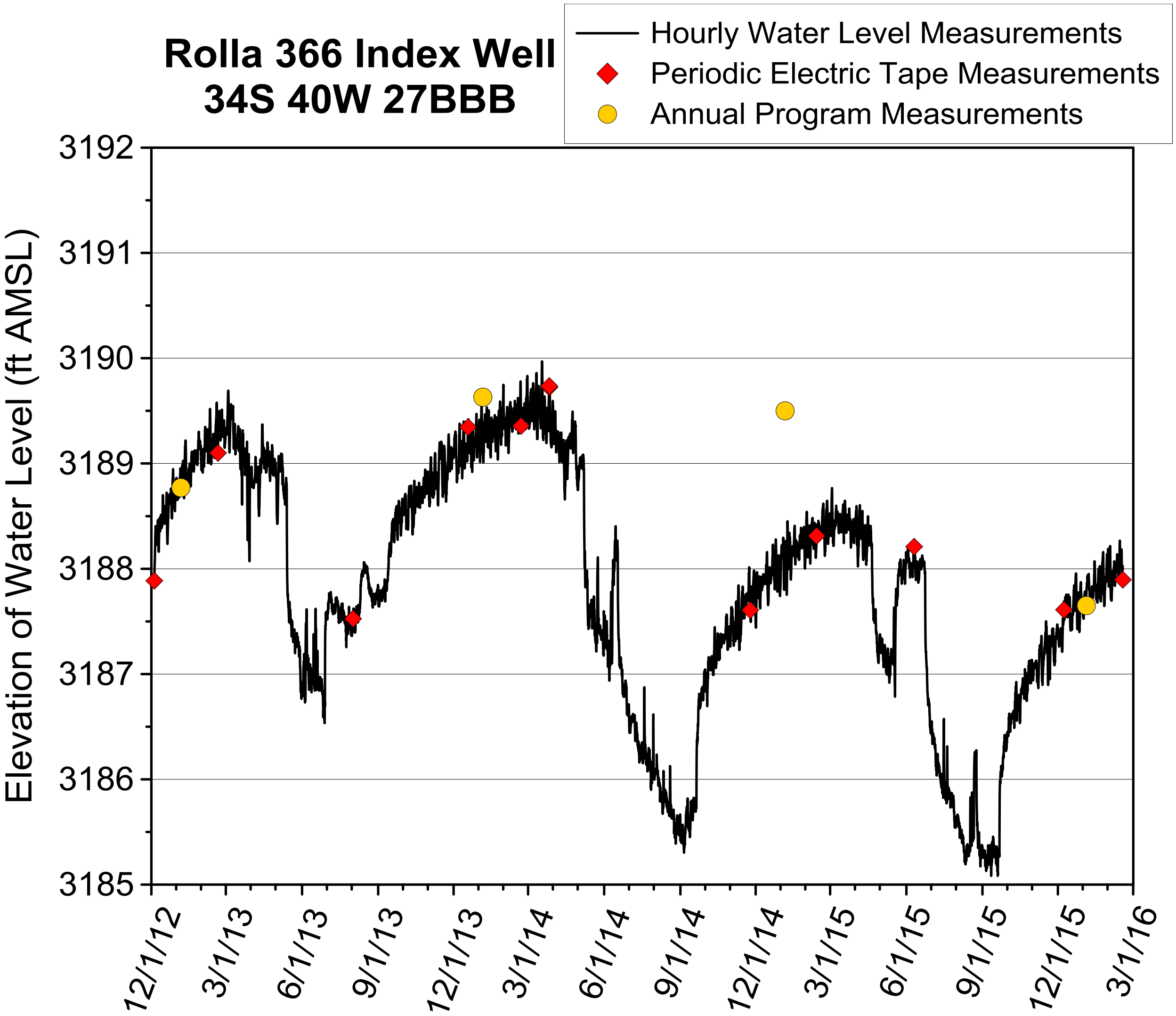


Figure 15—Rolla 366 index well hydrograph—total data run to 2/17/16. A water-level elevation of 3,188 ft corresponds to a depth to water of 187 ft below land surface (lsf). The top of the 10-ft screen is 356 ft below lsf (elevation of 3,019 ft) and the bottom of the aquifer is 399 ft below lsf (elevation of 2,976 ft); note the suspect 2014 and 2015 annual program measurement.

Table 15—General characteristics of the Rolla 366 index well hydrograph and local water-use data.

		2013	**2014**	**2015**
Minimum Water-Level Elevation	Feet	3,186.5	3,185.3	3,185.1
	Date	6/28/13	9/5/14	9/11/15 & 9/19/15
Maximum Observed Recovery Elevation	Feet	3,189.7	3,190.0	3,188.8
	Date	3/3/13	3/17/14	3/3/15
Apparent Recovery	Feet	NA	3.5	3.5
Annual Change in Maximum Observed Recovery	Feet	NA	+0.3	-1.2
Recovery Season	Start	NA	9/12/13	9/20/14
	End	3/9/13	3/17/14	4/20/15
	Length (Days)	NA	185.6	212.1
Pumping During Recovery Season	Length (Days)	NA	5.3	8.5
Length of Pumping Season	Days	186	187	153.0
2-mi Radius Water Use[a]	Irrigated Acres	1,331	1,331	NA
	Total (ac-ft)	1,553.6	1,295.9	NA
	Irrigation Use Only (ac-ft)	1,448.0	1,211.0	NA
	Use per Irrigated Acre (ft)	1.09	0.91	NA

[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

3.2.1.4.2. Measurement Comparisons

Table 16—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
	3,188.82[d]	NA	Transducer
1/5/2014	3,189.63[e]	+0.86[e] (+0.27)	Steel tape
	3,189.08[c]	+0.21	Transducer
	3,189.28[d]	+0.46	Transducer
1/5/2015	3,189.50[f]	-0.13[e,f] (-1.2)	Steel tape
	3,188.15[c]	-0.93	Transducer
	3,188.09[d]	-1.19	Transducer
1/4/2016	3,187.65	-1.85[f] (NA)	Steel tape
	3,187.77[c]	-0.38	Transducer
	3,187.77[d]	-0.32	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, not corrected for barometric pressure.

[d] Average of values over time interval 0800–1600, corrected for barometric pressure using KGS barometric correction program.

[e] Suspect 2014 annual measurement value.

[f] Suspect 2015 annual measurement value.

3.2.2. Colby Index Well

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 all 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.

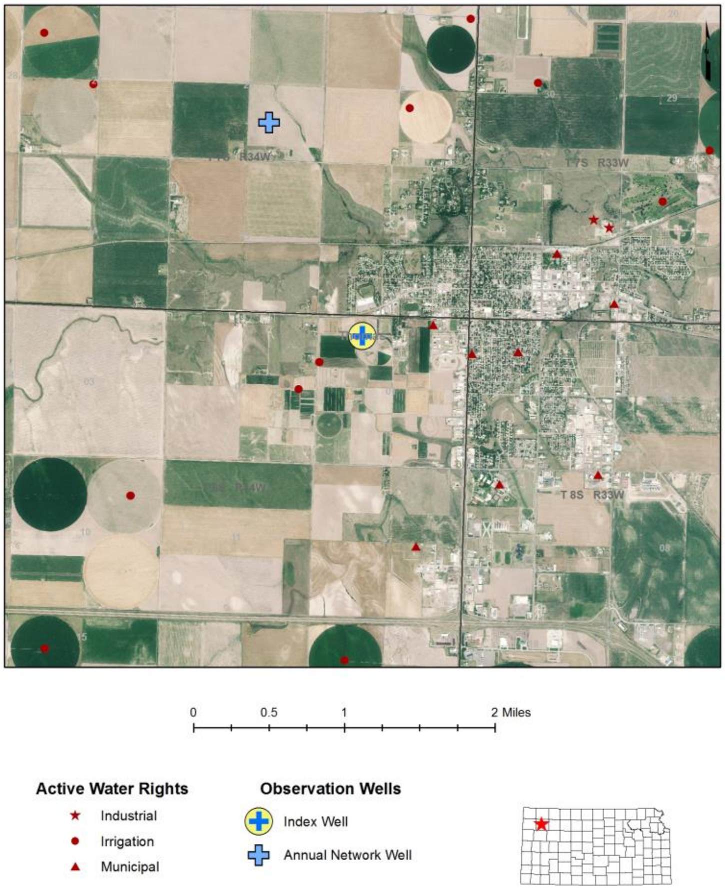


Figure 16—Aerial view of Colby index well, an additional annual program well, and nearby points of diversion.

Figure 16 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 is not currently available. 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.

3.2.2.1. *Hydrograph and General Observations*

Figure 17 shows the hydrograph for the Colby index well, table 17 summarizes its general characteristics, and table 18 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 2014–2015 recovery began on September 10, 2014, and ended on March 18, 2015. In addition to an extended period of pumping from November 29 to December 16, 2014, there was sporadic pumping throughout the recovery period. The 2015 pumping season began with an initial pumping period slightly more than one month. This was followed by a period of little pumping from April 22 to June 20, 2015. This break in pumping was likely due to planting of summer crops and late spring rains. Other than a break from July 15 to July 28, 2015, sustained pumping continued until the end of the pumping season on September 5, 2015. The 2015–2016 recovery was continuing at the time of the download used for this report (March 14, 2016). As with the 2014–2015 recovery, there has been sporadic pumping throughout the recovery period. Water-use data for 2015 will be available later in 2016. In 2014, water use within the 2-mi radius surrounding the index well was 2,575 ac-ft, the majority of which appears to have been municipal pumping for the city of Colby; irrigation pumping was only about 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 2016, the water level was more than 148 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).

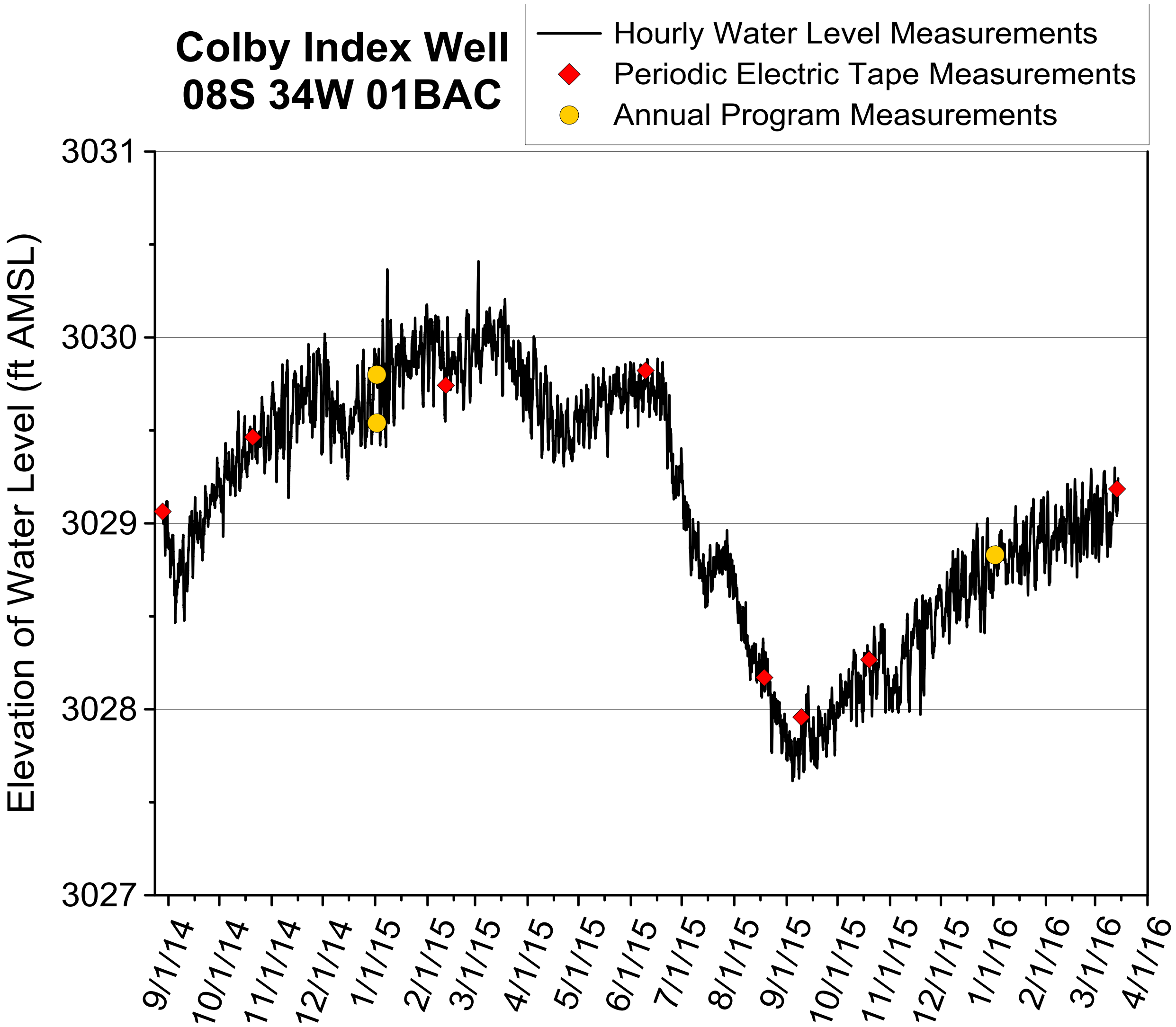


Figure 17—Colby index well hydrograph—total data run to 3/14/16. A water-level elevation of 3,029 ft corresponds to a depth to water of 148 ft below land surface (lsf). Total depth of the well is 175 ft below lsf (elevation of 3,002 ft). Information about the screened interval is not currently available. The base of the aquifer is estimated to be 250–300 ft below lsf (see text).

Table 17—General characteristics of the Colby index well hydrograph and local water-use data.

		2014	2015
Minimum Water-Level Elevation	Feet	3,028.5	3,027.6
	Date	9/4/14	9/4/15
Maximum Observed Recovery Elevation	Feet	NA	3,030.4
	Date	NA	3/3/15
Apparent Recovery	Feet	NA	1.9
Annual Change in Maximum Observed Recovery	Feet	NA	NA
Recovery Season	Start	NA	9/10/14
	End	NA	3/18/15
	Length (Days)	NA	189
Pumping During Recovery Season	Length (Days)	NA	35.5
Length of Pumping Season	Days	NA	170
2-mi Radius Water Use[a]	Irrigated Acres	695	NA
	Total (ac-ft)	2,575	NA
	Irrigation Use Only (ac-ft)	855	NA
	Use per Irrigated Acre (ft)	1.23	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 18—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
	NA	NA	Transducer
1/2/2015	3,029.80	-0.79 (NA)	Steel tape
	3,029.79[c]	NA	Transducer
	3,029.74[d]	NA	Transducer
1/2/2016	3,028.83	-0.97 (NA)	Steel tape
	3,028.84[c]	-0.95	Transducer
	3,028.74[d]	-1.0	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, not corrected for barometric pressure.

[d] Average of values over time interval 0800-1600, corrected for barometric pressure using KGS barometric correction program.

3.2.3. Belpre Index Well

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. The original transducer 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 of 2015, the transducer 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.

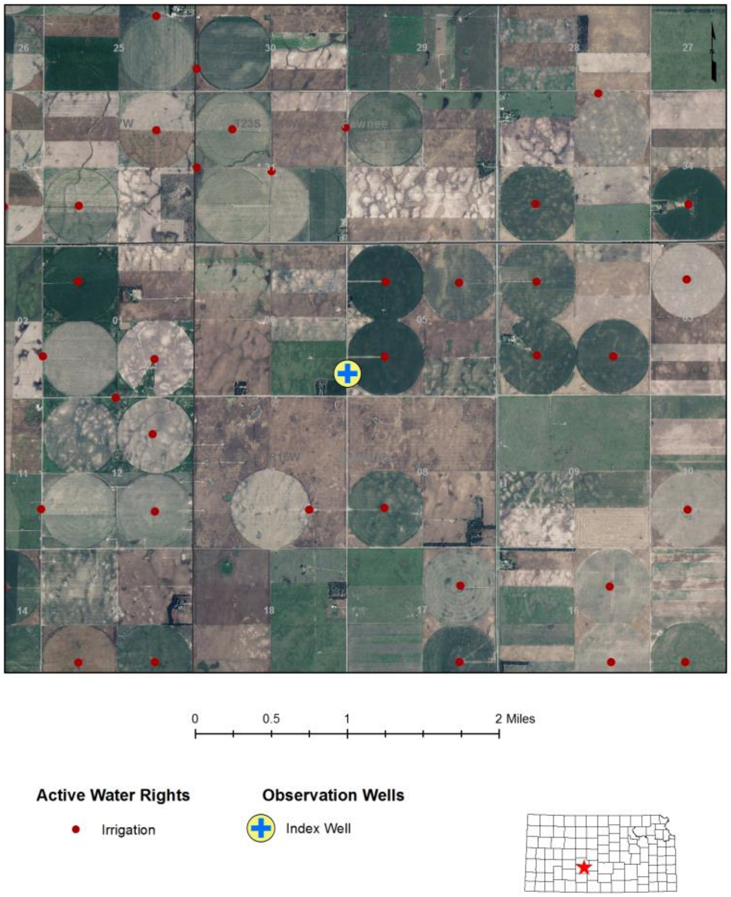


Figure 18—Aerial view of the Belpre index well and nearby points of diversion.

Figure 18 is an aerial view of the Belpre index well site (T. 24 S., R. 16 W., 05 CBB 01) 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 instrumented (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.

3.2.3.1. *Hydrograph and General Observations*

Figure 19a shows the hydrograph for the Belpre 109 index well, table 19 summarizes its general characteristics, and table 20 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 impact of individual nearby pumping wells is not discernible; the water-level response to pumping appears to be more integrated in nature.

The 2014–2015 recovery began on September 23, 2014, and ended on June 20, 2015. There was little pumping during the recovery period. The 2015 pumping season was characterized by sustained pumping until the end of the pumping season on September 6, 2015. The 2015–2016 recovery was continuing at the time of the download used for this report (February 24, 2016). As with the 2014–2015 recovery, there has been little pumping during the recovery period. The recovery plot for 2015–2016 appears to have a more concave-downward curvature than that for 2014–2015. That increased curvature is likely a product of regional pumping activity during the recovery period. Water-use data for 2015 will be available later in 2016. In 2014, water use within the 2-mi radius surrounding the index well was 2,004 ac-ft. The 2014 water use was applied on 2,332 acres, resulting in water use per acre irrigated of 0.85 ft (table 19).

A noteworthy feature of the Belpre hydrograph is the numerous upward spikes, such as that marked by the asterisk on Figure 19a. An expanded view of the period in the vicinity of that spike is shown in Figure 19b. The rapid rise (A) followed by the gradual decline (B) indicates a recharge event that is most likely dissipated by lateral flow. 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. A smaller recharge event is also seen at C on Figure 19b. Both recharge events are associated with precipitation events on the same day (or late in the preceding day).

The Belpre 109 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 28 years, the general trend has been downward with a total decline of 11.0 ft since January of 1988 (decline rate of 0.39 ft/yr).

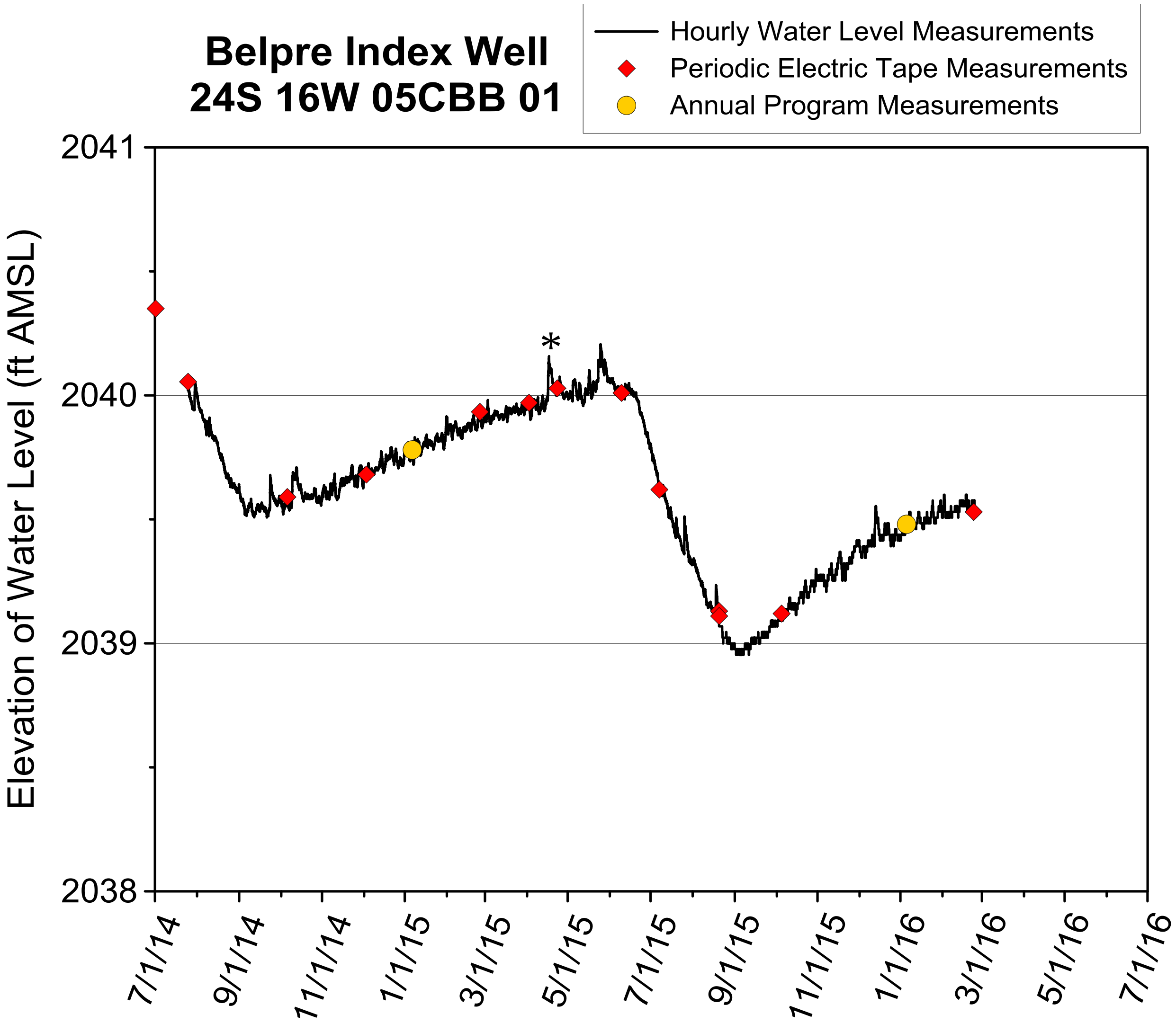


*Figure 19a—Belpre index well hydrograph—total data run to 2/24/16. A water-level elevation of 2,040 ft corresponds to a depth to water of 40 ft below land surface (lsf). The top of the 20-ft screen is 89 ft below lsf (elevation of 1,951 ft) and the bottom of the screen is 109 ft below lsf (elevation of 1,931 ft). The base of the aquifer is estimated to be 175–200 ft below lsf (see text). Note that the resolution of the datalogger was inadvertently reduced in the summer of 2015 producing the more pixelated plot following that time. The resolution will be corrected at the next download. * defined in text.*

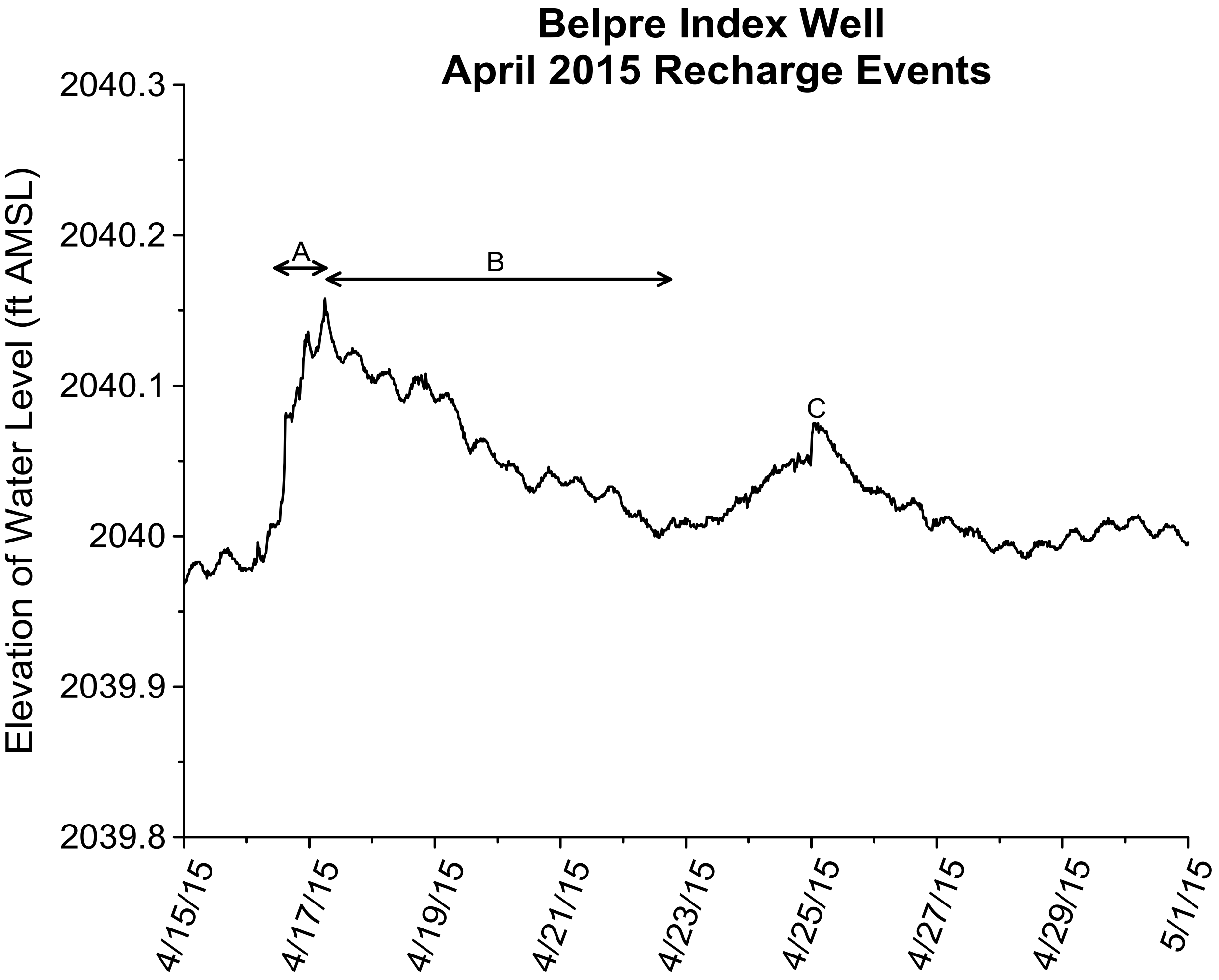


Figure 19b —Expanded view of Belpre index well hydrograph for the last half of April 2015 (interval beginning at the asterisk on Figure 19a). A-C *defined in text.*

Table 19—General characteristics of the Belpre index well hydrograph and local water-use data.

		2014	2015
Minimum Water-Level Elevation	Feet	2,039.5	2039.0
	Date	9/12/14 and 9/21/14	9/11/15
Maximum Observed Recovery Elevation	Feet	NA	2040.2
	Date	NA	5/25/15
Apparent Recovery	Feet	NA	0.70
Annual Change in Maximum Observed Recovery	Feet	NA	NA
Recovery Season	Start	NA	9/23/14
	End	NA	6/20/15
	Length (Days)	NA	269.7
Pumping During Recovery Season	Length (Days)	NA	5.6
Length of Pumping Season	Days	NA	83.0
2-mi Radius Water Use[a]	Irrigated Acres	2,332	NA
	Irrigation Use Only (ac-ft)	2,003.9	NA
	Use per Irrigated Acre (ft)	0.85	NA

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

Table 20—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
	NA	NA	Transducer
1/6/2015	2,039.78	-0.67 (NA)	Electric tape
	2,039.76[c]	NA	Transducer
	2,039.78[d]	NA	Transducer
1/5/2016	2,039.48	-0.30 (NA)	Electric tape
	2,039.48[c]	-0.28	Transducer
	2,039.48[d]	-0.30	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, not corrected for barometric pressure.

[d] Average of values over time interval 0800–1600, corrected for barometric pressure using KGS barometric correction program.

3.2.4. 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 2015. The KGS formally took over the collection of water-level data for these wells in mid-year 2014, while GMD4 continued to maintain the sensors. At that time, each SD-6 well had a transducer in the water column that was 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 existing equipment is being 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. Both sets of equipment are currently in all but the Beckman index well; the original equipment should be removed in summer 2016. Unless indicated in the discussion in the following sections, the data from the two transducers overlay each other except when affected by anomalous spikes produced by high temperatures in the datalogger housing. In future reports, the original transducer will be used until the KGS transducer/datalogger unit was placed in the well. After that, the KGS transducer/datalogger unit will be used.

Figure 20 provides an aerial view of the SD-6 index wells and Table 21 summarizes site characteristics and information about each well. In this section, we provide a brief overview and interpretation of the hydrographs from each of these wells.

Hydrographs for all five LEMA wells up until the time of the download for this report (March 14, 2016) 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.

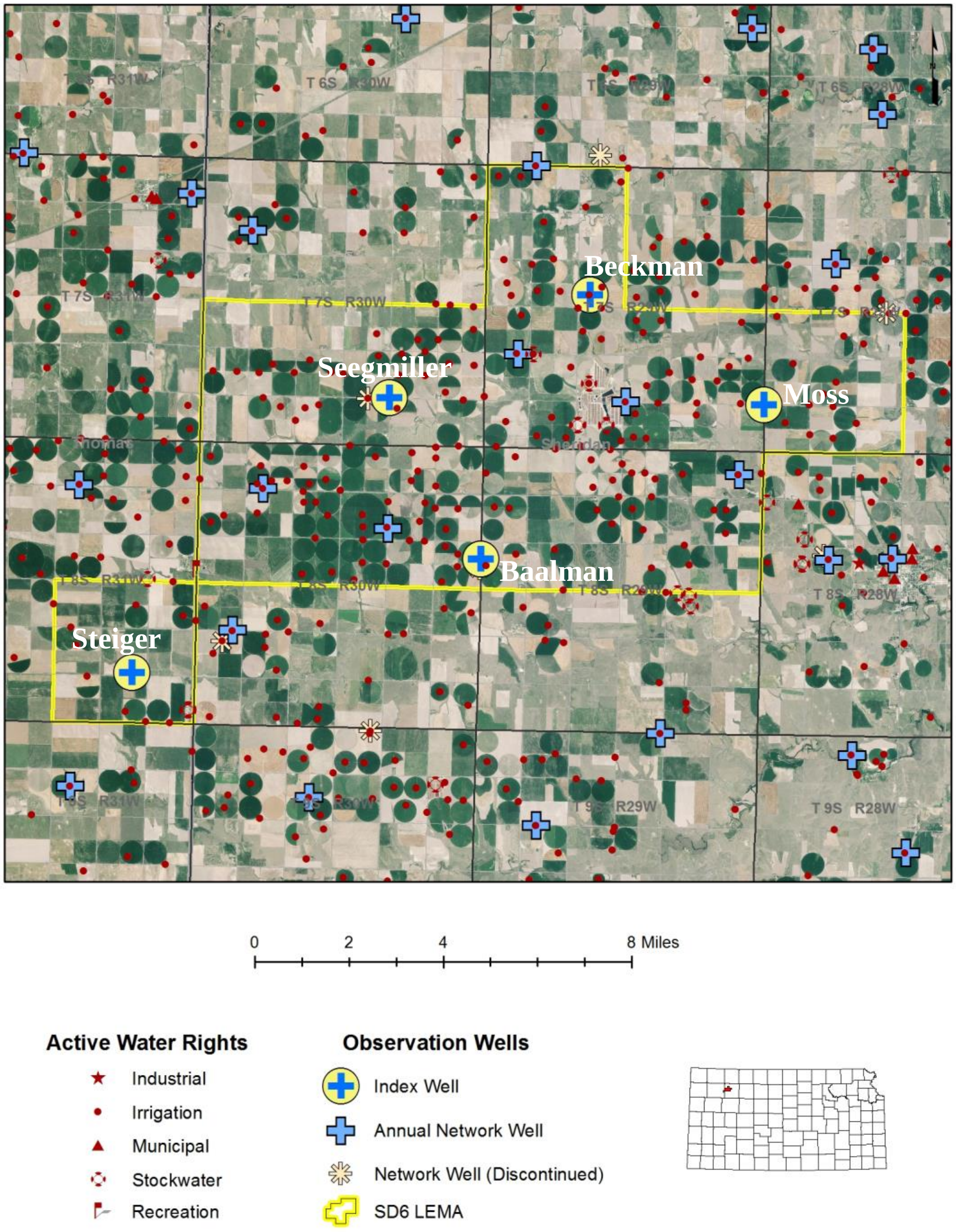


Figure 20—Aerial view of the SD-6 index wells, additional annual program wells, and points of diversion.

Table 21—Characteristics of the SD-6 index wells.

Site	2016 WL elev. (ft)[a]	2016 Saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2014 Water Use (ac-ft)		
					1-mi circle	2-mi circle	5-mi circle
Baalman 1	2,714.48				781	2,672	16,420[d]
Baalman 2[b]	2,713.41[c]	78.41	262	260–270	770	2,792	16,415[d]
Beckman[b]	2,683.25[c]				676	3,142[h]	14,826[e]
Moss[b]	2,626.91[c]	53.91	243	205–245	229	2,600	16,690[f]
Seegmiller[b]	2,741.60[c]	73.60	265	225–265	719	3,136	16,282[e]
Steiger[b]	2,850.74[c]	62.74	177	145–185	218	1,167[i]	11,502[g]

[a] 2016 annual tape water-level measurements from WIZARD database.
[b] Not an annually measured index well.
[c] 2016 WL measurements from hand measurements taken 03/14/2016.
[d] Includes 653.23 ac-ft of non-irrigation stock water.
[e] Includes 564.48 ac-ft of non-irrigation stock water.
[f] Includes 476.38 ac-ft of non-irrigation stock water, 381.97 ac-ft of non-irrigation municipal water, and 0.61 ac-ft of non-irrigation industrial water.
[g] Includes 33.91 ac-ft of non-irrigation stock water and 4.03 ac-ft of non-irrigation recreational water.
[h] Includes 222.65 ac-ft of non-irrigation stock water.
[i] Includes 20.82 ac-ft of non-irrigation stock water.

3.2.4.1. *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. 20). Monitoring originally began on May 5, 2012, in an existing well, Baalman index well 1. The existing well was relatively small diameter (1.25 in Sch 80), 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 was drilled in August 2015 and monitoring in that well began on August 19, 2015. Well construction information for Baalman index well 1 is not available but construction information is available for Baalman index well 2 (see Appendix A).

3.2.4.1.1. Hydrograph and General Observations

Figure 21a and 21b shows the hydrographs for Baalman index wells 1 and 2, respectively; table 22 summarizes the general characteristics of the Baalman index well 1 hydrograph (the hydrograph for Baalman index well 2 will be described in future reports); and table 23 compares the manual and transducer measurements from the well. The broadening of the hydrograph troughs observed in fig. 21a from 2013 on may be a product of the blockage in the well casing and is not consistent with any of the other SD-6 index wells. Thus, there is considerable uncertainty about the quality of the data from Baalman index well 1. This uncertainty is increased by the lack of agreement between the August 2015 and later data from the two Baalman index wells (figures 21a and 21b). Our conclusion was that Baalman index well 1 was not providing an accurate representation of water-level responses; the transducer and datalogger were therefore removed from the well on March 14, 2016. All future assessments of the Baalman index well hydrograph will be based on the data from Baalman index well 2 hydrograph. An analysis of water-level fluctuations induced by variations in barometer 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 2 behaves as an unconfined aquifer.

Water use data for 2015 will be available later in 2016. The reported 2014 use (2,672 ac-ft for a 2-mile radius centered on the index well) was 90 ac-ft more than in 2013, the first year of the SD-6 LEMA, and 1,222 ac-ft less than in 2012. Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.84 ft (10 inches)/acre in the vicinity of the Baalman index well.

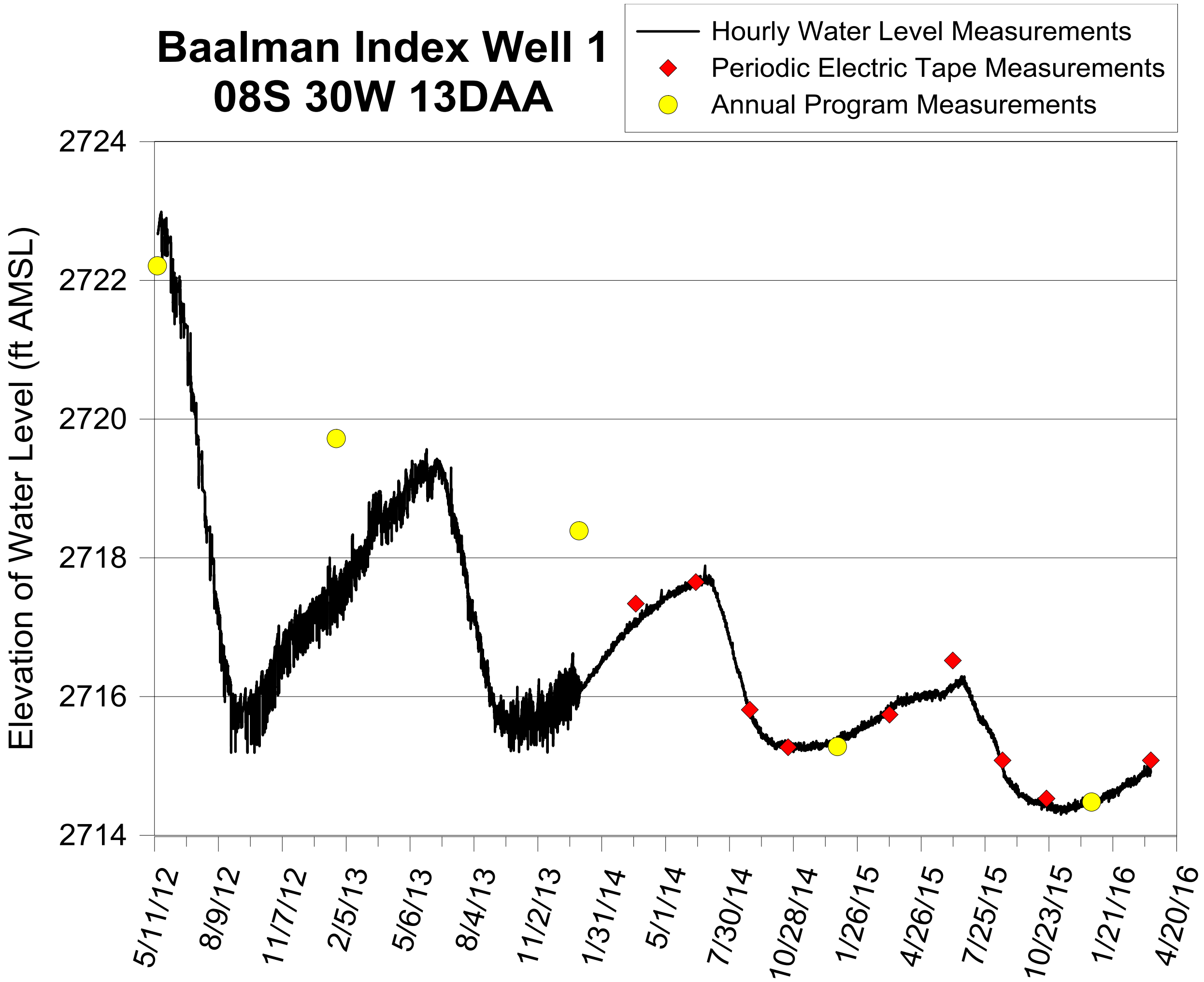


Figure 21a—Baalman index well 1 hydrograph—total data run to 3/14/16. A water-level elevation of 2,718 ft corresponds to a depth to water of 183.83 ft below land surface (lsf). Well construction information not available. High-frequency fluctuations in 2012 and 2013 were produced by operation of a nearby small capacity well. Differences between manual and transducer measurements are likely due to the small diameter (1.25 in Sch 80) of the well. The broadening of the water-level troughs in late summer and fall is discussed in text.

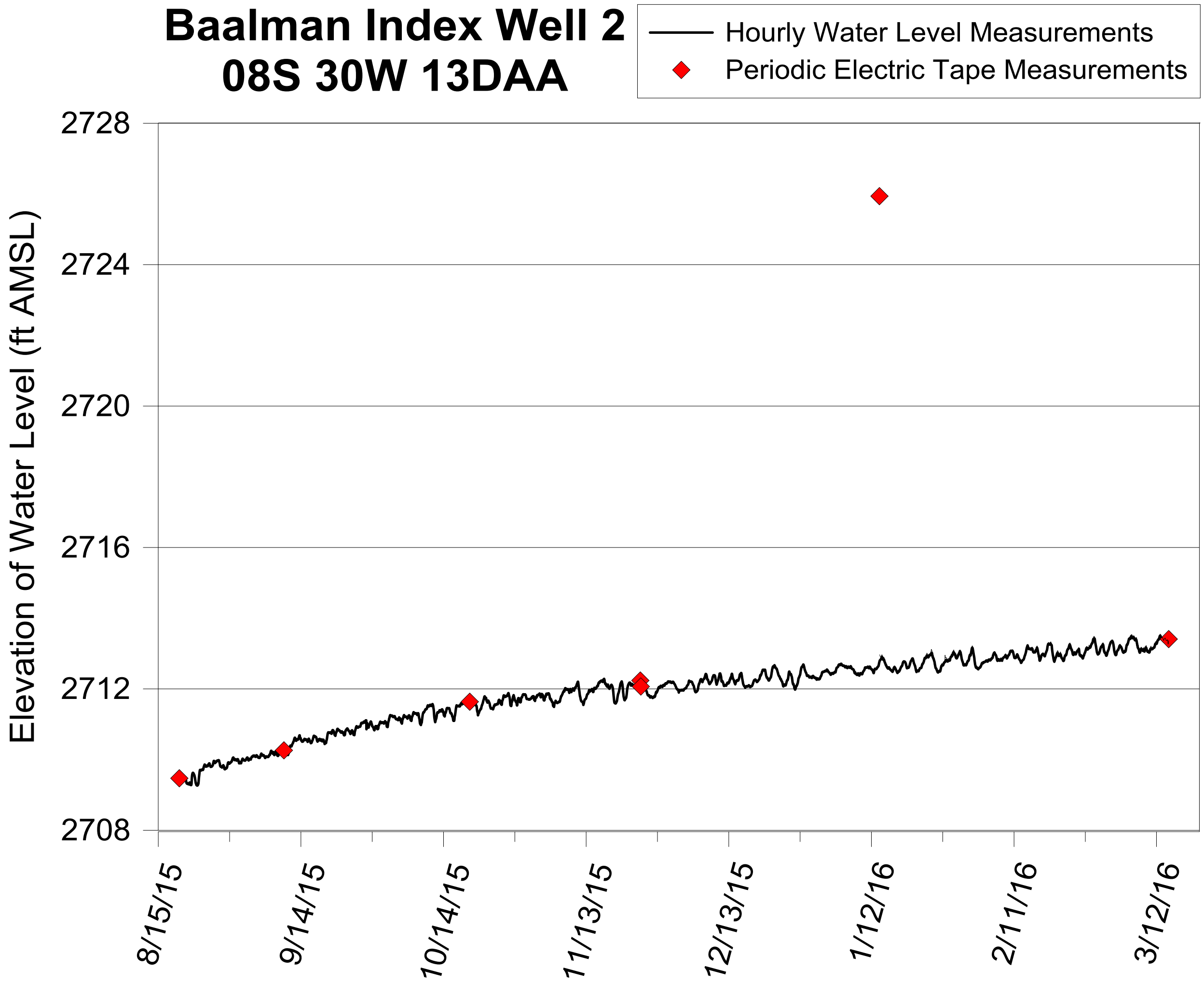


Figure 21b—Baalman index well 2 hydrograph—total data run to 3/14/16. A water-level elevation of 2,712 ft corresponds to a depth to water of 185.00 ft below land surface (lsf); the top of the 10-ft screen is 260 ft below lsf (elevation of 2,637.0 ft), and the bottom of the aquifer is 262 ft below lsf (elevation of 2,635.0 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 1 hydrograph and local water-use data.

		2012	**2013**	**2014**	**2015**
Minimum Water-Level Elevation	Feet	2,715.2	2,715.2	2,715.2	2,714.3
	Date	8/26/12	10/6/13 and 11/15/13	10/28/14	11/8/15
Maximum Observed Recovery Elevation	Feet	NA	2,719.6	2,717.9	2,716.3
	Date	NA	5/29/13	6/25/14	6/22/15
Apparent Recovery	Feet	NA	4.4	2.7	1.1
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-1.7	-1.6
Recovery Season	Start	NA	8/26/12	9/24/13	11/14/14
	End	NA	6/12/13	7/2/14	6/25/15
	Length (Days)	NA	289.8	280.5	223.5
Pumping During Recovery Season	Length (Days)	NA	NA	NA	NA
Length of Pumping Season	Days	NA	104	135	142
2-mi Radius Water Use	Irrigated Acres	3,081	3,134	3,150	NA
	Total (ac-ft)	3,893.9	2,581.5	2,671.9	NA
	Use per Irrigated Acre (ft)	1.26	0.82	0.85	NA

Table 23—Annual water-level measurement[a] comparison with transducer measurements, Baalman index well 1.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/22/2013	2,719.72[d]	NA	Steel tape
	2,717.55	NA	Transducer
12/30/2013	2,718.39[d]	-1.33[e] (-1.68)	Steel tape
	2,716.12[c]	-1.43	Transducer
12/29/2014	2,715.28	-3.11[e] (-1.59)	Steel tape
	2,715.33[c]	-0.79	Transducer
12/22/2015	2,714.48	-0.80 (NA)	Steel tape
	2,714.44[c]	-0.89	Transducer

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=392124100364001). Baalman index well 2 will be used by the annual program in future years.

[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, not corrected for barometric pressure.

[d] Annual measurement appears to be in error.

[e] Affected by apparent errors in annual measurements.

3.2.4.2. *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. 20). The well was installed in the gravel pack of an irrigation well; the stickup 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 currently not available.

3.2.4.2.1. Hydrograph and General Observations

Figure 22 shows the complete hydrograph for the Beckman index well and table 24 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 very limited impact on water levels in the Beckman index well. An analysis of water-level fluctuations induced by variations in barometer 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.

The 2014–2015 recovery began on September 9, 2014, and ended on June 20, 2015. Other than pumping in October 2014 and early spring of 2015, there was little pumping during the recovery period. The 2015 pumping season was characterized by many small pumping periods, the longest of which was the final 14-day period of the pumping season ending on September 6, 2015. Recovery was ongoing at the time of the download for this report (March 14, 2016).

Water-use data for 2015 will be available later in 2016. The reported 2014 use (3,142 ac-ft for a 2-mi radius centered on the index well) was 210 ac-ft less than in 2013, the first year of the SD-6 LEMA, and 2,511 ac-ft less than in 2012. Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been less than 0.83 ft (10 inches)/acre in the vicinity of the Beckman well.

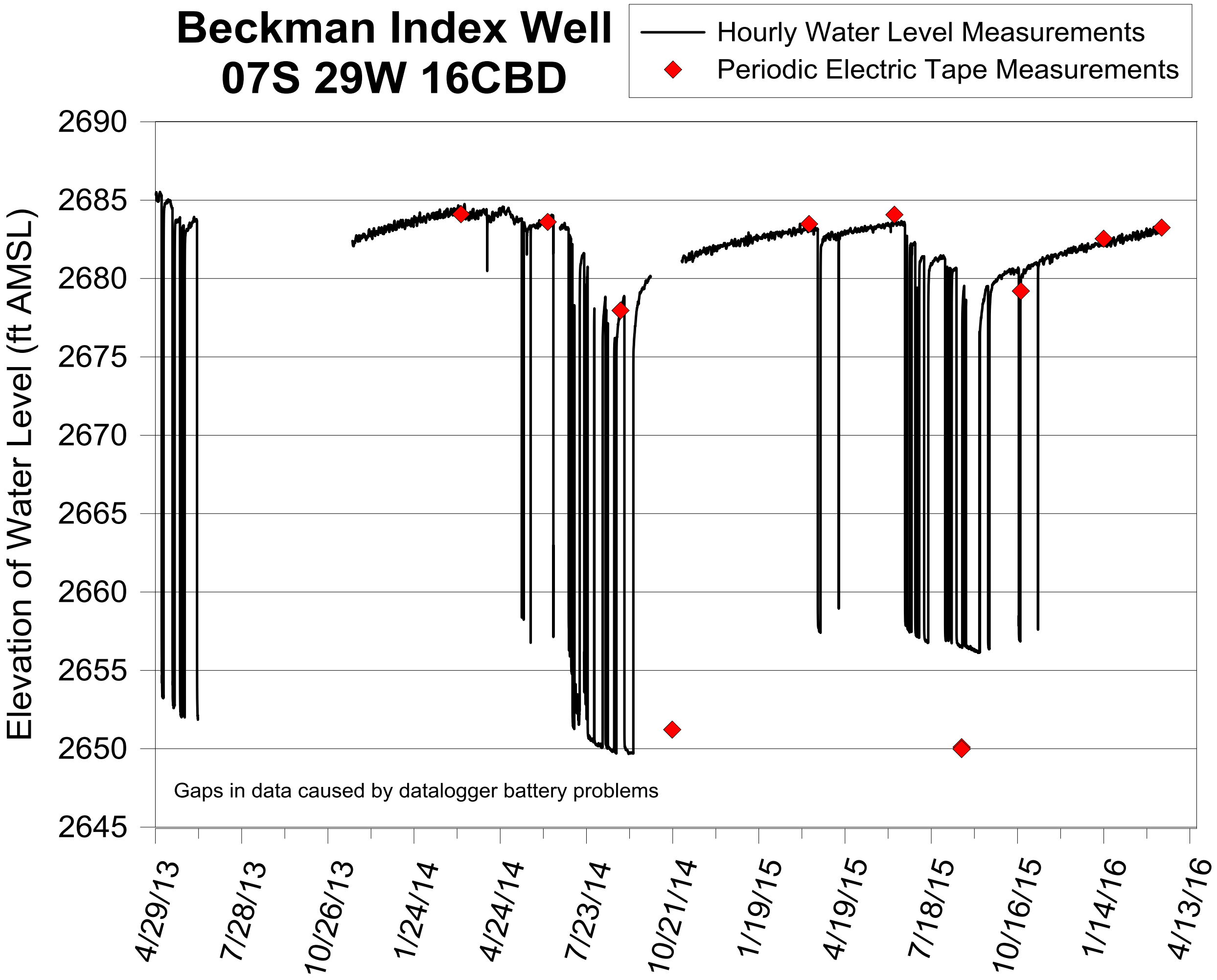


Figure 22—Beckman index well hydrograph—total data run to 3/14/16. A water-level elevation of 2,650 ft corresponds to a depth to water of 230.15 ft below land surface (lsf). The difference between the electric tape measurement in the summer of 2015 and the hourly measurements from the transducer is thought to be caused by a change in calibration specifications associated with the resumption of monitoring in late October 2014.

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

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

[a] 2012 Irrigated Acres—3,730, Irrigation use only—5,402.7 ac-ft, Use per Irrigated Acre—1.45 ft
2013 Irrigated Acres—3,837, Irrigation use only—3,123.8 ac-ft, Use per 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.

3.2.4.3. *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. 20). The well is screened over the bottom 38 ft of the High Plains aquifer, which was approximately 54 ft in thickness in January 2016. Monitoring began on May 22, 2012, and has continued with few problems beyond occasional spurious values produced by datalogger overheating.

3.2.4.3.1. Hydrograph and General Observations

Figure 23 shows the complete hydrograph for the Moss index well and table 25 summarizes its general characteristics. The impact 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 21). 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 2014–2015 recovery began on August 24, 2014, and ended on June 22, 2015; there appeared to be very little pumping during the recovery period. Other than an approximately three-week period of little pumping beginning on July 7, pumping was sustained from June 22, 2015, until the end of the pumping season on September 12, 2015. Recovery was ongoing at the time of the download for this report (March 14, 2016).

Water-use data for 2015 will be available later in 2016. The reported 2014 use (2,600 ac-ft for a 2-mi radius centered on the index well) was 127 ac-ft more than in 2013, the first year of the SD-6 LEMA, and 1,462 ac-ft less than in 2012. Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been slightly under 1 ft/acre in the vicinity of the Moss well.

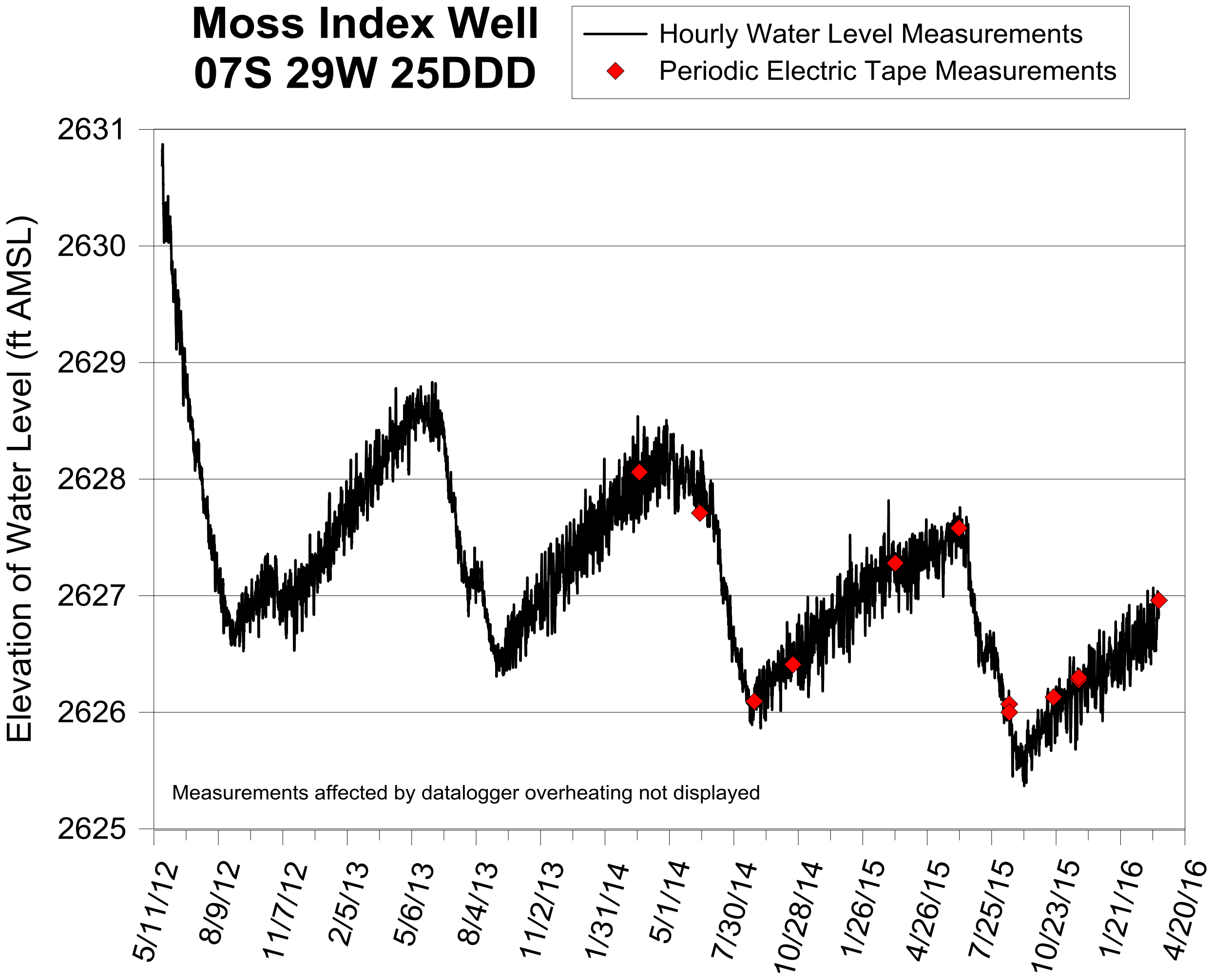


Figure 23—Moss index well hydrograph—total data run to 3/14/16. A water-level elevation of 2,627 ft corresponds to a depth to water of 191.44 ft below land surface (lsf); The top of the 40-ft screen is 205 ft below lsf (elevation of 2,613.4 ft), and the bottom of the aquifer is 243 ft below lsf (elevation of 2,575.4 ft).

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

		2012	2013	2014	2015
Minimum Water-Level Elevation	Feet	2,626.5	2,626.3	2,625.9	2,625.4
	Date	9/13/12	9/1/13	9/5/14	9/8/15
Maximum Observed Recovery Elevation	Feet	NA	2,628.8	2,628.5	2,627.8
	Date	NA	6/13/13	3/17/14	3/3/15
Apparent Recovery	Feet	NA	2.3	2.2	1.9
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-0.3	-0.7
Recovery Season	Start	NA	8/31/12	9/12/13	8/24/14
	End	NA	5/21/13	5/1/14	6/22/15
	Length (Days)	NA	263.2	231.0	301.8
Pumping During Recovery Season	Length (Days)	NA	15.7	0	0
Length of Pumping Season	Days	NA	114.0	115.0	78.0
2-mi Radius Water Use	Irrigated Acres	2,725	2,577	2,644	NA
	Total (ac-ft)	4,062.2	2,473.2	2,599.9	NA
	Use per Irrigated Acre (ft)	1.49	0.96	0.98	NA

3.2.4.4. *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. 20). The well is screened over the bottom 40 ft of the High Plains aquifer, which was approximately 74 ft in thickness in January 2016. Monitoring began on May 15, 2012, and has continued with few problems beyond occasional spurious values produced by datalogger overheating.

3.2.4.4.1. Hydrograph and General Observations

Figure 24 shows the complete hydrograph for the Seegmiller index well and table 26 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 2014–2015 recovery began on August 22, 2014, and ended on June 25, 2015; other than a six-day pumping period in mid-April 2015, there was very little pumping during the recovery period. Sustained pumping began on June 25 and largely continued until July 15, after which there was a 19-day period during which most pumps in the area were not active. The pumping season concluded with a 16-day period of sustained pumping ending on September 5, 2016 during which most of the wells in the area were active. Recovery was ongoing at the time of the download for this report (March 14, 2016).

Water-use data for 2015 will be available later in 2016. The reported 2014 use (3,136 ac-ft for a 2-mi radius centered on the index well) was 262 ac-ft more than in 2013, the first year of the SD-6 LEMA, and 2,335 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.

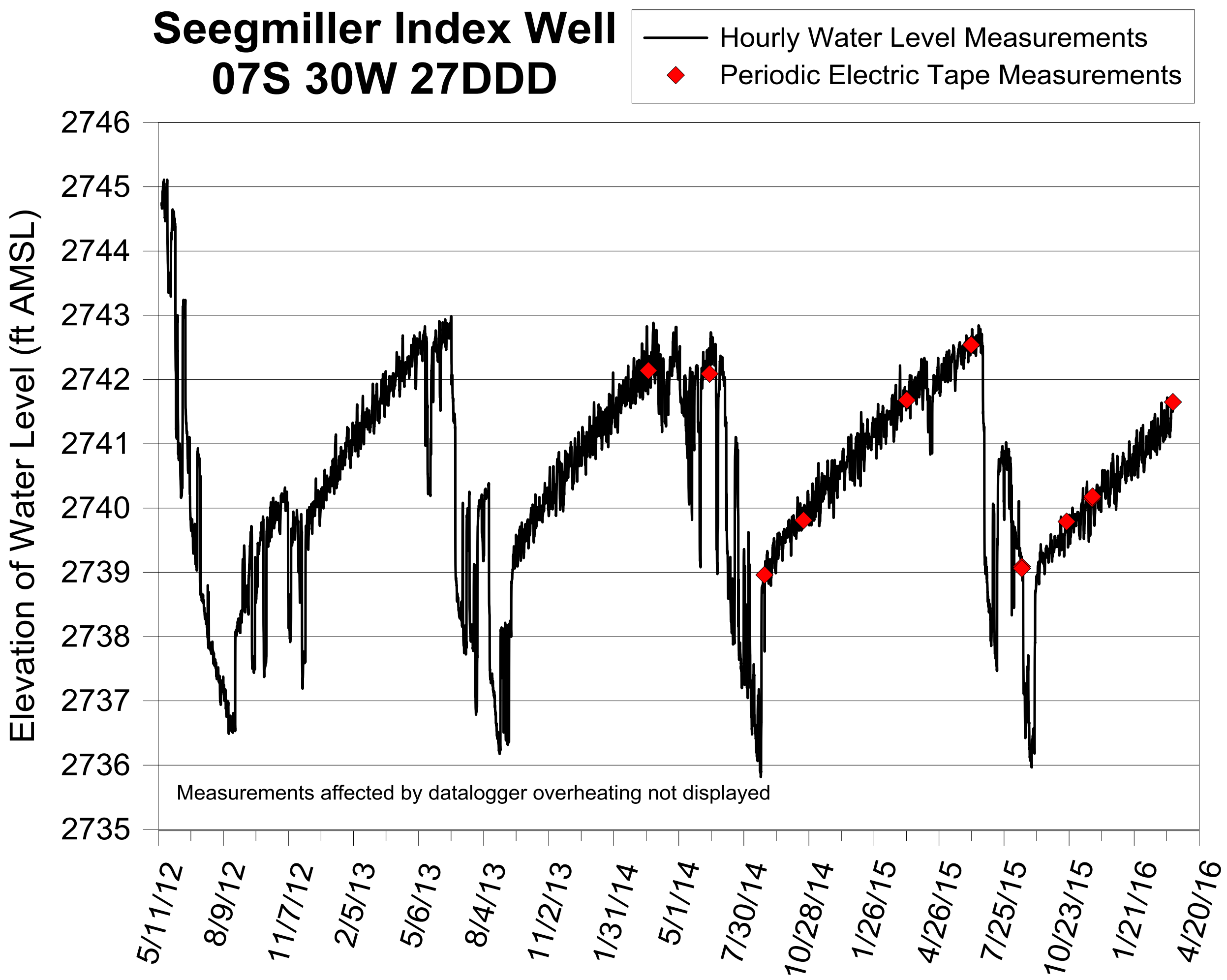


Figure 24—Seegmiller index well hydrograph—total data run to 3/14/16. A water-level elevation of 2,740 ft corresponds to a depth to water of 195.69 ft below land surface (lsf); the top of the 40-ft screen is 225 ft below lsf (elevation of 2,710.7 ft), and the bottom of the aquifer is 265 ft below lsf (elevation of 2,670.7 ft).

Table 26—General characteristics of the Seegmiller index well hydrograph and local water-use data.

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

3.2.4.5. *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. 20). The well is screened over the bottom 32 ft of the High Plains aquifer, which was approximately 63 ft in thickness in January 2016. Monitoring began on May 15, 2012, and has continued with few problems beyond spurious values produced by datalogger overheating.

3.2.4.5.1. Hydrograph and General Observations

Figure 25 shows the complete hydrograph for the Steiger index well, and table 27 summarizes the local water-use data. The impact of individual pumping wells is difficult to discern on the Steiger hydrograph beyond the vicinity of A on figure 25. 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 2015 will be available later in 2016. The reported 2014 use (1,167 ac-ft for a 2-mile radius centered on the index well) was 81 ac-ft more than in 2013, the first year of the SD-6 LEMA, and 723 ac-ft less than in 2012. Since the establishment of the SD-6 LEMA, the water use per irrigated acre has been approximately 0.9 ft (11 in)/acre in the vicinity of the Steiger well.

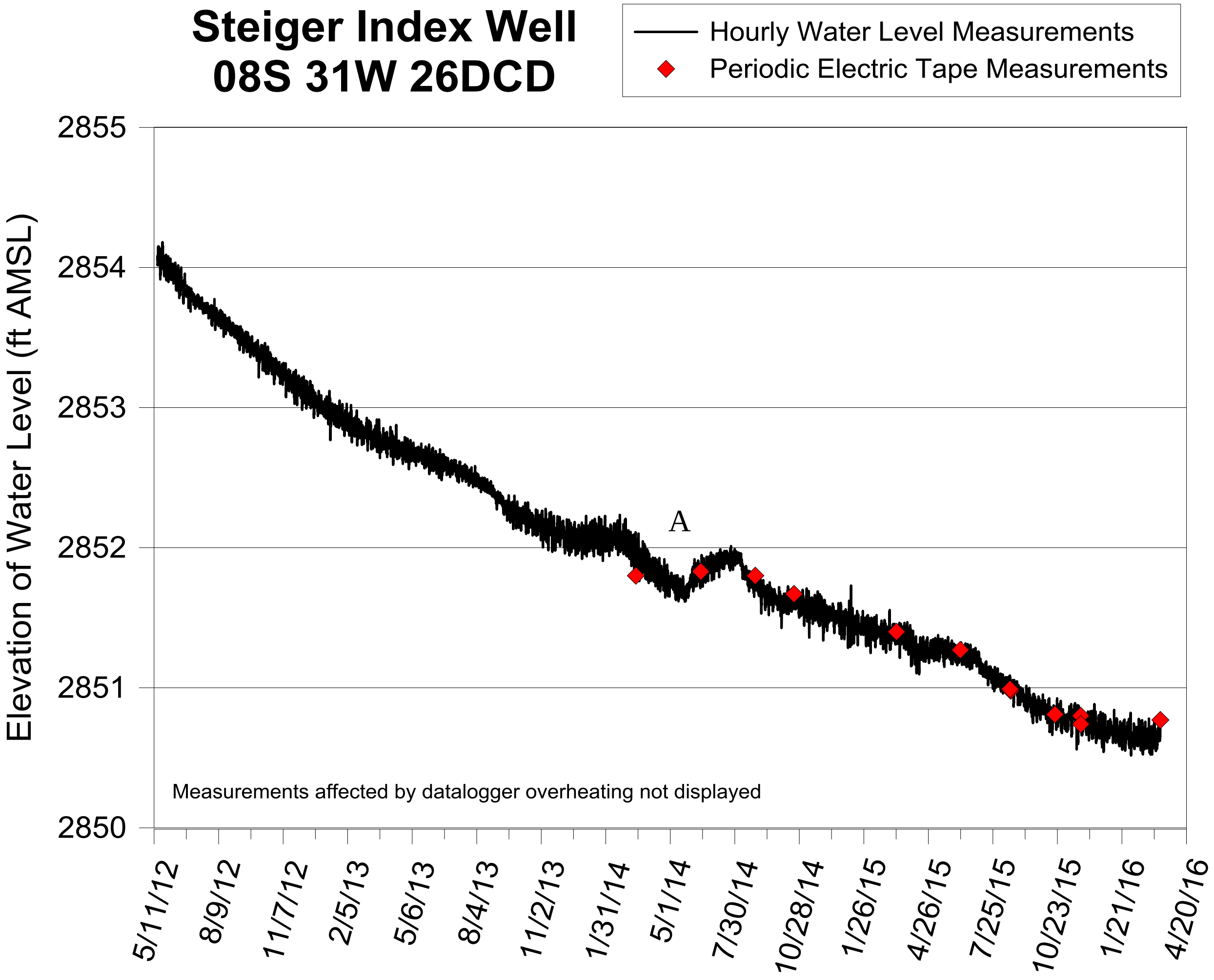


Figure 25—Steiger index well hydrograph—total data run to 3/14/16. A water-level elevation of 2,851 ft corresponds to a depth to water of 116.53 ft below land surface (lsf); the top of the 40-ft screen is 145 ft below lsf (elevation of 2,822.5 ft), and the bottom of the aquifer is 177 ft below lsf (elevation of 2,790.5 ft). A defined in text.

Table 27—Steiger index well local water-use data[a]*.*

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

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

3.2.5. New GMD1 Index Wells

3.2.5.1. *Lane County Site*

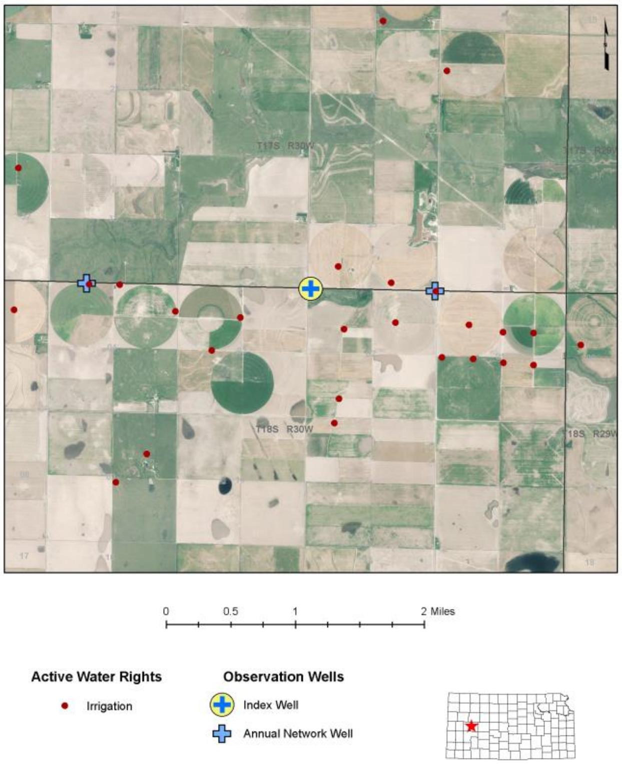


Figure 26—Aerial view of Lane County site, additional annual program wells, and nearby points of diversion.

Figure 26 is an aerial view of the Lane County site (T. 18 S., R. 30 W., 2 BBB) at a scale that shows the recently drilled index well, and nearby annual program wells and points of diversion. The location of 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. Just under one mile east of the index well is an annual program well (T. 18 S., R. 30 W., 2 AAA) that has been measured since 1972. The water level has fallen a little over 16 ft in the course of the monitoring period.

The Lane index well was drilled, completed, and developed March 29–30, 2016. The well was drilled using a 6.25 in drag bit to 140 ft below land surface (all following measurements are with respect to land surface). A yellow sandstone (driller's description) or yellow ochre (weathered shale) was encountered at 118 ft and black shale was encountered at 130 ft (WWC-5 form for well provided in Appendix A). The bottom of the aquifer was assumed to be the start of the weathered shale at 118 ft. The screened interval of the well was set from 105 to 115 ft in a fine to coarse sand interval; a sump was installed from 115 to 125 ft for accumulation of fines that might move into the well. Gravel pack was placed (tremied into the borehole) from 95 to 140 ft, and grout was placed (tremied) from the top of the gravel pack to the surface. The following day, the liquid grout had settled 14 ft below surface so bentonite pellets and water were used for the surface seal. The static water level in the well was 82.85 ft below land surface prior to development. Thirty minutes after the air lift development was completed, the static water level in the well was 84.64 ft. Thus, it appears that the saturated interval at the Lane County site is approximately 33 ft in thickness. The transducer and telemetry system will be installed in the Lane County well in early June 2016, and an interpretation of the hydrograph will be provided in a subsequent report.

3.2.5.2. *Wichita County Site*

Figure 27—Aerial view of Wichita County site, an additional annual program well, and nearby points of diversion.

Figure 27 is an aerial view of the Wichita County site (T. 16 S., R. 38 W., 16 CCCA) at a scale that shows the recently drilled index well, an additional annual program well, and nearby points of diversion. The location of 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, and it was close enough to Ladder Creek to observe whether the aquifer might be getting recharge from the creek. Just a little over two miles to the southeast of the index well is an annual program well (T. 16 S., R. 38 W., 26 BBB) that has been measured since 1968. The water level has fallen a little more than 51 ft in the course of the monitoring period.

The Wichita index well was drilled and completed March 31–April 1, 2016. The well was drilled using a 6.25 in drag bit to 200 ft below land surface (all following measurements are with respect to land surface). A yellow soapstone (driller's description) or yellow ochre (weathered shale) was encountered at 190 ft, and black shale was encountered at 195 ft (WWC-5 form for well provided in Appendix A). The bottom of the aquifer was assumed to be the start of the weathered shale at 190 ft. The screened interval of the well was set from 175 to185 ft in a sequence of fine to medium sand with a few clay layers; a sump was installed from 185 to 195 ft for accumulation of fines that might move into the well. Gravel pack was placed (tremied into the borehole) from 166 to 200 ft, and grout was placed (tremied) from the top of the gravel pack to the surface. The following day, the liquid grout had settled 17 ft below surface so bentonite pellets and water were used for the surface seal.

On April 4, we tried to develop the well but found that 19 ft of fines had filled the sump and all but one foot of the screened interval. We couldn't get enough water through that one foot of open screen to airlift the fines out of the well. On April 11, the drill crew returned to the site and used the drill rig to pump water down the well to flush the fines up to the surface. They were successful in clearing all but one foot of fines out of the sump.

The static water level in the well was 158.6 ft below land surface prior to development. Thirty minutes after the air lift development was completed, the static water level in the well was 160.0 ft. Thus, it appears that the saturated interval at the Wichita County site is approximately 30 ft in thickness. The transducer and telemetry system will be installed in the Wichita County index well in early June 2016, and an interpretation of the hydrograph will be provided in a subsequent report.

3.2.5.3. *Wallace County Site*

Figure 28—Aerial view of Wallace County site, additional annual program wells, and nearby points of diversion.

Figure 28 is an aerial view of the Wallace County site (T. 14 S., R. 42 W., 10 BAA) at a scale that shows the recently drilled index well, two additional annual program wells, and nearby points of diversion. The location of the index well site was chosen because it is in the area of some of the largest saturated thickness in GMD1 and appears to have sufficient saturated thickness, relative to the recorded declines in the area, to serve as a monitoring well for a number of years. A half a mile to the north of the index well is an annual program well (T. 14 S., R. 42 W., 10 BAA) that has been measured annually since 1977. The water level has fallen approximately 103 ft in the course of the monitoring period.

The Wallace County index well was drilled and completed April 6–8, 2016. The well was drilled using a 6.25 in drag bit to 405 ft below land surface (all following measurements are with respect to land surface). A black shale was encountered at 394 ft, which was assumed to be the bottom of the aquifer (WWC-5 form for well provided in Appendix A). The screened interval of the well was set from 375 to 385 ft in a fine to coarse sand sequence; a sump was installed from 385 to 395 ft for accumulation of fines that might move into the well. Gravel pack was placed (tremied into the borehole) from 365 to 400 ft, and grout was placed (tremied) from the top of the gravel pack to the surface. The following day, the liquid grout had settled 14 ft below surface so bentonite pellets and water were used for the surface seal.

On April 8, we tried to develop the well but found that 20 ft of fines had filled the sump and all of the screened interval. We cleaned out the grout from the tremie pipe and installed the pipe in the casing to a depth of approximately 355 ft and used the pump on the drill rig to pump water down the pipe to flush out the fines. After about an hour of flushing, the screen and sump were cleared to 393.5 ft. The well was then developed using airlifting for four hours. After development, the bottom of the well was measured at 394.2 ft (less than one foot of fines remaining in the sump.). The depth to water was 259.7 ft below land surface. Thus, it appears that the saturated interval at the Wallace County site is approximately 134 ft in thickness.

The transducer and telemetry system will be installed in the Wallace County index well in early June 2016, and an interpretation of the hydrograph will be provided in a subsequent report.

3.2.6. 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.

3.2.6.1. *SC-8 Site*

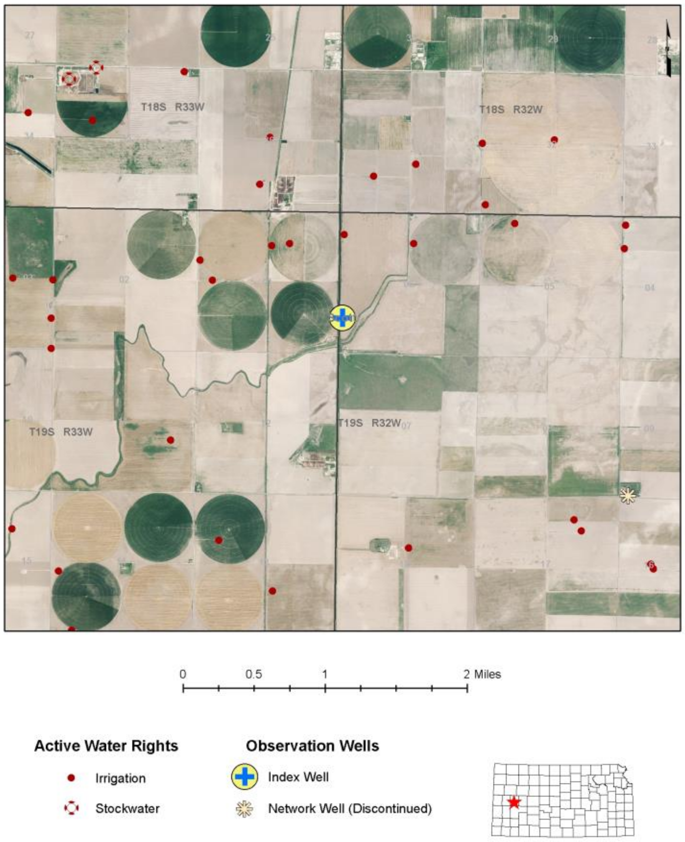


Figure 29—Aerial view of SC-8 site and nearby points of diversion.

Figure 29 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 well is located just 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. However, that field does not appear to have been irrigated during the monitoring period. The fields adjacent to the site to the west have been irrigated during the monitoring period.

3.2.6.1.1. Hydrograph and General Observations

Figure 30a displays the complete hydrograph for the SC-8 well. The approximately four 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 up 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 is the large number of upward spikes in the water level, such as the one marked by A on figure 30a. Smaller spikes can also be observed in 2013 and 2014 after removal of the fluctuations produced by variations in barometer 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. An expanded view of a three-day period around A in fig. 30a is presented in fig. 30b. There likely is an opening in the well casing at the surface that allows the flow to enter the well. We will closely examine the well during our site visits in 2016 to try to identify and, if possible, seal that point of entry.

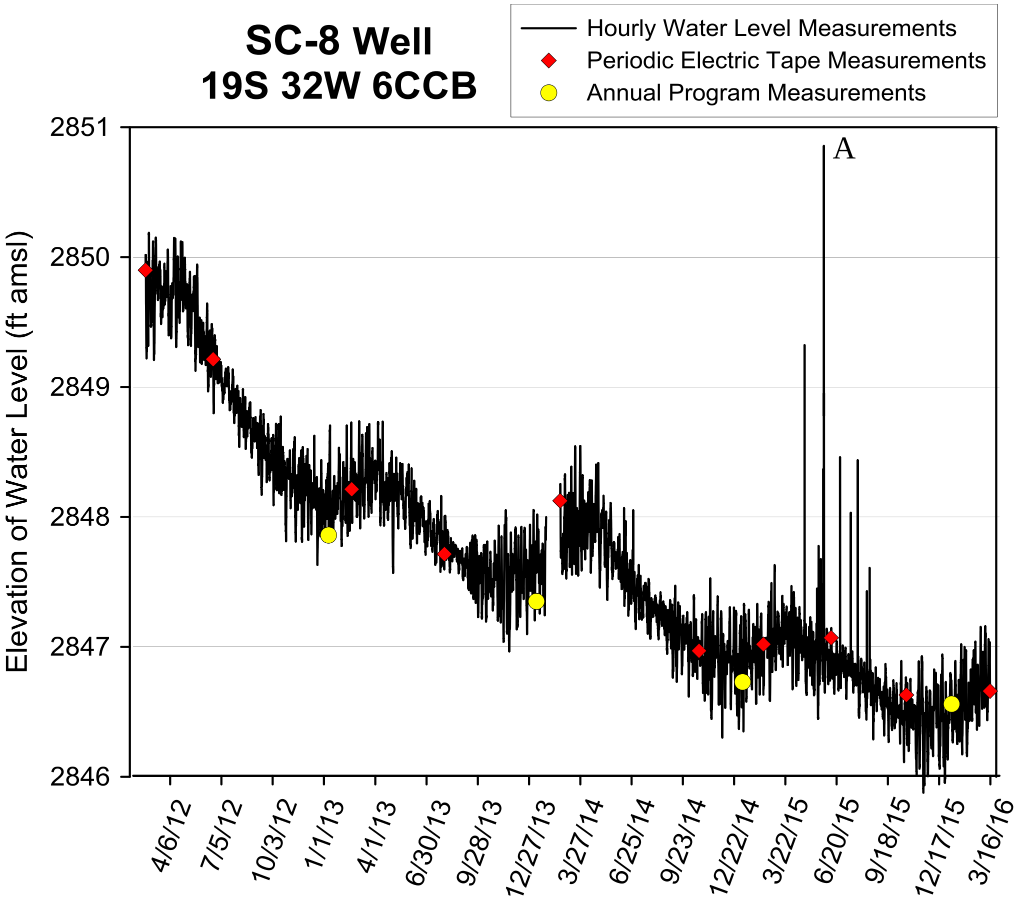


Figure 30a—SC-8 well hydrograph—total data run until 3/15/16. A water-level elevation of 2,847 ft corresponds to a depth to water of 89 ft below land surface (lsf). Bottom of well is approximately 102 ft below lsf (elevation of 2,835 ft). Note that transducer measurements have been corrected from earlier reports for an incorrect offset parameter. A defined in text.

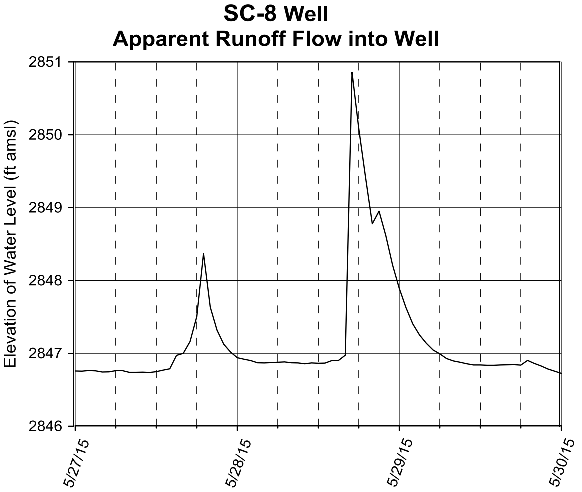


Figure 30b—Expanded view of SC-8 well hydrograph for three days in late May 2015 (A in fig. 30a). Each spike is associated with a precipitation event.

3.2.7. 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. 31). 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 28 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 32 shows hydrographs from the Thomas index well and these three currently operating expansion wells. Data from the closest expansion wells (TH9 and TH11) are briefly examined here. The interpretation of these hydrographs and those from wells TH7 and TH10 will be explored further in 2016.

Table 28—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–Current	Active irrigation well, sensor installed and removed each year by KGS and GMD4 at land owner’s request. Sensor not installed for the 2012–2013 recovery. Sensor still in well at time of this report (3/24/16).
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–Currrent	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.

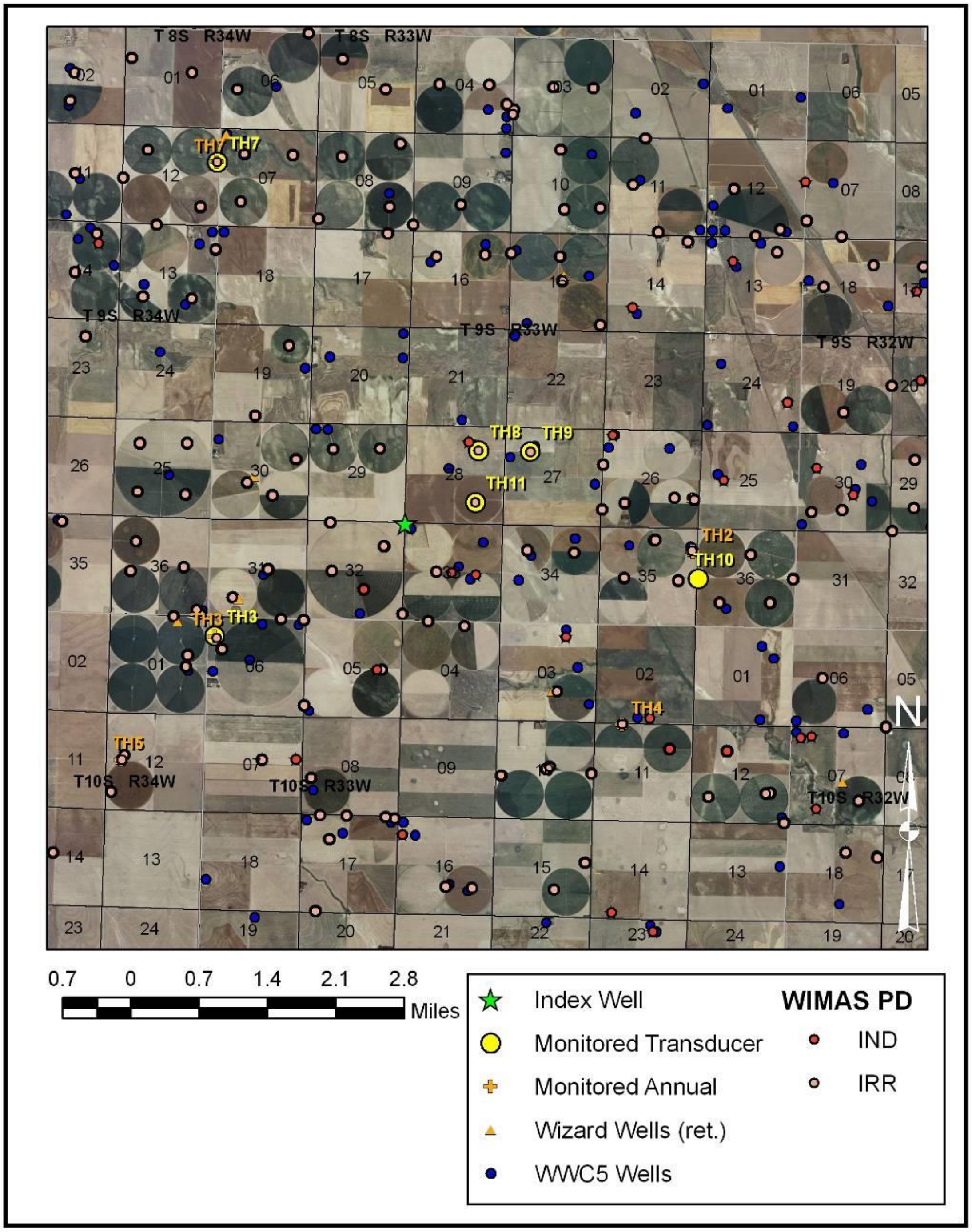


Figure 31—Aerial view of portion of Thomas County in the vicinity of the index well, showing the index well, nearby wells that have or had been equipped with transducers, surrounding annual program wells, and points of diversion in the area.

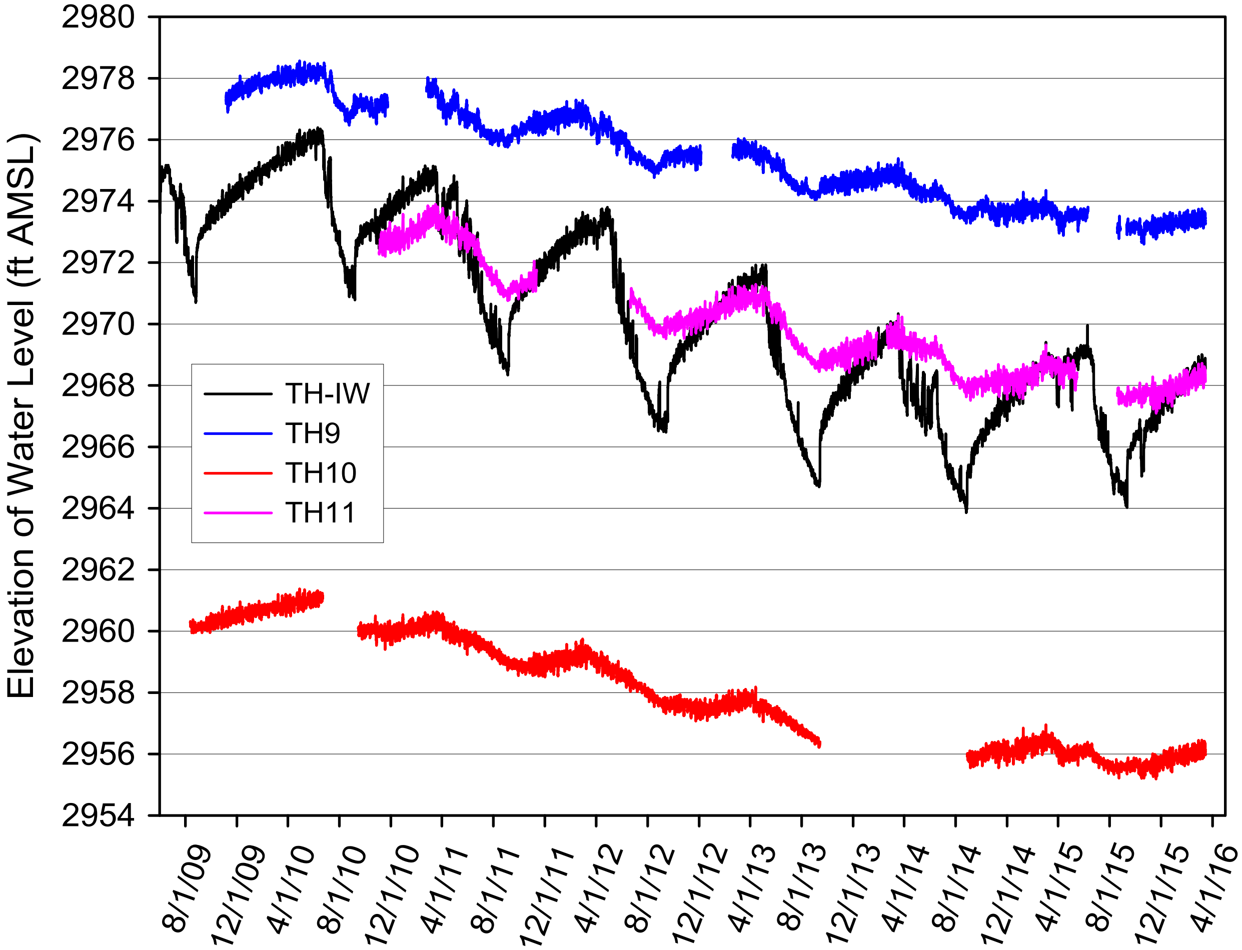


Figure 32—Hydrograph comparison from the Thomas index well (TH-IW) and currently continuously operating Thomas expansion wells—total data run to 3/15/16. The general water-level trend indicates west-to-east groundwater flow. The elevation of the water level in TH10 has been increased 6.75 ft over the 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. 33a). 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. 31]) in the TH9 hydrograph but are still clearly apparent. However, there are a few instances where the responses are greater (e.g., A and B on fig. 33a), 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. A more detailed analysis and interpretation of the well TH9 hydrograph will be pursued in 2016.

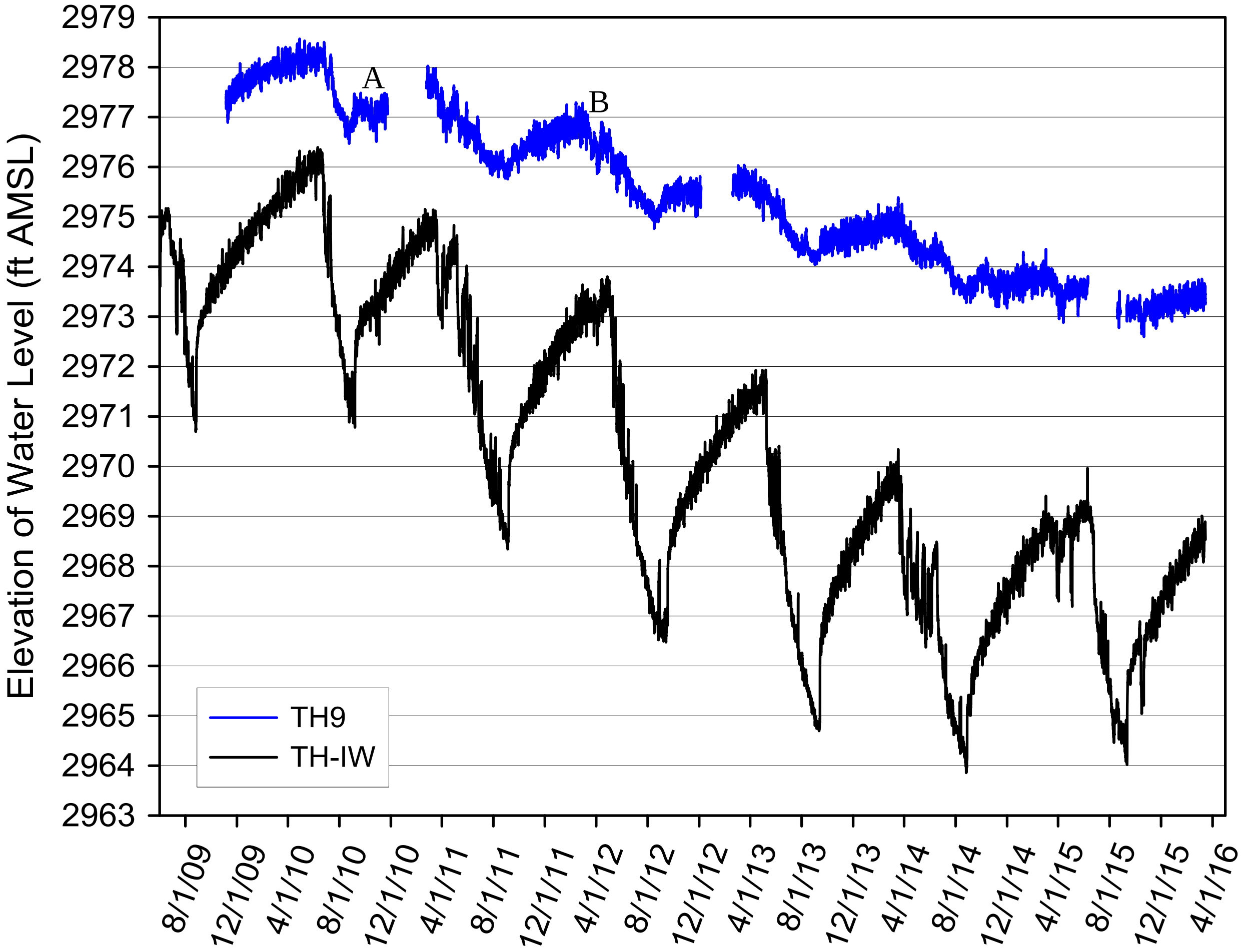


Figure 33a—Hydrograph comparison of Thomas index well (TH-IW) and expansion well TH9—total data run to 3/15/16. TH9 is located approximately 1.5 miles northeast of the index well (0.75 miles north, 1.25 miles east). A and B defined in text.

The hydrograph at well TH11 also appears to be responding to many of the same pumping events as the Thomas index well (fig. 33b), 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. A more detailed analysis and interpretation of the well TH11 hydrograph will be pursued in 2016.

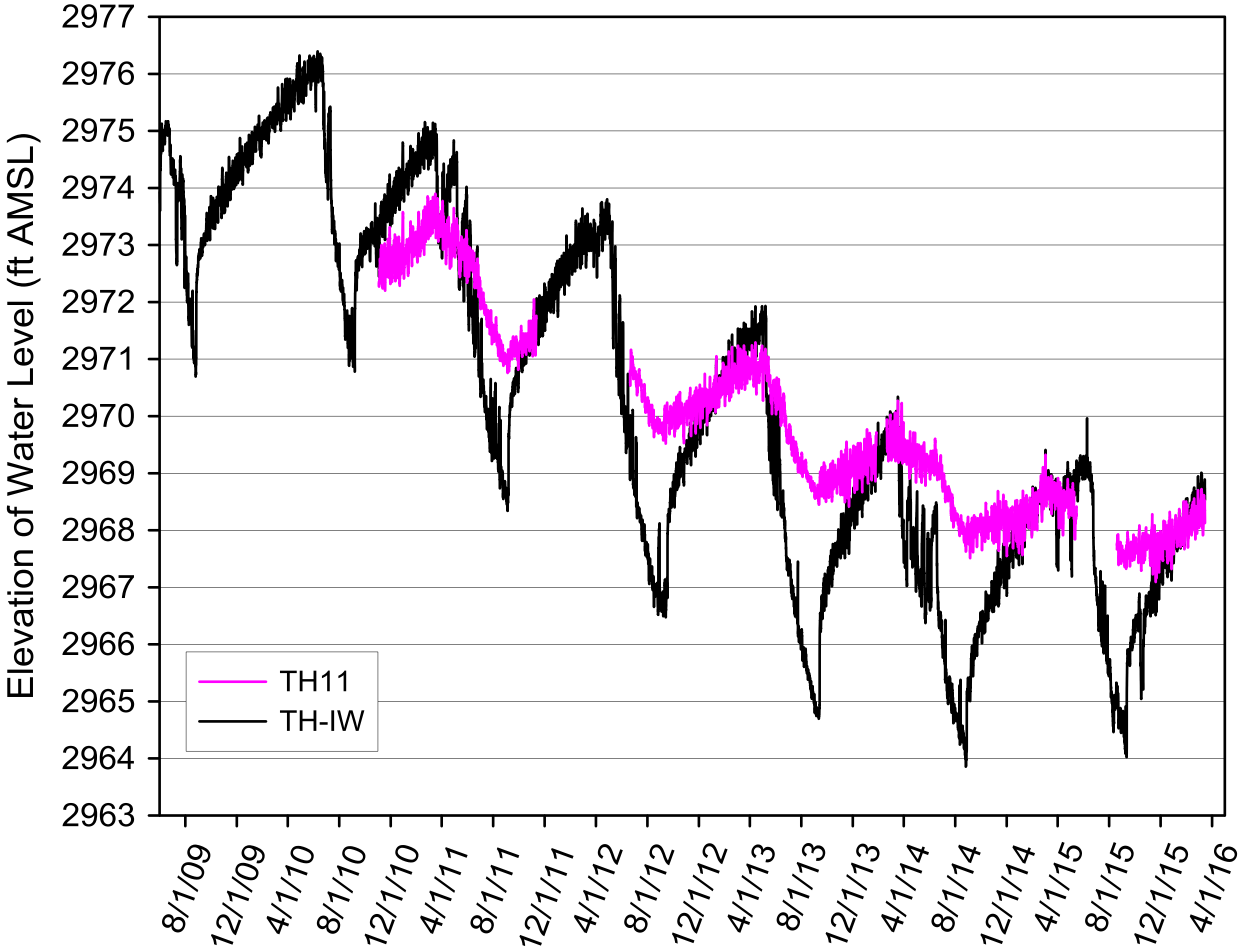


Figure 33b—Hydrograph comparison of Thomas index well (TH-IW) and expansion well TH11—total data run to 3/15/16. TH11 is about 0.70 miles east-northeast of the index well (0.25 miles north, 0.75 miles east).

3.2.8. Haskell County Expansion Wells

In mid-February 2014 and again in March 2015, we obtained from DWR all the water-level data acquired from the Haskell County expansion wells since our last report on those wells (Stotler et al., 2011). We will report on the interpretation of those data in a later report.

4. Interpretation of Water-Level Responses

4.1. *Extracting More Information from Water-Level Responses to Fluctuations in Barometric Pressure*

Significant effort has been expended over the course of this project to correct water-level measurements recorded by pressure transducers in the index wells. Common mechanisms beyond pumping that can affect the water level in a well include fluctuations in barometric pressure and tidal forces (earth tides). In previous project reports, earth-tide effects were shown to have a negligible impact on water-level measurements. The impact of changes in barometric pressure on water levels has been shown to be large enough to be of practical significance at one of the original index wells (Thomas County), the expansion wells in the vicinity of the Scott and Thomas index wells, the Rolla index well, the Colby index well, and all but one (Steiger index well) of the SD-6 LEMA wells. Given the expectation that the impact of barometric pressure will be large in unconfined portions of the HPA wherever the depth to water is on the order of or greater than that at the Thomas County index well (more than 200 ft), the KGS developed an Excel spreadsheet to assess the nature of the relationship between barometric-pressure fluctuations and water levels and to remove the impact of barometric-pressure fluctuations from water-level measurements (Bohling et al., 2011). The nature of the relationship between barometric-pressure fluctuations and water levels is captured in the barometric response function (BRF) that is obtained as part of the spreadsheet calculations. In previous project reports, early efforts to extract information about site hydrostratigraphy from the BRF were described. In 2012 and 2013, initial work on getting more information from the BRFs began; it appears that it should be possible to get information from the BRFs about, among other things, the nature of the hydraulic connection between the well and the formation, the viability of annular seals, and an estimate of the bulk pneumatic diffusivity of the vadose zone. Relatively little time was available for this work in 2015, so an update on this aspect of the project work will be provided in a future report.

4.2. *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 four 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, 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.

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 3.1.1.1. The data from the 2015 pumping season indicate that conditions have considerably 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 44.0 ft in height at the maximum observed drawdown for 2015 (water column height was likely considerably less in the immediate vicinity of the irrigation wells). This height was 6.7 ft greater than at the maximum observed drawdown in 2014, and 8.7 ft greater than that in 2012; these increases are undoubtedly a result of the court-ordered shutdowns described in section 3.1.1.1. 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.

Scott County

The 2015 water-level data did little to help refine the assessment of conditions in the vicinity of the Scott index well because of the high level of noise in the transducer measurements as described in section 3.1.2.1. Figure 34a, 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 (2008), B (2009), C (2010), D (2011), E (2012), F (2013), G (2014), and H (2015) on fig. 5a. Although these data are relatively "noisy" as a result of pumps cutting on and off and the suspected clogged vent tube in 2015, a consistent picture still emerges for all seven 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 2015 pumping seasons have enabled us to reinterpret those portions of the plot. Figure 34b is a plot of drawdown versus the logarithm of duration of pumping for pumping periods beginning at D (2011), F (2013), G (2014), and H (2015) on fig. 5a (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. In addition, the coincidence 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. If we can identify the location of the pumping well and calculate its pumping rate, we can obtain estimates of transmissivity and specific yield (drainable porosity) from the data in fig. 34b, similar to what was done earlier in this project using data from wells in the unconfined interval at the Haskell site (Butler et al., 2012; Butler, Stotler, et al., 2013).

The 2009 and 2010 pumping period data in fig. 34a are parallel to but earlier in time than the 2011–2014 data (noise in the 2015 data make it difficult to assess conditions in 2015). 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 35 shows the result after 2009 pumping times have been multiplied by 1.56 (* on fig. 35—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. 35—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 responds as a homogeneous unit in the vicinity of the Scott index well and that decreases in saturated thickness during the monitoring period have 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 2016.

The 2014 annual report (Butler et al., 2015) presented an assessment of recovery data from four complete recovery seasons (2009–2010, 2011–2012, 2012–2013, 2013–2014) and one continuing recovery season (2014–2015). Figure 36a presents an update of the recovery assessment with the complete 2014–2015 and 2015–2016 recovery seasons (September 16, 2015, was the start of recovery for the 2015–2016 recovery). The 2014–2015 recovery data have been corrected for the suspected clogged vent tube as described in Butler et al. (2015). Note that the water levels during the 2015–2016 recovery are above previous years' recovery. In addition, the data become considerably less noisy at A with the replacement of the transducer and cable as described in section 3.1.2.1. After examining the record closely, we found that the water-level records after A essentially paralleled the previous years' recovery data. We took the average value of the 2015–2016 recovery data from days 45 to 135 and subtracted the average value of the 2011–2012 recovery data (a recovery period that was little affected by pumping) from days 45 to 135. That difference (0.390 ft) was then subtracted from the 2015–2016 recovery data from day 45 to the time of the last download prior to this report (March 15, 2016). The corrected 2015–2016 transducer measurements are plotted on fig. 36b with the previous years' recovery data. The 2015–2016 recovery data now approximately overlie the data from previous years. The water use in 2009 and 2012 differed by about 22% (largest use difference for the years shown in fig. 36b); the durations of the 2009 and 2012 pumping periods differed by about 20%. Water-use data for 2015 are not yet available. The interpretation of the similarity of the recovery plots for six complete 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 2016.

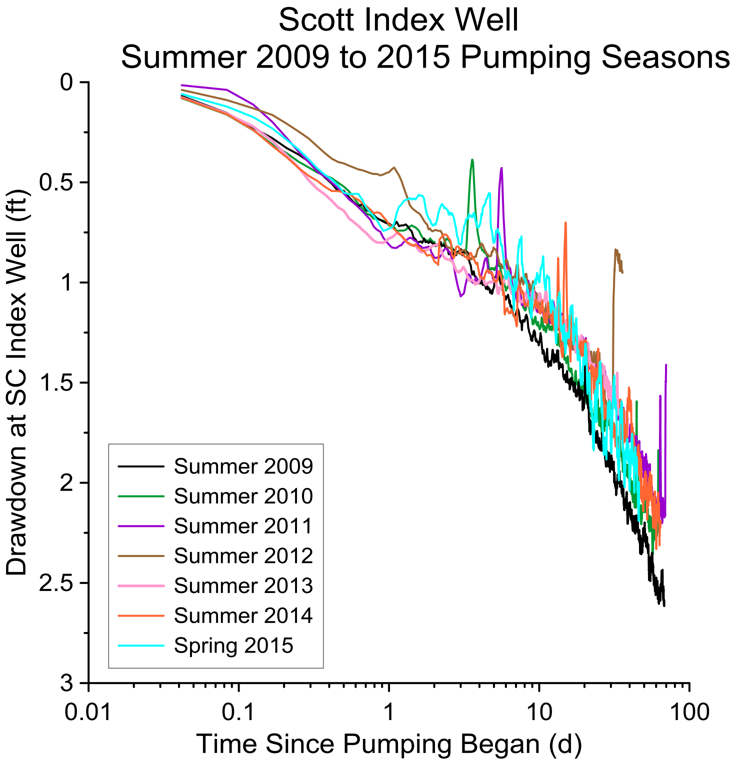


Figure 34a—Drawdown in the Scott index well versus the logarithm of pumping time for pumping periods beginning at points A (2008), B (2009), C (2010), D (2011), E (2012), F (2013), G (2014), and H (2015) on fig. 5a.

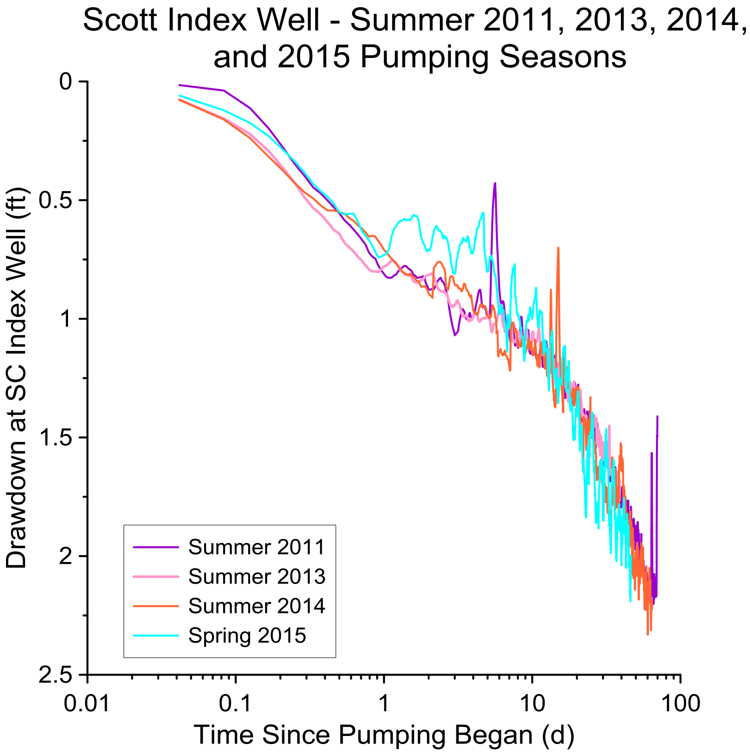


Figure 34b—Drawdown in the Scott index well versus the logarithm of pumping time for 2011, 2013, 2014, and 2015 pumping periods beginning at points D, F, G, and H, respectively, on fig. 5a.

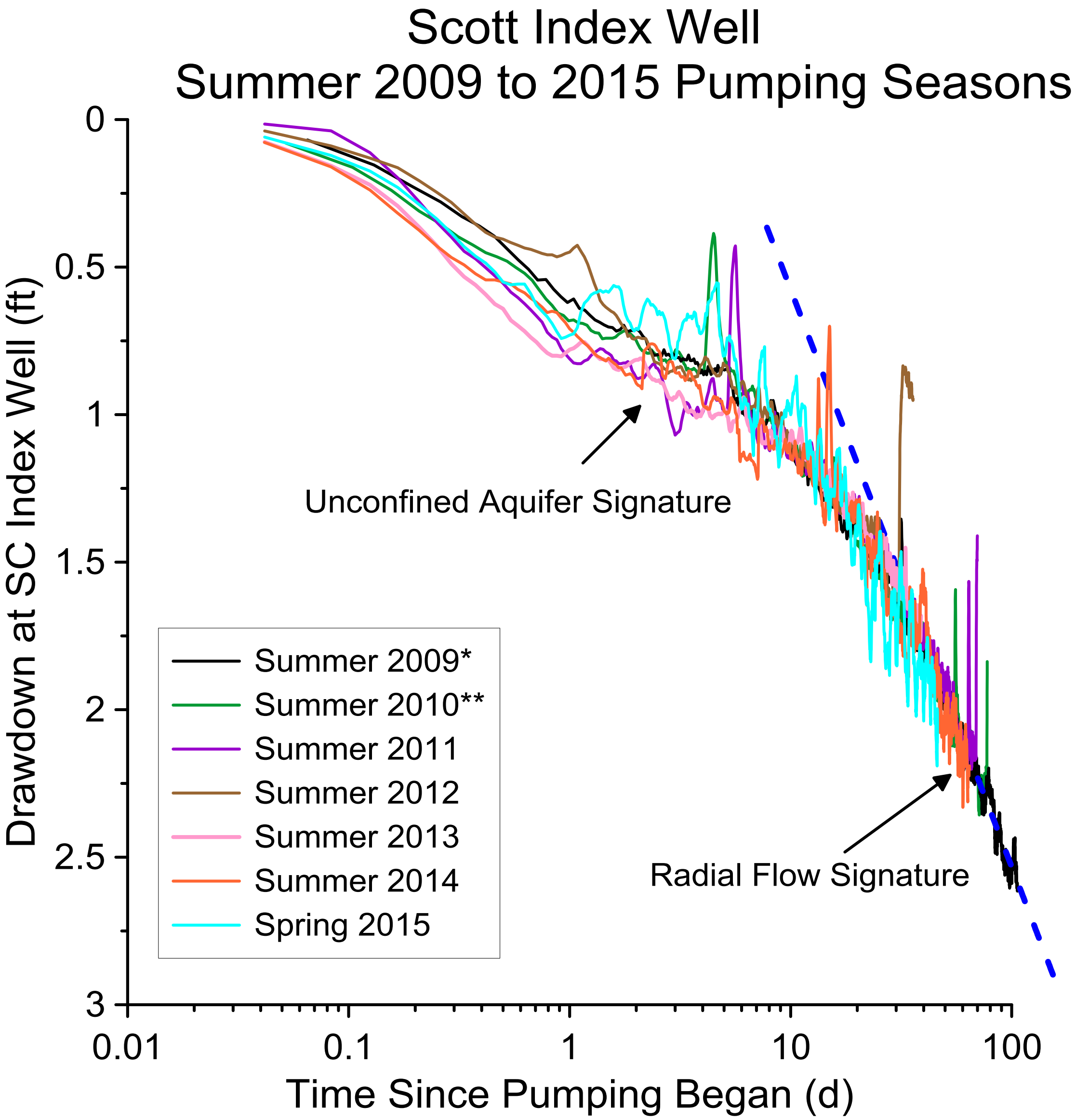


*Figure 35—Drawdown in the Scott index well versus the logarithm of pumping time for pumping seasons beginning at points B (2009), C (2010), D (2011), E (2012), F (2013), G (2014), and H (2015) on fig. 5a. * and **—pumping times modified as explained in text. 2008 pumping period not plotted because of noise produced by pumping cutoffs and restarts.*

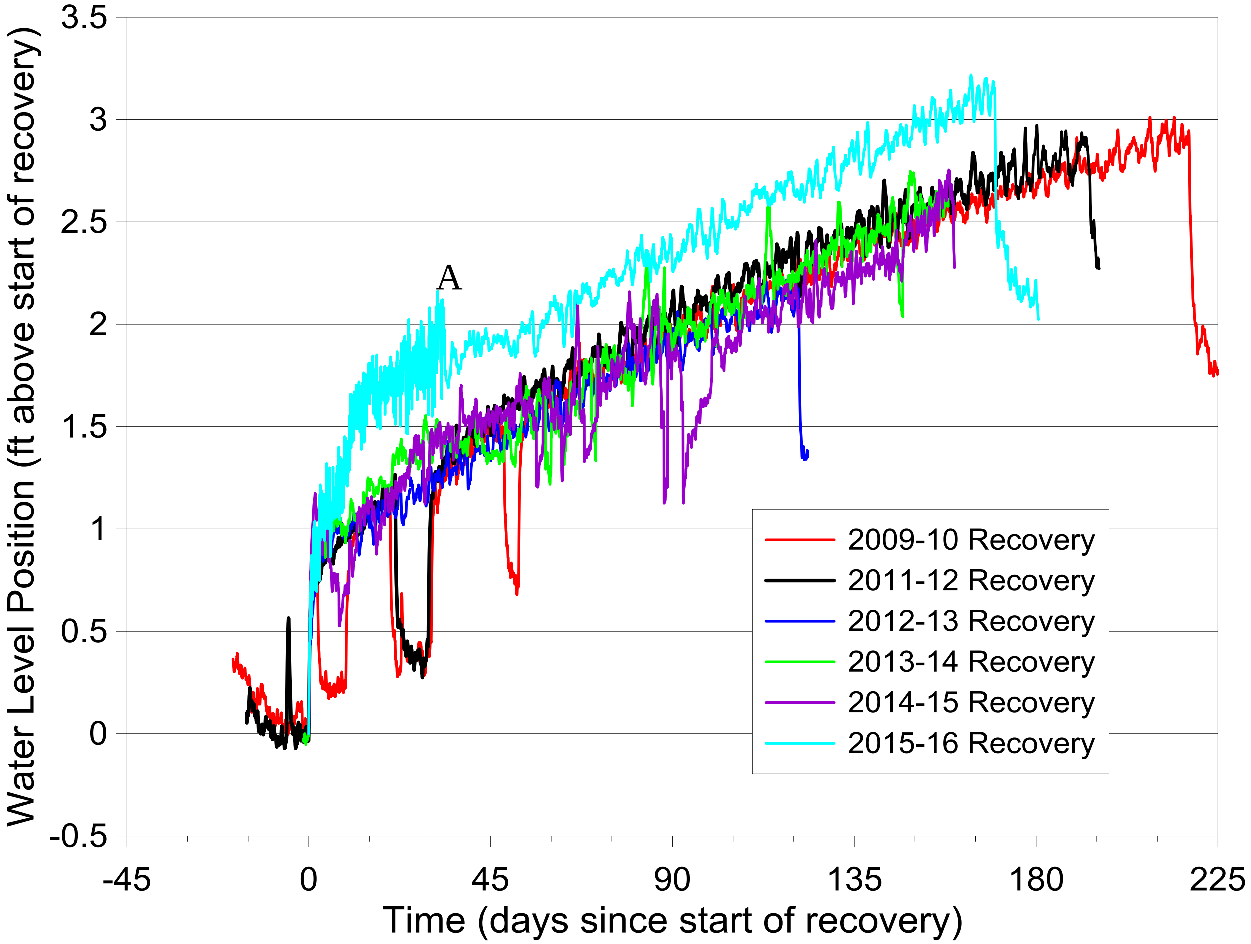


Figure 36a—Water levels in the Scott index well for the 2009–2010, 2011–2012, 2012–2013, 2013–2014, 2014–2015, and 2015–2016 recovery periods. Recovery for the 2009–2010, 2011–2012, 2012–2013, 2013–2014, 2014–2015, and 2015–2016 recovery periods calculated from points I, J, K, L, M, and N, respectively, on fig. 5a. Recovery data for 2014–2015 have been corrected as described in Butler et al. (2015). Note the separation between the 2015–2016 recovery and the previous years and the change in noise level in the 2015–2016 recovery data beginning at A.

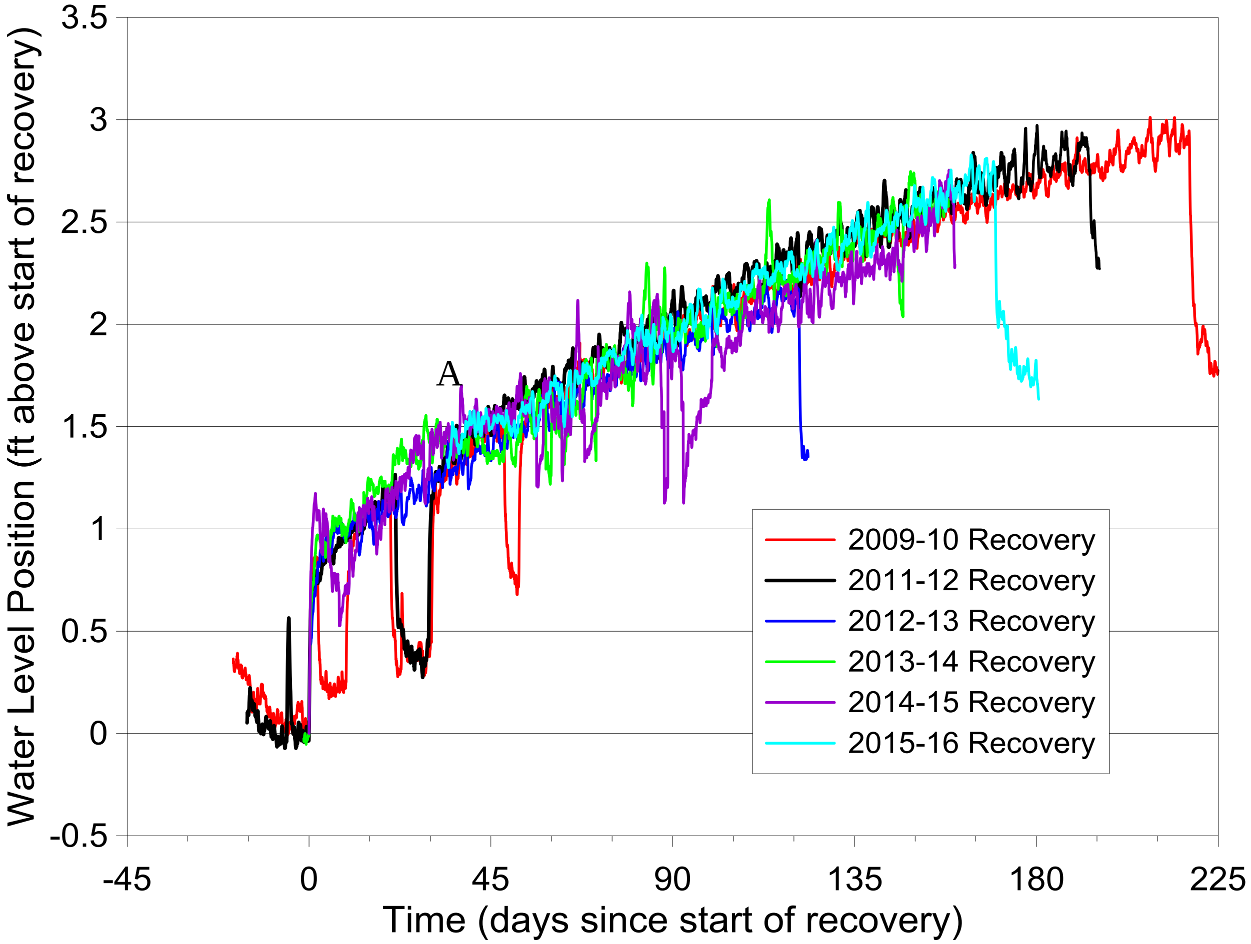


Figure 36b—Water levels in the Scott index well for the 2009–2010, 2011–2012, 2012–2013, 2013–2014, 2014–2015 (corrected), and 2015–2016 (corrected) recovery periods. Recovery for the 2009–2010, 2011–2012, 2012–2013, 2013–2014, 2014–2015, and 2015–2016 recovery periods calculated from points I, J, K, L, M, and N, respectively, on fig. 5a. Note that only the corrected 2015–2016 recovery data beginning at A are plotted. Correction procedure is described in text.

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 2015 data.

An assessment of five complete and one continuing recovery seasons was presented in the 2014 annual report. Figure 37 presents an update of the recovery assessment with the results for the complete 2008–2009, 2009–2010, 2011–2012, 2012–2013, 2013–2014, and 2014-2015 recovery seasons and the still continuing 2015–2016 recovery. The 2009 and 2012 pumping seasons bound the range of conditions (water use and pumping duration) observed during the monitoring period (table 6). 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 following these irrigation seasons was essentially the same. The agreement between the superimposed recovery plots on fig. 37 is remarkable; the difference in the rate of water-level change between recovery periods is very small. The near-coincidence of recovery rates 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 the 2007–2008 and 2010–2011 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 2015 as described in Section 5.9; a recent article based on the approach is provided in Appendix B (Butler et al., 2016).

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.

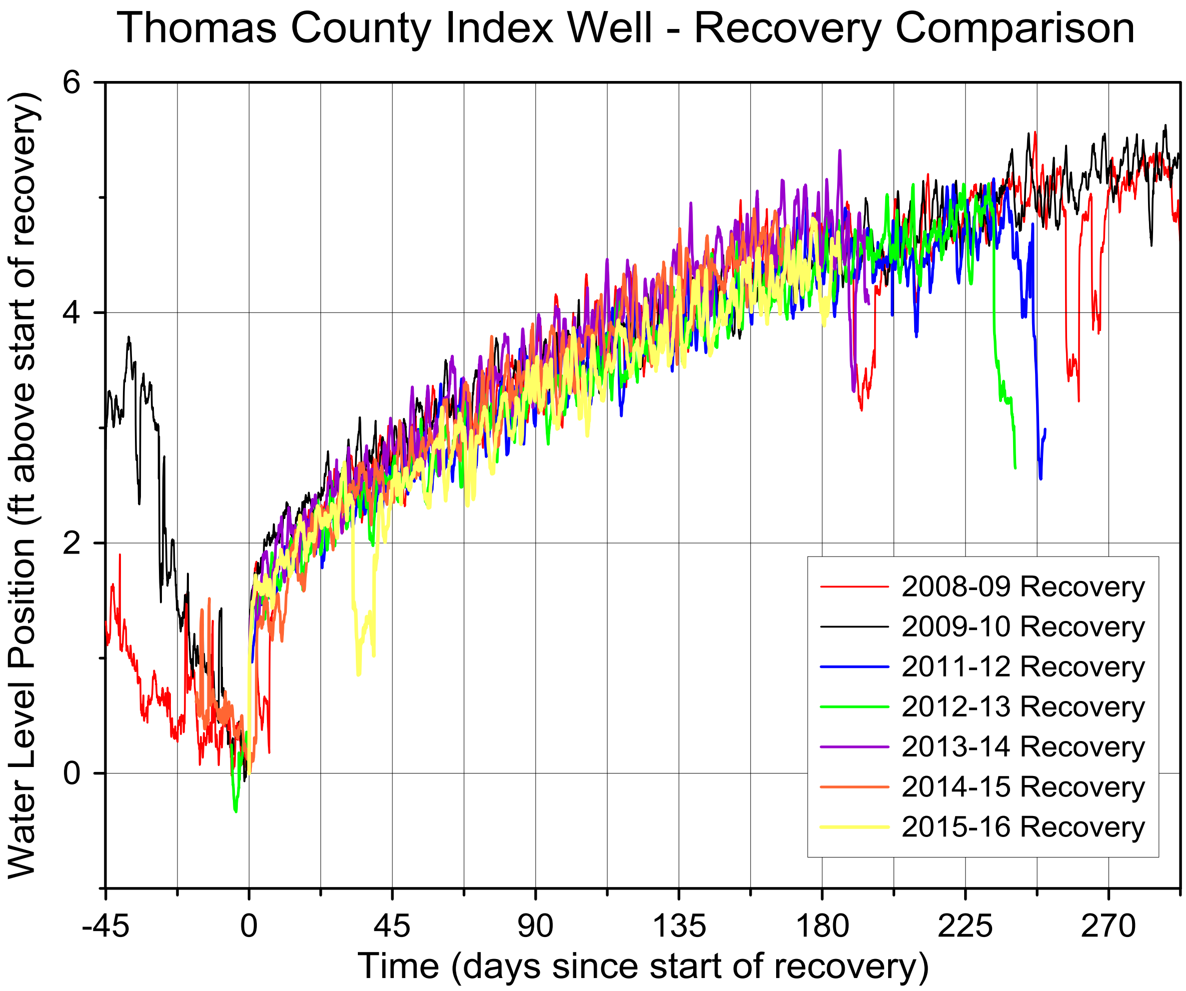


Figure 37—Water levels in the Thomas County index well for the 2008–2009, 2009–2010, 2011–2012, 2012–2013, 2013–2014, 2014–2015, and 2015–2016 recovery periods. Recovery for the 2008–2009, 2009–2010, 2011–2012, 2012–2013, 2013–2014, 2014–2015, and 2015–2016 recovery periods calculated from points A, B, C, D, E, F, and G, respectively, on fig. 7. Recovery period for 2010–2011 not included because of pumping during the early portions of that period.

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. These wells can also 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. 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 data in the new dataset generally produced only small changes in the previously calculated climatic index values. The new dataset was used to revise graphs and correlations of climatic indices for the 2014 index well report (Butler et al., 2015); these revisions and updates are also used in this report for 2015.

5.3. *Characterization of Climate Since Installation of 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 original three index wells was installed in GMDs 4, 1, and 3 in 2007; these wells provide annual records for complete 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. 38 displays these conditions since the start of monitoring at the original three index wells, 2008–2015. Conditions changed from near normal in 2008 across the three western climatic divisions 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 the end of 2014 in northwest and southwest Kansas, although the trend was to less severe drought. In west-central Kansas, the drought ended about halfway through 2014 and slightly wet conditions prevailed from the latter part of 2014 through 2015. The conditions in northwest and southwest Kansas during 2015 generally ranged from near normal to wet, respectively, although the summer of 2015 was somewhat dry in northwest Kansas.

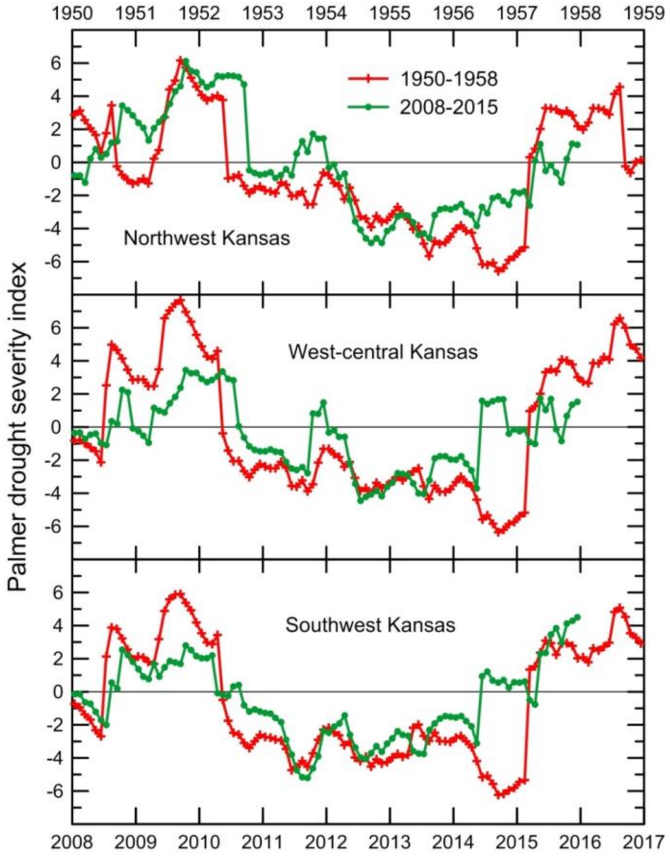


Figure 38—Comparison of monthly values of the Palmer Drought Severity Index (PDSI) for the three western climatic divisions of Kansas during 1949–1958 and 2008–2015. The monthly values are plotted as the middle of the month. Annual tick marks represent the beginning of a year.

Figure 38 also includes comparison of the monthly PDSI values during 1950 through 1958, which included the drought of the 1950s, with those for 2008 through 2015 (last year's report displayed 1949 through 1957; the 1950s drought period was shifted by one year in fig. 38 in this year's report to better match the general characteristics of 2008–2015). 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 SPI for October, 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. 39). 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 near normal, slightly wet, and wet in northwest, west-central, and southwest Kansas, respectively in 2015.

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. Prior to 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).

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 2015 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 2015 were 1,139, 1,352, and 1,674, respectively. The numbers of points of diversion that were added after 1997 were 48, 21, and 0 for these three counties, respectively. Thus, for the period 1996–2014, the main driver for water-level changes in the HPA in western Kansas was the amount of pumping from each well.

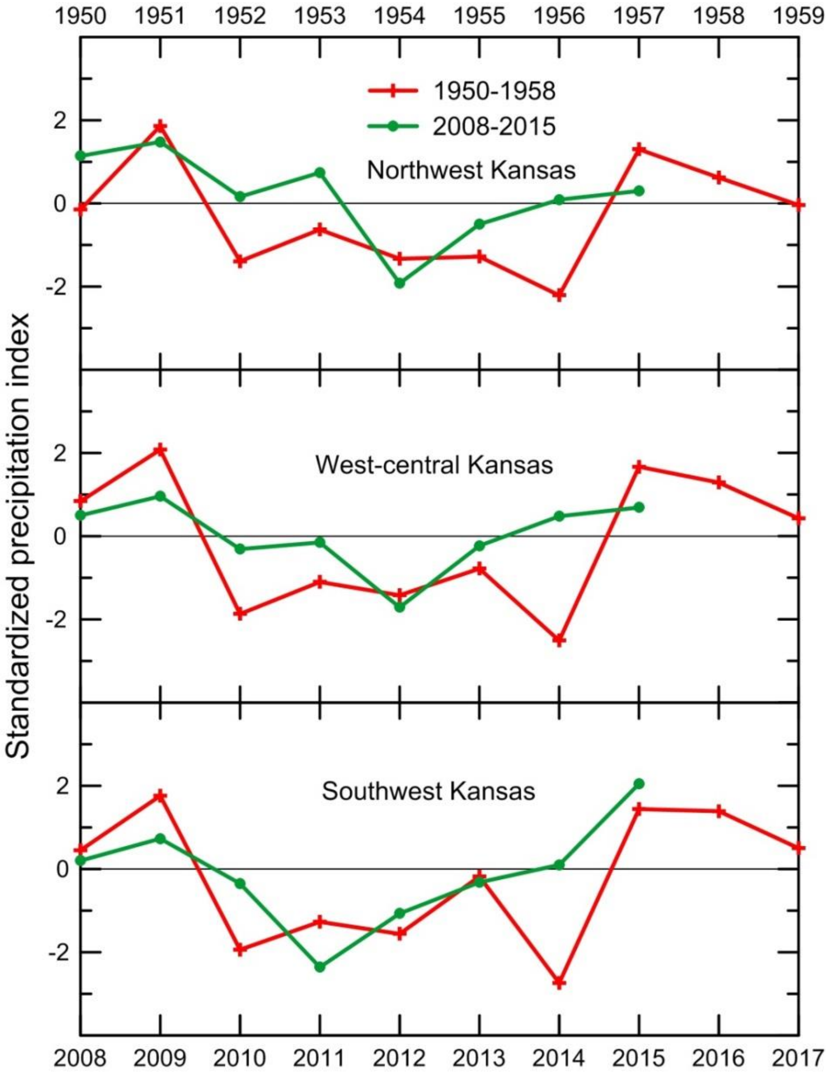


Figure 39—Comparison of the nine-month October SPI values for the three western climatic divisions of Kansas during 1950–1958 and 2008–2015. The nine-month October SPI correlates well with water-level changes in all three western GMDs (fig. 40).

5.4.1. Water-Level Change in the Groundwater Management Districts

The mean annual year-to-year changes in winter water-levels during 1996–2015 for the three western GMDs are displayed in fig. 40 based only on wells for which measurements were made during the winters of all years from 1996 to 2015. The values for 2015 were computed using the provisional data for the winter of 2016 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. 40. The annual water-level decline in northwest Kansas was greater in 2015 than in 2014, even though the SPI indicates that conditions were slightly wetter in 2015 than 2014. The reason is probably related to the spatial and temporal distribution of rainfall. The precipitation distribution was very spatially variable in 2015 in northwest Kansas and, although April was wet, the period of main irrigation water use (June–August) was dry over much of GMD4 (see the monthly values of PDSI in fig. 38). In contrast, the annual water-level decline in GMD1 in 2015 was less than in 2014, fitting the change toward slightly wetter conditions (slightly more positive SPI) from 2014 to 2015. The water-level decline in GMD3 was substantially smaller than in 2014, reflecting the change from normal to wet climatic conditions as indicated by the SPI.

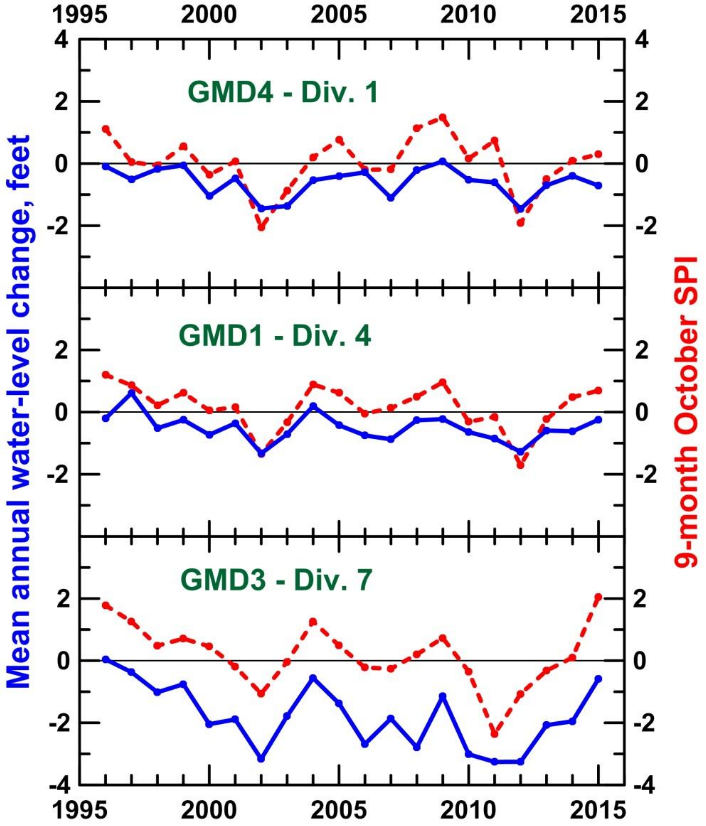


Figure 40—Mean annual water-level change in the HPA in GMDs 4, 1, and 3 and the nine-month October SPI for climatic divisions 1, 4, and 7, respectively, during 1996–2015. The water-level change for a particular year is the water-level difference between the following year and that year for continuously measured wells for 1996–2014 and between the 2016 provisional winter value and the 2015 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 Index Wells

Winter water levels have been measured by steel tape in the original three index wells since January 2008 (see tables 3, 5, and 7). Figure 41 shows the annual year-to-year water-level changes for both the tape and transducer values for 2008–2015 (values unadjusted for barometric pressure) 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 2008–2014 (fig. 41). 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 regional water levels in the GMDs in which they are located. However, as indicated earlier, the change for GMD4 in 2015 did not fit the overall change in climatic conditions; the water-level change at the Thomas County index well fits better the SPI change (see fig. 40). Also, the water-level decline at the Scott County index well in 2014 was enough lower than that of the GMD-wide decline that it could represent a significant difference for that year.

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 substantial decline in the index well water level from 2013 to 2014 is substantially different from the nearly constant decline amount for those two years for GMD3. This difference is mainly related to an 18-day pumping period during the winter that ended December 15, 2014, which caused an interruption in the recovery of the water level at the Haskell index well. The pronounced difference in annual water-level change from 2014 to 2015 (from a decline of 9–10 ft in 2014 for the transducer and tape measurements to a rise of 2–4 ft for these measurements in 2015) reflects that much less pumping occurred at this location in 2015, both because the weather was appreciably wetter and because of the court-ordered shutdown of nearby pumping wells described in section 3.1.1.1.

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

This section discusses water-level changes at the Colby index well (KSU Extension location) 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. Figure 42 displays the water-level changes for 1996–2015 for all three of these wells.

The USGS and then GMD4 measured monthly water levels in the existing Colby well from 1984 to the present (GMD4 started March 2009; the USGS continued some measurements until February 2012); these are in addition to the early January observations made by the USGS before 1997, the DWR 1997–2004, and the KGS 2005 to present. When all the data are plotted, the early January measurements for

2003 and 2010 display obvious errors (appear to be off by 1 ft) relative to the monthly measurements by the USGS and GMD4, which are typically made in mid-January. These errors (possibly due to incorrectly entering the depth-to-water value by 1.0 ft) affect both the water-level change value for the year before and after the observation date. The early January values were adjusted by +1.0 ft for 2003 and 2010 for use in computing water-level changes for this report. In addition, the mid-January value for 2007 was used instead of the KGS measurement on February 27 (delay in measurement due to heavy snow). The water-level change based on early January measurements gave slightly better or about the same correlations with climatic indices as the changes based on the mid-January observations, whereas the change computed from the mid-January measurements were correlated somewhat better with water use than changes from the early January observations. These data illustrate some of the factors that can impact individual annual water-level observations.

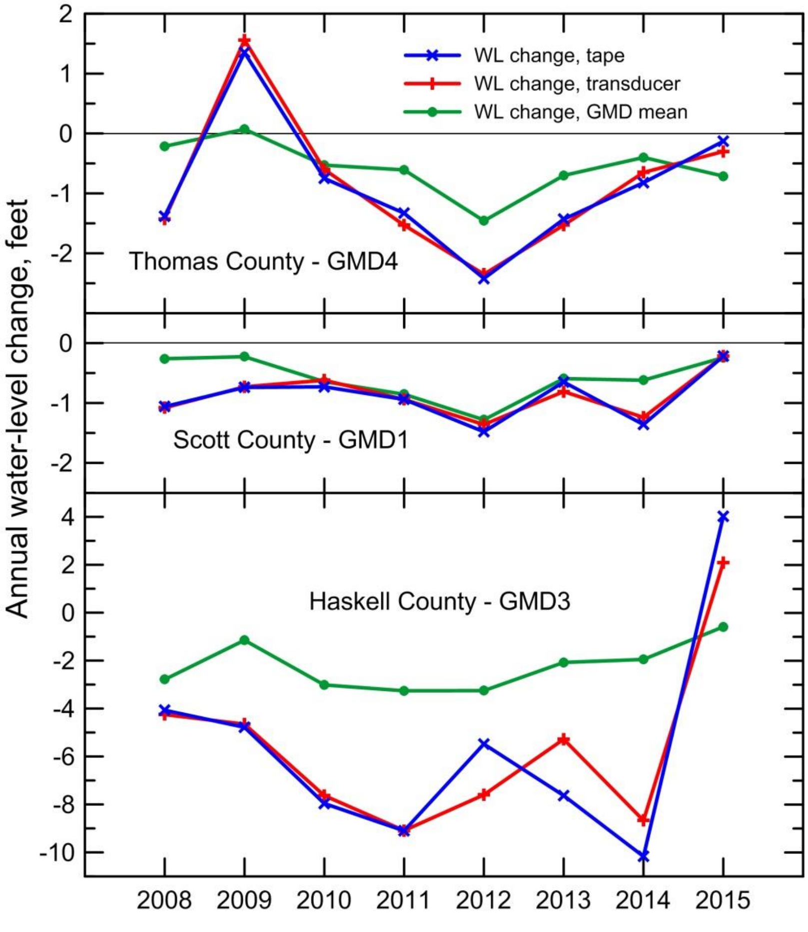


Figure 41—Annual winter water-level changes in the original three index wells and the mean annual changes in the three GMDs in western Kansas in which they are located. The value for a particular year is the water-level difference between the following year and that year. Note the different y-axis range 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.

Some differences exist in the annual water-level changes between the Colby and Thomas County index wells and the SC-8 and Scott County index wells. The range in water-level changes at the Colby well (1.95 ft, fig. 42) during 1996–2015 was substantially smaller than that for the Thomas County index well (fig. 41), whereas the range at the SC-8 well (5.56 ft, fig. 42) was much greater than that at the Scott County index well (fig. 41). The four years at the beginning of 1996–2015 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.

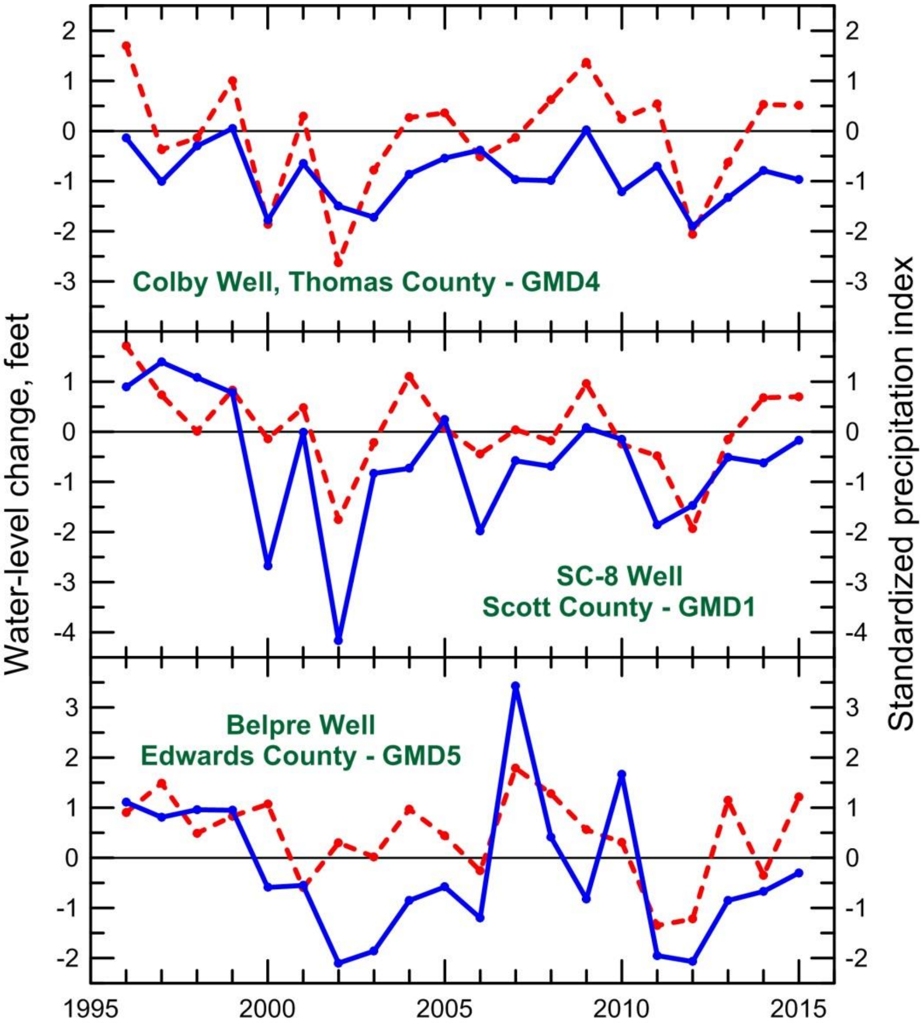


Figure 42—Annual water-level changes in the Colby index well, the SC-8 expansion well, and the Belpre index well 1996–2015, and the six-month September, nine-month September, and 12-month December SPI for these three wells, respectively. The blue lines and points represent the annual water-level change and the red dashed line is the SPI. The absolute range of the x-axes is the same for all three well graphs.

The water-level change was positive for seven and negative for 13 of the 20 years of record for the Belpre well during 1996–2015 (fig. 42). The location is affected by surface recharge and groundwater discharge to streams to a much greater extent than the index wells in the western (Ogallala) part of the HPA. The year 2007 was one with particularly large recharge, followed in 2010 by substantial but smaller recharge. The greatest declines occurred during two pairs of years: 2002–2003 and 2011–2012.

The annual water-level changes generally mimic the pattern in the SPI shown in fig. 42. 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 recharge and discharge to and from 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 two years' index well reports (Butler et al., 2014, 2015) 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 1996–2013, 1996–2014, and 1996–2015 are listed in table 29; the correlations are all highly statistically significant ($P < 0.001$). As indicated earlier, the final 2016 data for water-level changes for continuously measured wells in the GMDs are not yet available, so the provisional 2016 measurements were used for determining the correlations. The table has correlations 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. In general, the additional years of data after 2013 do not change the correlation significantly.

5.5.2. Correlations for the Thomas, Scott, and Haskell Index Wells

In the previous annual report (Butler et al., 2015), we reported the monthly period and the ending month for the SPI that give the optimum R^2 values for correlations between the climatic index and annual water-level change for the index wells for 2008–2013 and 2008–2014. For this year's report, we have added the R^2 values for these correlations for 2008–2015 (table 30).

The correlations for the Thomas index well are essentially the same for the tape measurements for 2008–2013, 2008–2014, and 2008–2015; the correlations for the transducer values are also similar for these periods. In contrast, the correlations for both the tape and transducer measurements for the Scott and Haskell index wells were substantially lower for 2008–2014 than for 2008–2013. The cause of the lower correlation for 2008–2014 for the Haskell well is related to the 18-day pumping period during December 2014, which interrupted the water-level recovery as indicated earlier.

The water-level decline for 2014 at the Scott County well is greater than expected for the climatic index; the 2014 decline for this well also is greater than the GMD1-wide water-level change as stated above in the discussion of fig. 41. However, as described later in a section on correlation of water-level change with radar precipitation for the index wells, the main reason for the lower correlation for the addition of the 2014 data is probably the unusually wet June, which shifted the point for 2014 to a higher SPI value than expected based on the 2008–2013 regression. The water-level decline for 2015 was not as great as expected for the climatic conditions. When the mean water-level decline for 2014 and 2015 is used along with the average SPI for these years, the correlation for the Scott County index well improves substantially to be close to statistically significant at P = 0.05.

Table 29—Coefficients of determination (R^2) for the correlation of mean annual water-level changes in GMDs 4, 1, and 3 with the nine-month October SPI for climatic divisions 1, 4, and 7 during 2008–2013, 2008–2014, and 2008–2015. All correlations are statistically significant at P = 0.001.

Period	**Water-Level Change Region – Climatic Division**	**R^2**
1996–2013	GMD4 – Division 1	0.74
1996–2013	GMD4, mean 2006, 2007 – Division 1	0.81
1996–2014	GMD4 – Division 1	0.75
1996–2014	GMD4, mean 2006, 2007 – Division 1	0.82
1996–2015	GMD4 – Division 1	0.73
1996–2015	GMD4, mean 2006, 2007 – Division 1	0.81
1996–2013	GMD1 – Division 4	0.72
1996–2014	GMD1 – Division 4	0.68
1996–2015	GMD1 – Division 4	0.69
1996–2013	GMD3 – Division 7	0.78
1996–2014	GMD3 – Division 7	0.79
1996–2015	GMD3 – Division 7	0.79

The correlations for the Haskell County index well were substantially greater for 2008–2015 than for 2008–2014 and in the same general range as for 2008–2013. The year of additional data helped in improving the correlation mainly because the SPI was much higher than any other year since 2008 and the water level recovered to produce a positive water-level change. Thus, the point for 2015 appreciably extends the range for the data and exerts an important control on the correlation, thereby decreasing the effect on the variance of the 2014 point (fig. 43).

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 gauges. 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 last year's index well report (Butler et al., 2015).

Table 30—Coefficients of determination (R^2) for the correlation of annual water-level changes at the three index wells with the nine-month October SPI for climatic divisions 1, 4, and 7 during 2008–2013, 2008–2014, and 2008–2015.

Period	**Index well, WL Measurement Type, and SPI for Climatic Division or Well Site**	**R^2**
2008–2013	Thomas County, tape – Division 1	0.53
2008–2014	Thomas County, tape – Division 1	0.53[a]
2008–2015	Thomas County, tape – Division 1	0.51[a]
2008–2013	Thomas County, transducer – Division 1	0.47
2008–2014	Thomas County, transducer – Division 1	0.46
2008–2015	Thomas County, transducer – Division 1	0.45
2008–2013	Scott County, tape – Division 4	0.46
2008–2014	Scott County, tape – Division 4	0.17
2008–2015	Scott County, tape – Division 4	0.25
2008–2015	Scott County, tape, mean 2014, 2015 – Division 4	0.46
2008–2013	Scott County, transducer – Division 4	0.50
2008–2014	Scott County, transducer – Division 4	0.33
2008–2015	Scott County, transducer – Division 4	0.24
2008–2015	Scott County, transducer, mean 2014, 2015 – Division 4	0.54[a]
2008–2013	Haskell County, tape – Division 7	0.50
2008–2014	Haskell County, tape – Division 7	0.16
2008–2015	Haskell County, tape – Division 7	0.55[a]
2008–2013	Haskell County, transducer – Division 7	0.78[b]
2008–2014	Haskell County, transducer – Division 7	0.46
2008–2015	Haskell County, transducer – Division 7	0.70[b]

[a] Significant at P = 0.05

[b] Significant at P = 0.01

An example of a precipitation image from this website is shown in fig. 44 for total annual precipitation during 2015. 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 45 illustrates the normal precipitation for Kansas (derived from PRISM climate data for 1981–2010).

Although the radar precipitation for the 2015 image (fig. 44) displays the typical general increase in normal precipitation from west to east across Kansas (fig. 45), it also indicates the substantial spatial variation in precipitation within regions such as climatic divisions and GMD areas. For example, in 2015 a band of lower than normal precipitation extended from Hamilton County across central Kearny County to west-central Finney County; the region surrounding this area generally had higher than normal precipitation. Parts of south-central GMD3 had particularly high precipitation in 2015. Figure 44 indicates that the locations of the three original index wells (Thomas, Scott, and Haskell) had above normal precipitation. We found last year that the more detailed variation in precipitation available from radar data generally better represented the climatic conditions affecting water-level change (gave higher correlations) than the much more widely spaced precipitation stations used in the SPI computation. For this year's report, we downloaded monthly radar precipitation data for 2015 for the Kansas region to update our data set for 2008–2014 for use in correlations with water-level changes.

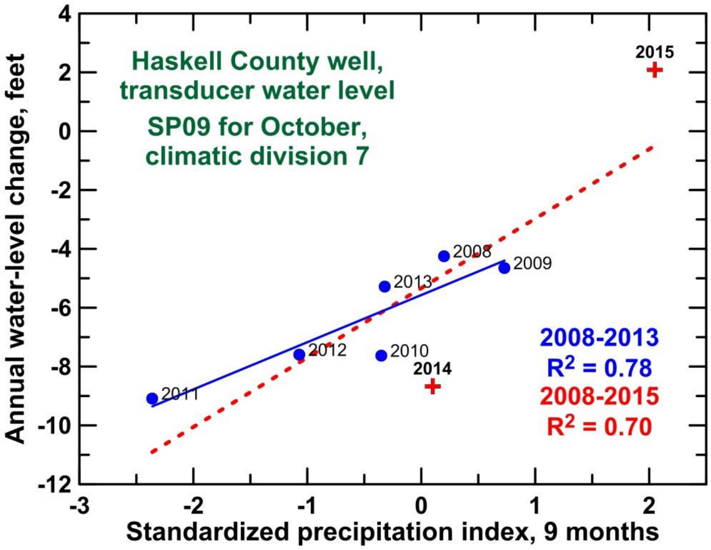


Figure 43—Annual water-level change for the Haskell County index well from transducer measurements versus the nine-month October SPI for climatic division 7. The blue line is the linear regression for 2008–2013 and the red dashed line is the regression for 2008–2015.

5.6.1. Correlations for the Groundwater Management Districts

In the previous year's 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 2015 by finding the monthly sum of spatial average precipitation for each of the areas of GMDs 1, 3, and 4 that gave the optimum correlation with the average annual water-level change for those

GMDs (fig. 46). As indicated earlier, the water-level data for 2016 for the GMD areas is provisional. The R^2 values range from 0.87 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 0.71 for GMD1 and GMD3. These compare to R^2 values of 0.81, 0.69, and 0.79 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 29). Figure 46 shows that 2015 was a generally normal year for precipitation for the GMD4 area but was substantially wetter than any other year during 2005–2015 for GMDs 1 and 3. Thus, the 2015 value exerts a substantial influence on the regression between water-level change and radar precipitation for GMDs 1 and 3.

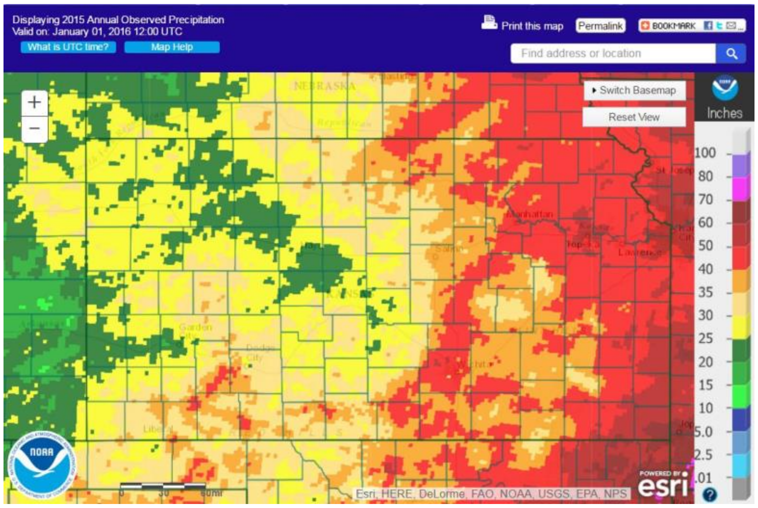


Figure 44—Total 2015 radar precipitation for Kansas. County lines and the state boundary are displayed.

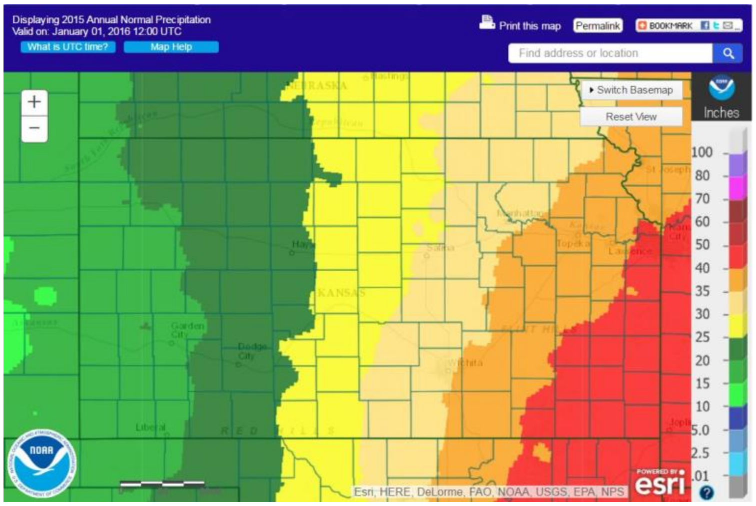


Figure 45—Normal annual precipitation for Kansas based on PRISM data for 1981–2010. The image is the same area as in fig. 44 for comparison purposes.

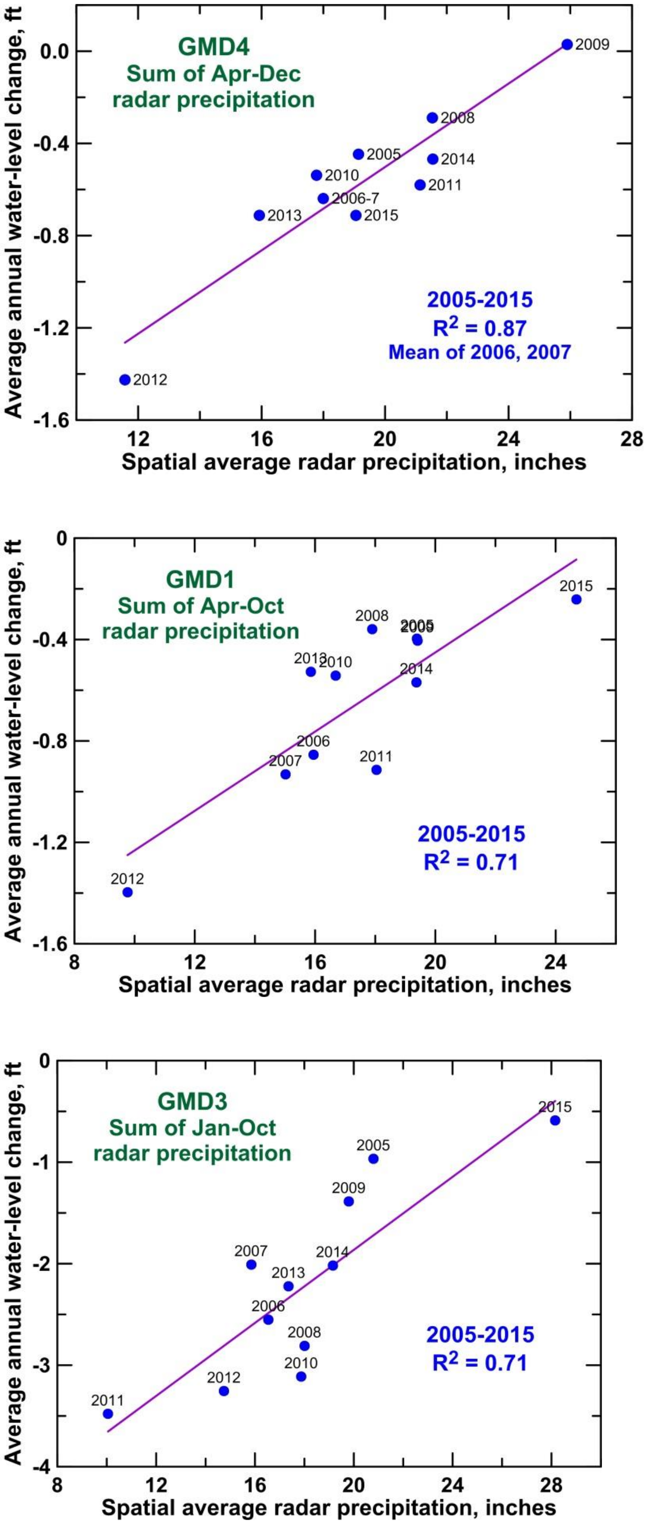


Figure 46—Correlation of mean annual winter water-level change during 2005–2015 for the three western Kansas GMDs with monthly sums of radar precipitation data for GMD areas. Values for 2005 and 2009 plot on top of each other for GMD1.

5.6.2. Correlations for the Thomas, Scott, and Haskell Index Wells

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 et al., 2015), 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. In this year's 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 31 for the one-point and the nine-point approach for both tape and transducer measurements.

Annual water-level changes and radar precipitation for 2008–2015 are well correlated with radar precipitation at the Thomas County index well for 2008–2015 (fig. 47); the highest correlation for the nine-grid point mean was found for the March–October sum of precipitation in contrast to March–December for 2008–2013 and 2008–2014 (table 31). The nine-grid point mean gives higher correlations than for the nearest grid point for all three periods. The R^2 values decrease each year because the additional values add to the variance in the data. However, as the number of values increases from six for 2008–2013 to eight for 2008–2015, the R^2 value needed for a particular level of significance decreases.

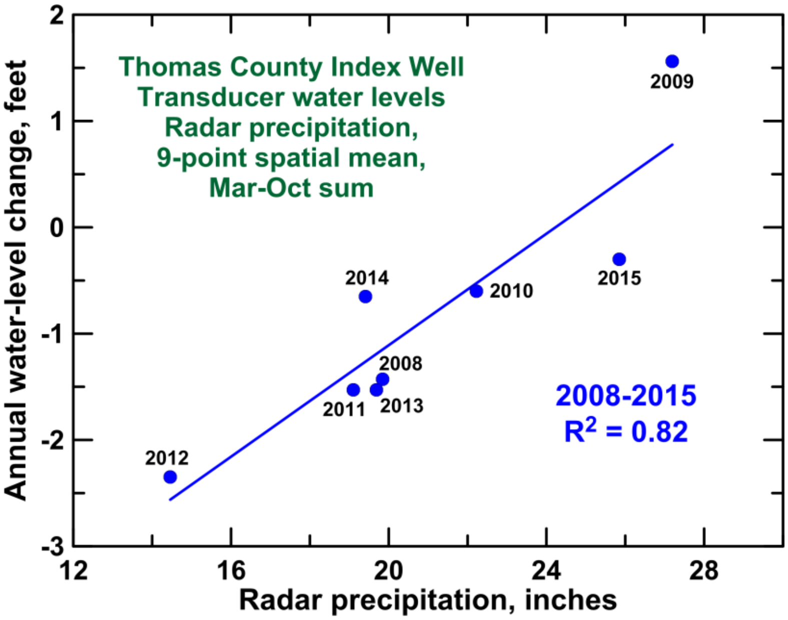


*Figure 47—Correlation of **annual** water-level change (transducer values) during 2008–2015 at the Thomas County index well with the sum of March–October radar precipitation for the spatial mean of the nine grid points centered on the index well.*

As indicated in last year's report, the correlations between the annual water-level changes (both tape and transducer) at the Scott County index well and the January–December sum of monthly radar precipitation around the well location were statistically significant for 2008–2013 (table 31). The correlations for 2008–2014 were substantially smaller. As described in last year's report, the 2014 data do not appear to fit the general trend for 2008–2013, probably because precipitation for June 2014 was unusually high at the Scott index well site (8.91 in for the nearest point, 8.67 in for the mean of the nine grid points centered on the site). A monthly precipitation of 4–5 in less would probably have been sufficient for pumping not to have been needed for irrigation. If the 2014 point were shifted to the left by 4–5 in of precipitation in fig. 48, the point would be in the general band of points for the 2008–2013 data. However, part of the shift in the 2014 point could still be related to somewhat greater pumping during 2014 than expected for the climatic conditions for the year due to low precipitation during the spring (April–May). This is similar to the greater water-level decline for the index well than that for the entire GMD1 area as discussed above (see fig. 41). The point for 2015 is at a lower water-level decline than expected for the precipitation (fig. 48); this might have resulted from focused recharge from the high 2014 precipitation occurring slowly over several months. If the mean values for 2014 and 2015 are used, the correlations for both tape and transducer values and nearest point and nine-point radar precipitation for 2008–2015 increase substantially (table 31), such that all are statistically significant at P = 0.01.

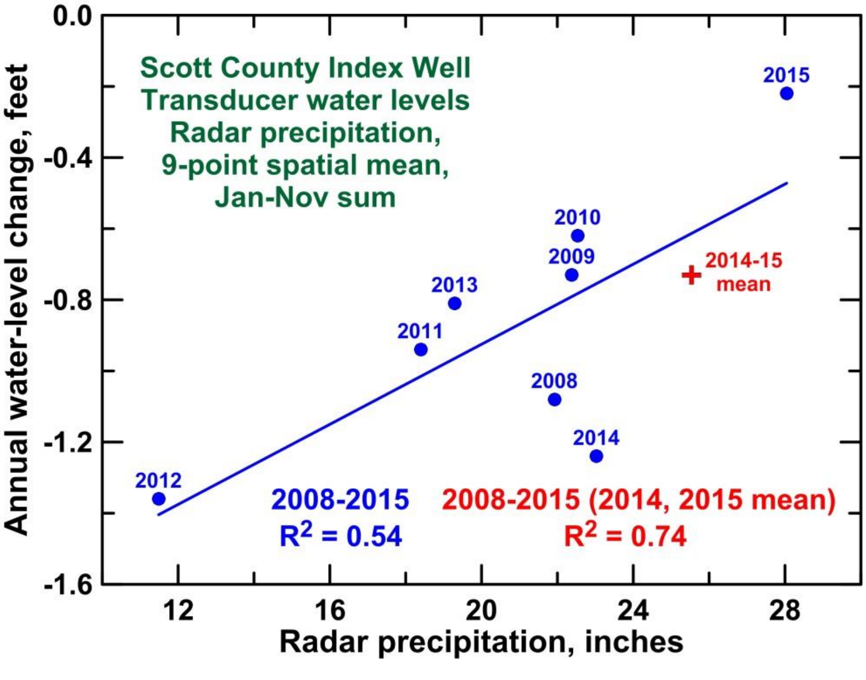


Figure 48—Correlation of annual winter water-level change (transducer values) during 2008–2015 at the Scott County index well with the sum of January–November radar precipitation for the spatial mean of the nine grid points centered on the index well. The point for the mean of 2014 and 2015 is also shown.

The annual water-level changes (both tape and transducer) at the Haskell County index well were well correlated with both the nearest grid point and nine-grid point mean of the March–November sum of monthly radar precipitation at the well location for 2008–2013 (table 31). When the data for 2014 are included, no statistically significant correlation exists. The 2014 water-level decline was much greater than expected for the climatic conditions because a nearby well was pumped for 18 days during December 2014 as described in last year's report. The correlations for 2008–2015 are again statistically significant (fig. 49), although the R^2 values are much lower than for the 2008–2013 data set. The improvement in the correlation from 2008–2014 to 2008–2015 is mainly due to the extreme values for 2015 (water-level rise instead of decline and much higher precipitation than for previous years), which exert a large influence on the regression. If the average water-level change and radar precipitation values for 2014 and 2015 are used for the 2008–2015 regressions, the correlation increases substantially to a level that is even greater than for 2008–2013 (table 31).

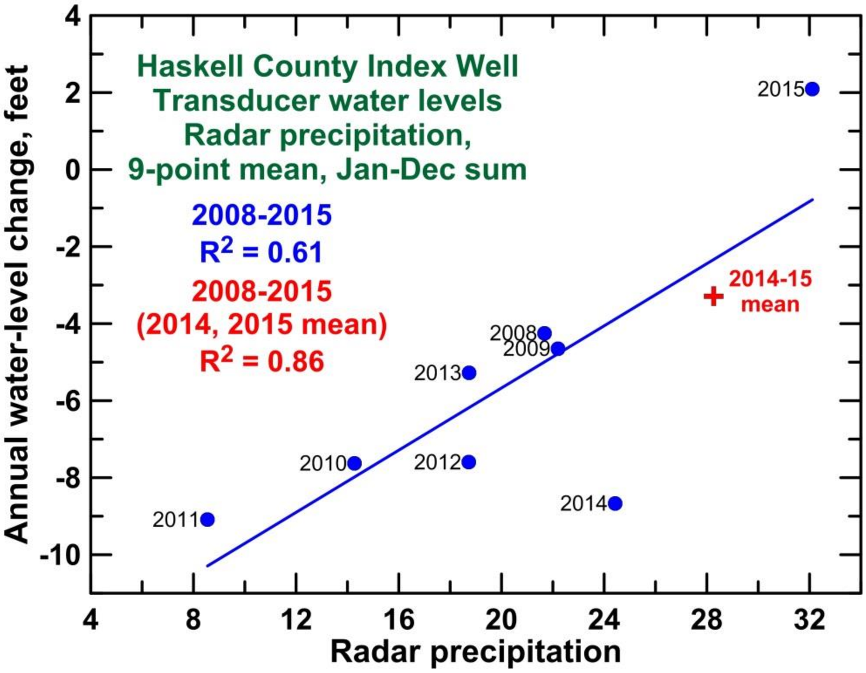


Figure 49—Correlation of annual winter water-level change (transducer values) during 2008–2015 at the Haskell County index well with the sum of annual radar precipitation for the spatial mean of the nine grid points centered on the index well. The point for the mean of 2014 and 2015 is also shown.

The R^2 values for the correlations between annual water-level change at the index wells with radar precipitation summarized in table 31 are all greater than the R^2 values for correlations of water-level change with the nine-month October SPI for climatic divisions during 2008–2015 for the Thomas and Scott counties index wells (table 30). Thus, radar precipitation data appear to be a better predictor of annual water-level change than SPI at these wells for 2008–2015. The correlations for the radar precipitation and SPI are roughly comparable for the Haskell County index well for 2008–2015, although the correlation with the transducer water-level change was somewhat higher for the SPI than radar precipitation. However, use of the mean values for 2014 and 2015 gives high correlations for the Haskell County index well that suggest that the nature of the variations introduced by the 2014 and 2015 values may produce apparent differences in correlation levels that are not really significantly different for the small number of points. As the number of years in the index well record increases, the apparent difference between the use of divisional SPI and radar precipitation should become more evident.

Table 31—Coefficient of determination (R^2 values) of the optimum correlation of annual water-level change with sum of monthly radar precipitation for the nearest grid point to the index well location and for the spatial mean of the nine grid points centered on the index well for 2008–2013, 2008–2014, and 2008–2015. The statistical significance is dependent on the number of samples and thus varies depending on the period.

Annual period	Monthly sum	Radar precipitation, nearest point		Radar precipitation, 9-point mean	
		Tape measurement	Transducer measurement	Tape measurement	Transducer measurement
			Thomas County Index Well		
2008–2013	Mar–Dec	0.82[a]	0.78[a]	0.97[a]	0.94[a]
2008–2014	Mar–Dec	0.81[a]	0.76[a]	0.96[a]	0.92[a]
2008–2015	Mar–Oct	0.67[a]	0.59[b]	0.88[a]	0.82[a]
			Scott County Index Well		
2008–2013	Jan–Dec	0.65[b]	0.81[a]	0.61[b]	0.77
2008–2014	Jan–Dec	0.18	0.43	0.21	0.49
2008–2015	Jan–Nov	0.49[b]	0.56[b]	0.48[b]	0.54[b]
2008–2014/2015 mean	Jan–Nov	0.59[b]	0.73[a]	0.59[b]	0.74[a]
			Haskell County Index Well		
2008–2013	Mar–Nov	0.78[a]	0.84[a]	0.79[a]	0.83[a]
2008–2014	Mar–Nov	0.06	0.20	0.13	0.29
2008–2015	Jan–Dec	0.47[b]	0.53[b]	0.52[b]	0.61[b]
2008–2014/2015 mean	Jan–Dec	0.85[a]	0.85[a]	0.86[a]	0.86[a]

[a] Significant at P = 0.01

[b] Significant at P = 0.05

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

The last two index well reports (Butler et al., 2014, 2015) showed that statistically significant correlations exist between annual water-level change and annual water use in the vicinity of the Thomas and Scott index wells. A significant correlation was found between water-level change and water use for tape measurements for a 1-mile radius water use for the Haskell well for 2008–2012. 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 due to the spurious nature of the 2012 tape water-level measurement. The R^2 values for the correlations for transducer measurements were updated for water use data in 2014 and compared to previous periods in table 32. Water-use within 3- and 4-mile radii was added to examine the changes in the correlations for the Thomas and Scott index wells.

The water-level change and water-use correlations for all radii around the Thomas County index well were all statistically significant. The larger the radius the greater the correlation up to the 3-mi radius (fig. 50), then the R^2 value reached a plateau. The R^2 values were generally lower for the additional year of data from 2013 to 2014 due to the increase in the variance with additional values. However, except for the 1-mi radius, the statistical significance remained about the same for the additional year of data.

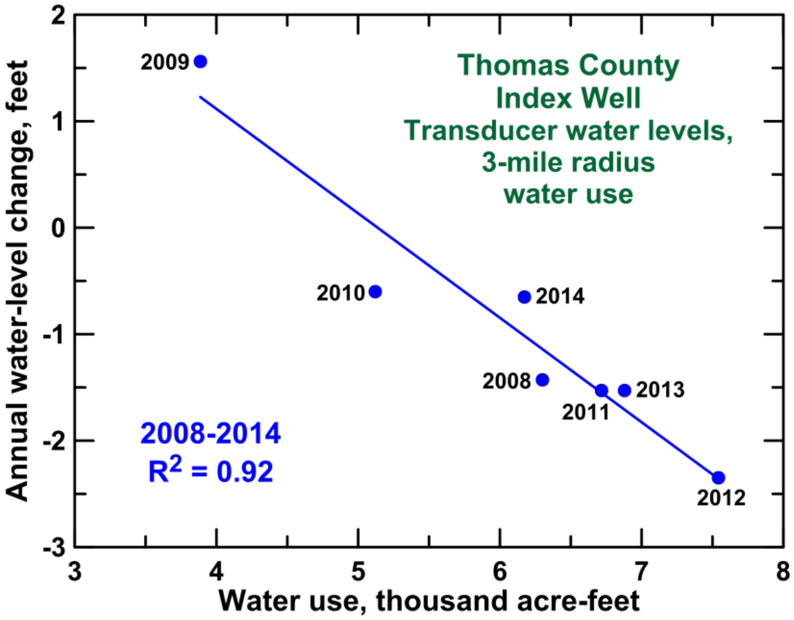


Figure 50—Correlation of annual water-level changes based on transducer measurements in the Thomas County index well with annual water use within a 3-mi radius during 2008–2014.

The correlations for the Scott County index well were only statistically significant for the 1-mi and 2-mi radii water use for 2008–2014 in comparison to significant correlations for the 2-mi, 4-mi, and 5-mi radii for 2008–2013. The plot for the 2-mi radius water use is displayed in fig. 51. The distribution of points in the plots suggest that the reported water use within certain areas surrounding the index well vary substantially from year to year and do not appear to be as well correlated with water-level change as for the Thomas index well area.

No statistically significant correlation was found for annual water-level change based on transducer measurements versus water use around the Haskell County index well for any of the three periods (2008–2012, 2008–2013, and 2008–2014) (table 32). The highest R^2 value is for the 1-mi radius water use for 2008–2012. Figure 52 shows that the distribution of points for 2013 and 2014 are substantially different from the trend for the 2008–2012 data. This reflects both late season pumping that affected the 2013 water-level change and the court-ordered shutdown of nearby pumping wells described in section 3.1.1.1.

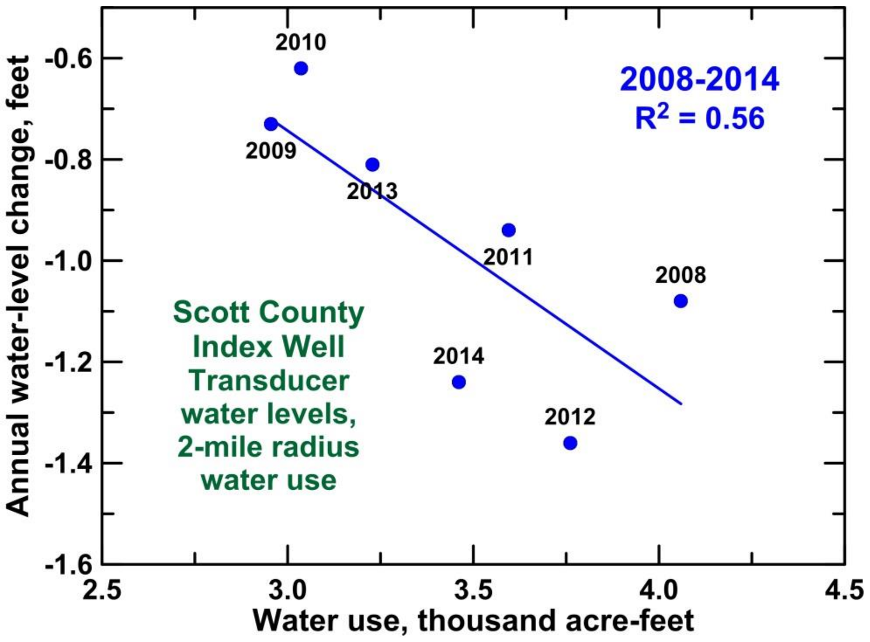


Figure 51—Correlation of annual water-level changes based on transducer measurements in the Scott County index well with annual water use within a 2-mi radius during 2008–2014.

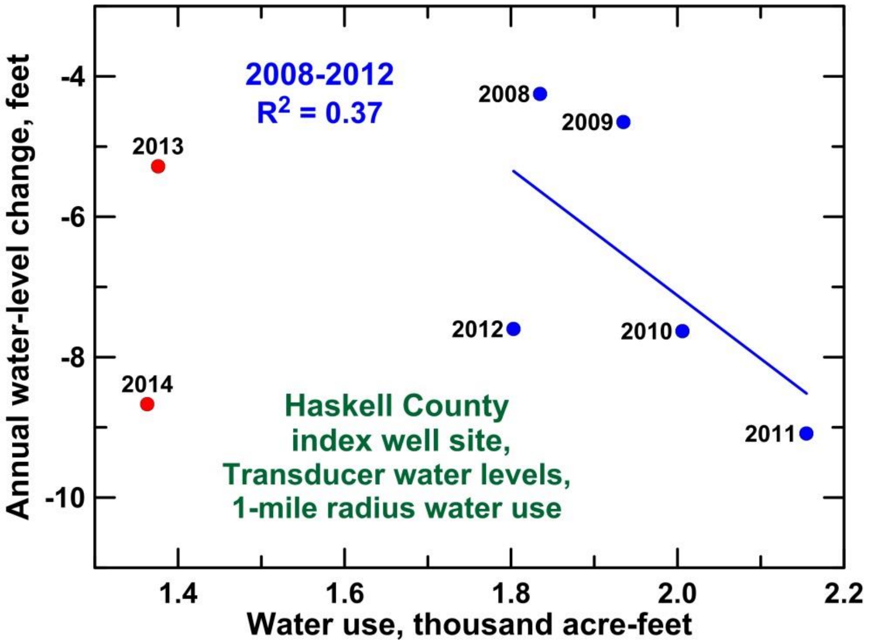


Figure 52—Correlation of annual water-level changes based on transducer measurements in the Haskell County index well with annual water use within a 1-mi radius during 2008–2014.

Table 32—Coefficient of determination (R^2 values) for correlation of annual water use around the index wells with annual water-level changes (transducer measurements) in the index wells for 2008–2013 and 2008–2014 for the Thomas and Scott wells and 2008–2012, 2008–2013, and 2008–2014 for the Haskell well.

Index well	**Period**	**Water use, 1-mi radius**	**Water use, 2-mi radius**	**Water use, 3-mi radius**	**Water use, 4-mi radius**	**Water use, 5-mi radius**
Thomas Co.	2008-2013	0.77[a]	0.81[a]	0.94[a]	0.93[a]	0.94[a]
Thomas Co.	2008-2014	0.69[b]	0.83[a]	0.92[a]	0.89[a]	0.92[a]
Scott Co.	2008-2013	0.46	0.68[b]	0.52	0.69[b]	0.65[b]
Scott Co.	2008-2014	0.55[b]	0.56[b]	0.22	0.43	0.43
Haskell Co.	2008-2012	0.37	0.20			0.29
Haskell Co.	2008-2013	0.28	0.26			0.35
Haskell Co.	2008-2014	0.01	0.01			0.05

[a] Significant at P = 0.01

[b] Significant at P = 0.05

5.8. *Correlation of Annual Water Use with Radar Precipitation*

Last year's index well report (Butler et al., 2015) described the high correlations between annual water use (within selected areas around the index well) and radar precipitation for the Thomas and Scott index wells for 2008–2012 and 2008–2013. 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 2008–2014 are listed in tables 33 and 34 based on the optimum R^2 obtained by varying the range and number of months for which the radar precipitation was summed. For 2008–2014, additional areas (3-mi and 4-mi radii) for water use around the Thomas and Scott index wells 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 highest R^2 values for the Thomas County index well are for 2008–2012 (table 33). The correlations are generally lower for succeeding years as might be expected as additional data are added, which increases the statistical variance. However, the statistical significance of the correlations remains approximately the same. The nine-point spatial mean of radar precipitation around the index well usually gives a greater correlation than the nearest radar precipitation grid point to the index well. The nine-grid point mean represents an area that is 59.6 mi^2 in comparison to an area of 6.6 mi^2 for a single grid point; the areas of 1-, 2-, 3-, 4-, and 5-mi radii of water use are 3.1, 12.6, 28.3, 50.2, and 78.5 mi^2, respectively. The correlation for the 1-mi to 5-mi range in water use radius tended to increase from 1-mi to 3-mi and then reached an approximate plateau in R^2 value, although the differences with water use radii were not large. A graph for 2008–2014 for the 3-mi radius water use and nine-point spatial mean of radar precipitation is shown in fig. 53a. The correlations for the 3-mi to 5-mi water use radii indicate that radar precipitation appears to explain at least 90% of the variation in water use. Optimum correlations were found mainly for March–December sums of radar precipitation for 2008–2014. As the number of data years increases for the index wells, more definitive determinations of optimum correlations could be obtained, just as for the 19 years of data currently available for the GMD-wide datasets (1996–2014) of water use and divisional climatic indices.

Table 33—Correlation (R^2 values) of annual use around the Thomas County index well with the sum of monthly radar precipitation for the nearest grid point to the index well location and for the mean of the nine grid points centered on the index well for 2008–2012, 2008–2013, and 2008–2014. The monthly precipitation sum used for 2008–2012 and 2008–2013 (February–October) is the same as in table 26 of last year's index well report. The monthly sums for 2008–2014 are those optimized for R^2. All of the correlations are statistically significant at P = 0.01 except for the nearest point radar precipitation for 2008–2013 for all water use radii.

Annual period	**Precipitation, month sum**	**Water use, radius, mi**	**R^2**
Nearest Point Radar Precipitation			
2008–2012	Feb–Oct	1	0.97
2008–2012	Feb–Oct	2	0.94
2008–2012	Feb–Oct	5	0.93
2008–2013	Feb–Oct	1	0.67
2008–2013	Feb–Oct	2	0.66
2008–2013	Feb–Oct	5	0.70
2008–2014	Mar–Dec	1	0.75
2008–2014	Mar–Dec	2	0.72
2008–2014	Mar–Dec	3	0.77
2008–2014	Mar–Dec	4	0.74
2008–2014	Mar–Dec	5	0.78
9-Point Mean Radar Precipitation			
2008–2012	Feb–Oct	1	0.90
2008–2012	Feb–Oct	2	0.93
2008–2012	Feb–Oct	5	0.98
2008–2013	Feb–Oct	1	0.80

2008–2013	Feb–Oct	2	0.83
2008–2013	Feb–Oct	5	0.91
2008–2014	Mar–Nov	1	0.81
2008–2014	Jan–Oct	2	0.86
2008–2014	Mar–Oct	3	0.92
2008–2014	Mar–Oct	4	0.90
2008–2014	Mar–Dec	5	0.93

The correlations for the Scott County index well varied substantially with period and water use radius (table 34). The highest correlations were for the 1-mi and 5-mi radius for 2008–2012 and 2008–2013 and the 5-mi radius for 2008–2014 for both the nearest point and nine-point spatial mean of radar precipitation. However, as for the Thomas index well, the statistical significance of these high correlations remained about the same due to the increase in the number of observations with each added year, even though the R^2 was lower due to the greater variance. In great contrast to these highly statistically significant correlations are the very low R^2 and statistically insignificant correlations for the 2-mi radius for all three periods, as well as for the 1-, 3-, and 4-mi radii for 2008–2014. It appears that either the amount of pumping from selected irrigation wells was anomalous relative to precipitation within these areas or that substantial uncertainty exists in the pumping record of some of the wells. The reason that the 5-mi water use radius gave high correlations is probably due to the averaging out of the anomalous pumping within the larger area for the pumping data. The optimum correlations for 2008–2014 were for the February–October sum of radar precipitation. A graph of the 5-mi radius water use versus the nine-point spatial mean of radar precipitation (fig. 53b) indicates that 2011 and 2013 were the years for which points deviated the most from the linear regression.

The highest correlations for the Haskell County index well are those between the 1-mi radius water use and radar precipitation at both the nearest point and nine-point spatial mean for 2008–2012 (table 35), although the statistical significance is at the $P = 0.05$ level and not as high as for the Thomas and Scott index wells, for which the high correlations are significant at the $P = 0.01$ level. No correlations are statistically significant for 2008–2013. In comparison to 2008–2012, significant correlations exist for both the nearest point and nine-point mean of radar precipitation versus the 5-mi radius water use for 2008–2014, although the R^2 is not nearly as high as for 2008–2012. As indicated earlier, the change in pumping due to the court-ordered shutdown of nearby wells is expected to have changed the relationship between the amount of pumping and precipitation. The shift from the significant correlation for the 1-mi water use radius in 2008–2012 to that for the 5-mi radius in 2008–2014 might represent a more subregional than a specific location correlation. However, using this radius makes the point for 2008 the most anomalous relative to the linear regression in a plot of the 5-mi radius water use versus radar precipitation (fig. 53c). In comparison, the most anomalous point for a plot (not shown) of the 1-mi radius water use versus radar precipitation for 2008–2014 is 2013. The optimum correlation for 2008–2014 is for the February–October sum of radar precipitation.

Table 34—Correlation (R^2 values) of annual use around the Scott County index well with the sum of monthly radar precipitation for the nearest grid point to the index well location and for the mean of the nine grid points centered on the index well for 2008–2012, 2008–2013, and 2008–2014. The monthly precipitation sum used for 2008–2012 and 2008–2013 (February–October) is the same as in table 26 of last year's index well report. The monthly sums for 2008–2014 are optimized for R^2.

Annual period	**Precipitation, month sum**	**Water use, radius, mi**	**R^2**
Nearest Point Radar Precipitation			
2008–2012	Feb–Oct	1	0.90[a]
2008–2012	Feb–Oct	2	0.32
2008–2012	Feb–Oct	5	0.96[a]
2008–2013	Feb–Oct	1	0.87[a]
2008–2013	Feb–Oct	2	0.31
2008–2013	Feb–Oct	5	0.85[a]
2008–2014	Mar–Nov	1	0.37
2008–2014	Feb–Oct	2	0.25
2008–2014	Feb–Oct	3	0.27
2008–2014	Feb–Oct	4	0.44
2008–2014	Feb–Oct	5	0.79[a]
9-Point Mean Radar Precipitation			
2008–2012	Feb–Oct	1	0.82[a]
2008–2012	Feb–Oct	2	0.22
2008–2012	Feb–Oct	5	0.92[a]
2008–2013	Feb–Oct	1	0.80[a]
2008–2013	Feb–Oct	2	0.22
2008–2013	Feb–Oct	5	0.79[a]
2008–2014	Mar–Nov	1	0.39
2008–2014	Feb–Oct	2	0.17
2008–2014	Feb–Oct	3	0.18
2008–2014	Feb–Oct	4	0.35
2008–2014	Feb–Oct	5	0.77[a]

[a] Significant at P = 0.01

Table 35—Correlation (R^2 values) of annual use around the Haskell County index well with the sum of monthly radar precipitation for the nearest grid point to the index well location and for the mean of the nine grid points centered on the index well for 2008–2012, 2008–2013, and 2008–2014. The monthly precipitation sum used for 2008–2012 and 2008–2013 (February–October) is the same as in table 26 of last year's index well report. The monthly sums for 2008–2014 are optimized for R^2.

Annual period	**Precipitation, month sum**	**Water use, radius, mi**	**R^2**
Nearest Point Radar Precipitation			
2008–2012	Feb–Oct	1	0.74^b
2008–2012	Feb–Oct	2	0.33
2008–2012	Feb–Oct	5	0.46
2008–2013	Feb–Oct	1	0.22
2008–2013	Feb–Oct	2	0.24
2008–2013	Feb–Oct	5	0.39
2008–2014	Jan–Dec	1	0.45
2008–2014	Jan–Nov	2	0.47
2008–2014	Jan–Nov	5	0.57^b
9-point Mean Radar Precipitation			
2008–2012	Feb–Oct	1	0.75^b
2008–2012	Feb–Oct	2	0.30
2008–2012	Feb–Oct	5	0.45
2008–2013	Feb–Oct	1	0.25
2008–2013	Feb–Oct	2	0.24
2008–2013	Feb–Oct	5	0.44
2008–2014	Jan–Dec	1	0.43
2008–2014	Jan–Nov	2	0.42
2008–2014	Feb–Oct	5	0.56^b

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

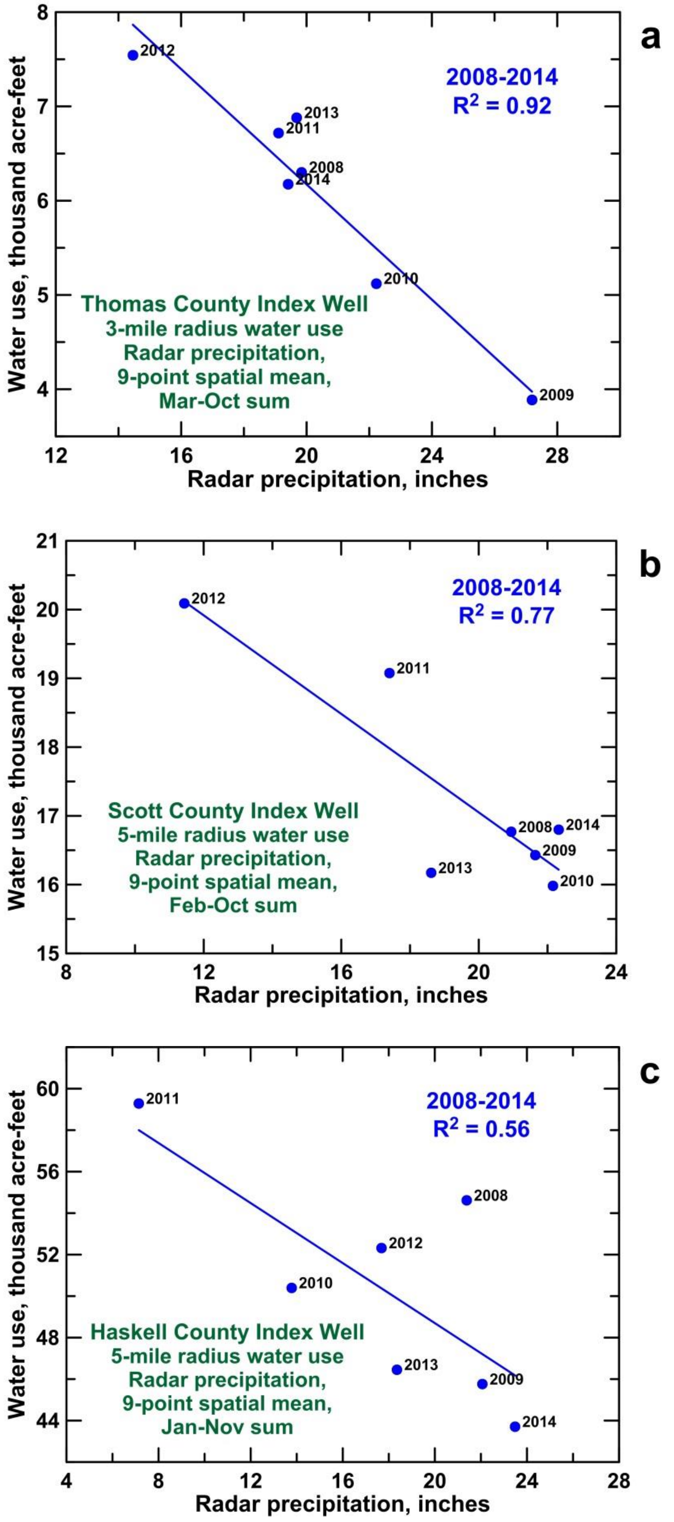


Figure 53—Correlation of annual water use with the nine-point spatial mean of radar precipitation at the Thomas, Scott, and Haskell index wells for 2008–2014.

5.9. *Theoretical Support for Annual Water-Level Change versus Water Use Relationships*

In the previous work of this project (Whittemore et al., 2016), we have found a linear relationship between annual water-level change and water use. In last year's report (Butler et al., 2015), we developed the initial framework for the theoretical support for this linear relationship. This year, we more fully developed the theoretical support. That support, which is described in the Butler et al. (2016) publication in Appendix B, will be summarized here.

We begin by writing a simple water balance equation that holds for any particular area of an aquifer:

$$\text{Water Volume Change in Aquifer} = \text{Net Inflow} - \text{Pumping} \tag{1}$$

We can express this equation in terms of parameters for an unconfined aquifer as follows:

$$\Delta WL * Area * S_Y = I_{ua} * Area - Q \tag{2}$$

where:

ΔWL = average annual water-level change over aquifer area, [L];
$Area$ = aquifer area under consideration, [L^2];
I_{ua} = annual net inflow per unit area into aquifer, [L];
Q = total annual pumping in aquifer area, [L^3];
S_y = average specific yield for aquifer area, [-].

In deep water-table condition, such as in GMDs 1, 3, and 4, we would expect relatively little variation in I_{ua} from year to year. We also would expect little variation in S_y from year to year for averaging areas above a few tens of square miles. Thus, for those conditions, we can simplify equation (2) to (3):

$$\Delta WL = \frac{I_{ua}}{S_y} - \frac{Q}{Area * S_y} = b - aQ \tag{3}$$

where a (=1/($Area$*S_y)) and b (=I_{ua}/S_y) are constants (slope and intercept of best-fit line, respectively).

Equation (3) indicates that, given the conditions noted in the previous paragraph, a plot of ΔWL versus Q should be linear, which is what we have found in our analyses of 1996–2013 annual water-level changes in GMD4 (Butler et al., 2016—see Appendix B) and in the analyses of water-level changes at the index wells discussed in the previous sections.

Thus, we can estimate the S_y and I_{ua} of any particular area of an aquifer from the slope (a) and intercept (b) of the best-fit line to the ΔWL versus Q plot. More importantly, we can also use the equation to estimate the impact of proposed pumping reductions on annual water-level changes in a theoretically defensible manner. For example, equation (3) can be rearranged to estimate the Q that would produce no change in water levels ($Q_{\Delta WL=0}$):

$$Q_{\Delta WL=0} = \frac{b}{a} = I_{ua} * Area \tag{4}$$

Finally, equation (3) provides a very rapid means of predicting future water-level changes for a given annual pumping; the annual pumping for a projected climatic condition can be estimated using the relationships discussed in the previous sections and Whittemore et al. (2016).

5.9.1. Application to Thomas County Index Well

Figure 54a is the 2008–2014 ΔWL versus Q plot for a circular area with a 5-mi radius centered on the Thomas County index well. The average annual water-level change over the area is approximated by the annual water-level change at the index well, while the water use is the total reported annual water use for that area. As shown in fig. 54a, the equation for the best-fit line through these data is:

$$\Delta WL = 3.48 - 0.33Q \qquad (5)$$

The equation for the best-fit line through the 2008–2013 data presented in last year's report (Butler et al., 2015) was essentially the same (ΔWL=3.46-0.33Q), indicating that the addition of the 2014 value made little difference.

Using the definitions of the slope and intercept in equation (3), we can calculate the S_y for this area (50,265 acres) from the slope (0.33) of the ΔWL vs Q plot. Thus,

$$S_y = (Area*0.33)^{-1} = 0.06 \qquad (6)$$

as was also determined for the 2008–2013 dataset; this value is appropriate for a sand, clay, and silt mixture (majority sand with lesser amounts of clay and silt).

Given this S_y, we can estimate I_{ua} from the intercept (3.48):

$$I_{ua} = 3.48*S_y = 0.21 \text{ ft/yr or } 2.5 \text{ inches/yr} \qquad (7)$$

as was also determined for the 2008–2013 dataset.

We can also calculate the reduction in average annual water use that would have been required to have had no change in water level over the 2008–2014 monitoring period. The average reported use for this period was 13,434 ac-ft and the water use at $\Delta WL = 0$ can be calculated from equation (4) as 10,545 ac-ft. Thus, a 22% reduction in average annual water use would have produced essentially stable water levels over the monitoring period, the same result as obtained using the 2008–2013 dataset.

Equation (5) can be used to predict future annual water-level changes for a given reported water use assuming that the slope and intercept do not change with time. However, that assumption could be questionable under the following conditions:

a) Continuing aquifer depletion—as the saturated thickness diminishes, S_y could change, which would cause a change in the slope and intercept parameters in equation (5). However, the S_y change would likely be gradual and not great. Probably the maximum change we could expect at the scale of this example is a factor of two. The small and medium dashed lines in fig. 54b are the ΔWL vs. Q plots for a factor of two decrease and increase in S_y, respectively. It likely would be difficult to pick up such a change for some time unless the reported water use was near the upper end of the historical range. Note that the Q at $\Delta WL = 0$ remains unchanged as it is solely a function of I_{ua};

b) Changing climatic conditions—As climatic conditions change, inflow into the area would likely change. Most projections indicate drier conditions in the future. The large dashed line in fig. 54b is the ΔWL vs. Q plot for a factor of two decrease in I_{ua} assuming no change in S_y. This change should be more readily detectable than a change in S_y as the line shifts downward to the left while retaining its original slope. Changes in climatic conditions could also result in changes in the duration and the onset and/or end of the pumping season. However, as long as the water-level measurements are taken at about the same time as current measurements and three or so months from the end of the pumping season, this should not produce scatter in the plot much beyond what we currently observe.

c) Changes in irrigation return flow—irrigation return flow and irrigation enhanced recharge could be significant contributors to the inflow into this area. If so, the inflow would likely decrease over time, regardless of climatic conditions, because of the transition to more efficient irrigation practices. Again, this condition would be recognized by the plot shifting downward to the left while retaining its original slope.

Three additional factors that could be responsible for the scatter in fig. 54a are:

a) Changes in atmospheric pressure—changes in atmospheric pressure can produce up to a foot change in water level at the Thomas index well and elsewhere in western Kansas where the water table is well more than 100 ft below land surface. Considerable “noise” can be introduced into the ΔWL data if the annual measurements in one year are taken at a time of a relatively low atmospheric pressure while the next year the measurements are taken at a time of relatively high atmospheric pressure.

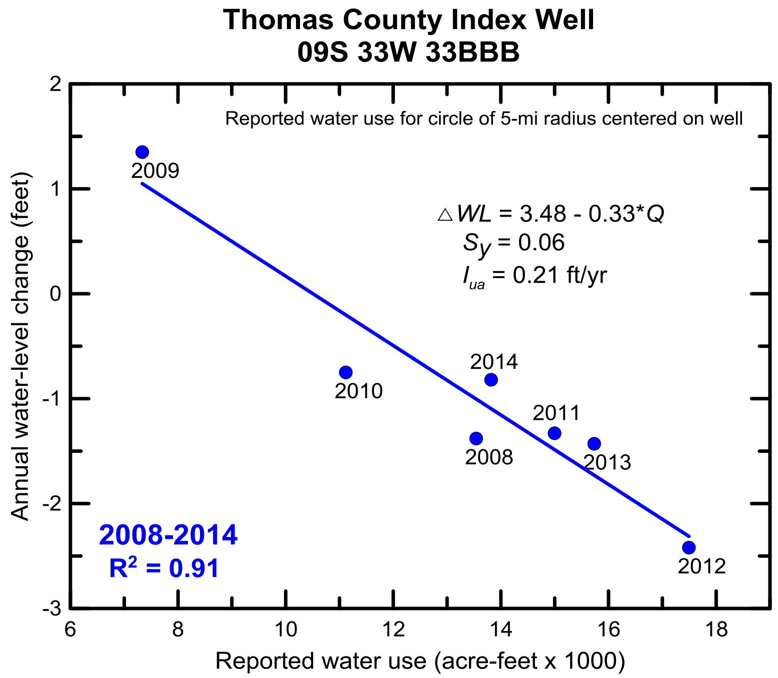
b) Out-of-season pumping—pumping near the time of the annual water-level measurement in early January can introduce considerable error into the relationship. However, there is typically very little out-of-season pumping in GMD4.

c) Measurement error—error in reported Q and the measured water levels can produce considerable scatter.

d) Fluctuations in I_{ua}—the scatter about the best-fit line in fig. 43b could be partially due to relatively small fluctuations in I_{ua} (all points fall within +/-0.2I_{ua} of best-fit line).

The ΔWL vs. Q plots in Butler et al. (2016—see Appendix B) use the average annual water change over a certain area. In this section, we have used the annual water-level change at the Thomas County index well in place of an areal average. Although this approximation of the areal average may not have a big impact on the slope of the best-fit line, it likely would alter the intercept and thus could affect the I_{ua} estimate somewhat.

a)



b)

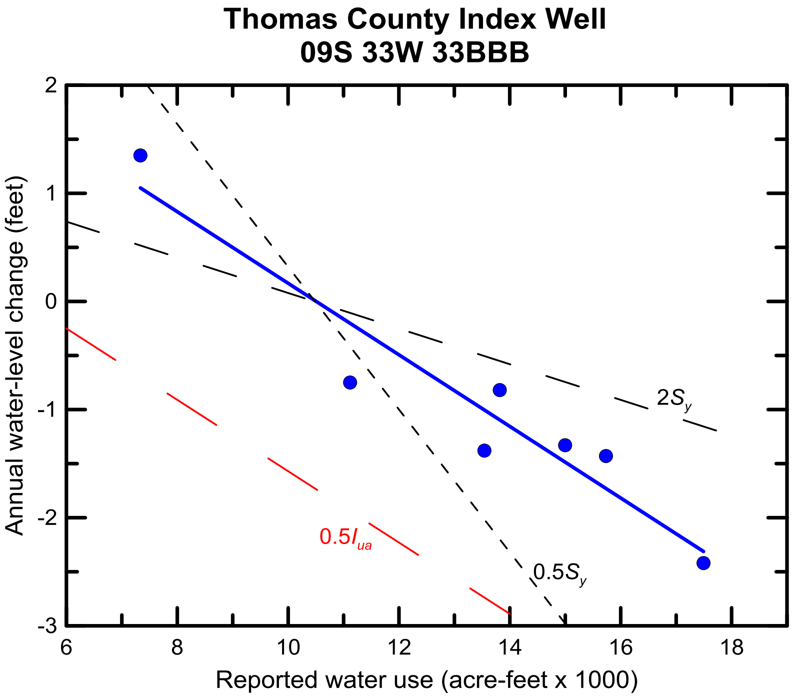


Figure 54—a) Reported water use versus annual water-level change at the Thomas County index well plot for the monitoring period (2008–2014; reported water use for 2015 not yet available). Solid line is the best-fit line with a slope of 0.33 and intercept of 3.48. b) Sensitivity of water use versus annual water-level change at the Thomas County index well to changes in specific yield (S_y) and net inflow per unit area (I_{ua}); black small and medium dashed lines indicate plot for a factor of two decrease and increase in S_y, respectively, and red large dashed line indicates plot for a factor of two decrease in I_{ua}.

6. Discussion of HPA Geochemistry Near the Index Wells

Groundwater sampling for geochemical and isotopic analysis is an ongoing part of the Index Well Program to determine the age and sources of water in the HPA. Data for samples collected this year from four of the monitoring wells installed in the Sheridan-6 (SD-6) LEMA complement data for groundwater samples collected from the three original index wells and irrigation wells near the Thomas County index well in 2011; irrigation wells in Thomas and Haskell counties in 2013; the border index wells in Morton, Stevens, and Seward counties in 2014; and core porewater from near the Thomas and Haskell index wells (Butler et al., 2012, 2014, 2015; Butler, Whittemore, et al., 2013; Katz et al., in review). Groundwater ^{14}C ages at the base of the aquifer are younger in GMD4 than in either GMD1 or GMD3, although, in all cases, the water sampled was recharged thousands of years ago. Over time, and with repeated application, irrigated water evaporates and salts become concentrated in groundwater recharge. However, with the exception of one site along the Oklahoma border, where the HPA is partially affected by natural saline formation water from deeper sedimentary (Permian) units, groundwater is fresh across all three GMDs, indicating an insignificant effect of irrigation water return flow on the total dissolved solids (TDS) concentration. As indicated later, however, an effect on nitrate concentration is observed at some locations that could be attributed to irrigation return flow or natural processes. Observations near the Thomas index well in core collected through the vadose zone support this conclusion, with high chloride masses concentrated in the upper 12 m of the 65 m unsaturated zone (Katz et al., in review). The multi-well nests at the border index well sites (Morton, Stevens, and Seward Counties) and core profiles (Thomas and Haskell sites) provide valuable information about depth-age relationships that cannot be obtained from a single, deep monitoring well. Combined with data from core profiles, geochemical evidence supports the conclusion that geological heterogeneities are increasingly important to water availability as water levels decline (Butler, Stotler, et al., 2013).

This year, samples were collected from four of the index wells located in the SD-6 LEMA (table 36). Sampling and analytical methods follow those described in previous reports (e.g., see Butler et al., 2015). Water was also collected as a grab sample from a pond located less than 300 yards from the southernmost SD-6 index well. The total dissolved solids (TDS) of water sampled from these wells is higher than in water sampled from index wells in Thomas, Scott, or Haskell counties, but less than Morton, Stevens, or Seward counties. Geochemical ratios (e.g., Br/Cl, SO_4/Cl, NO_3-N/Cl) computed for SD-6 index well groundwater are similar to those sampled in Thomas County (e.g., fig. 55). The pond water had a chemical composition similar to that of the sampled groundwaters in the area, although the nitrate concentration was lower than in the groundwater. The pond water contained measureable tritium activity, as would be expected for surface water with water sourced from recent precipitation, in comparison to the undetectable tritium activity in the sampled groundwater in table 36. Radiocarbon as a percent of modern carbon varied between 49.6 and 61.12 pMC, yielding uncorrected ages of 3,960 to 5,630 yr BP. These values are very similar to those observed previously in Thomas County (59–60 pMC, 3,820 to 4,600 yr BP). Of the western GMDs, the waters sampled from the HPA in GMD4 remain the youngest sampled at the base of the aquifer to date. Only the water-table wells at the rangeland Cimarron and Rolla sites have yielded younger water. A vertical gradient in groundwater age, with the youngest water near the water table, is typical. The shallower wells provide better information on local recharge ages, whereas deeper wells provide information about older recharge that occurred upgradient from the sample location. A comparison of ^{14}C with NO_3-N concentration indicates that, although a range of low to higher nitrate concentrations exist in the younger basal aquifer waters sampled across the western HPA, the highest nitrate concentrations occur only in the younger groundwaters (fig. 56). This can be an indication of mixing related to more recent recharge to the aquifer or an increase in recharge rates at some as yet undetermined point in the past. Combined, these data indicate water in Thomas and Sheridan counties is significantly younger than that sampled to date from GMDs 1 and 3. This supports earlier conclusions that there is a source of recharge to the aquifer in this area that is more recent than in the other two GMDs (Butler et al., 2015).

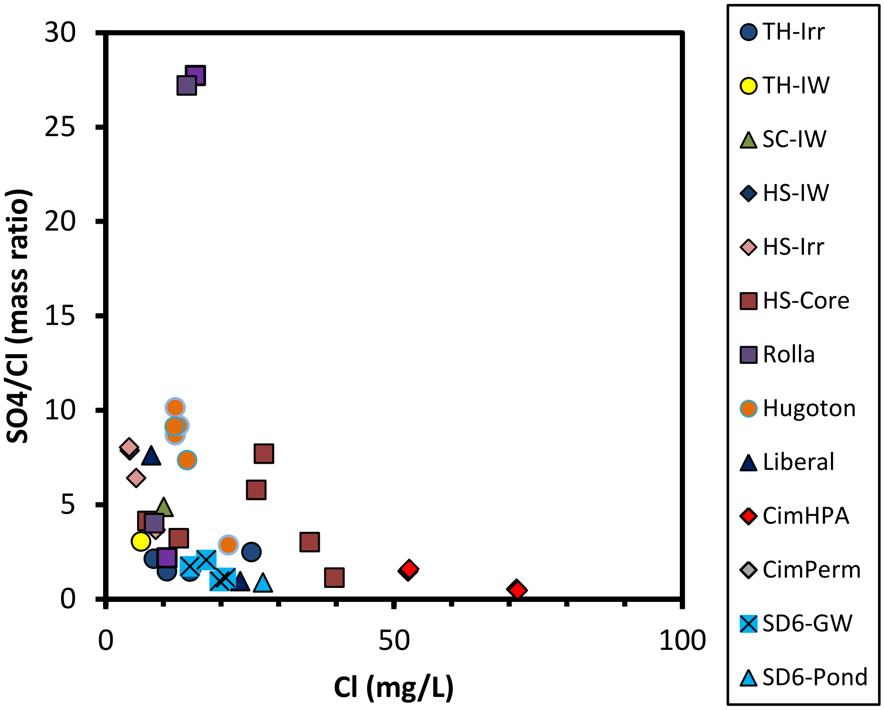


Figure 55—Comparison of SO_4/Cl vs. Cl for most of the index well study area.

Table 36—Geochemical data from the SD-6 LEMA area. Dissolved constituents are reported in mg/L.

Sample name	**Sample date**	**Ca**	**Mg**	**Na**	**K**	**HCO_3**	**Cl**	**SO_4**	**NO_3-N**	**Br**	**TDS sum, mg/L**	**3H (TU)**	**$d^{13}C$ [DIC] ‰ (PDB)**	**^{14}C[DIC] (pMC)**	**^{14}C[DIC] (yr BP)**
Moss	11/23/2015	60	17	18	6.0	243	20	18	4.9	0.14	339	<0.8	-3.36	61.12	3,960
Seegmiller	11/23/2015	44	17	25	6.2	221	21	23	4.4	0.18	324	<0.8	-3.51	49.60	5,630
Baalman	11/24/2015	45	17	26	6.4	225	15	25	3.2	0.12	317	<0.8	-3.37	51.75	5,290
Steiger Well	11/24/2015	43	18	35	7.4	241	17	36	2.7	0.13	345	<0.8	-4.48	59.72	4,140
Steiger Pond	11/24/2015	49	15	31	13.7	242	27	24	1.4	0.12	323	2.2			

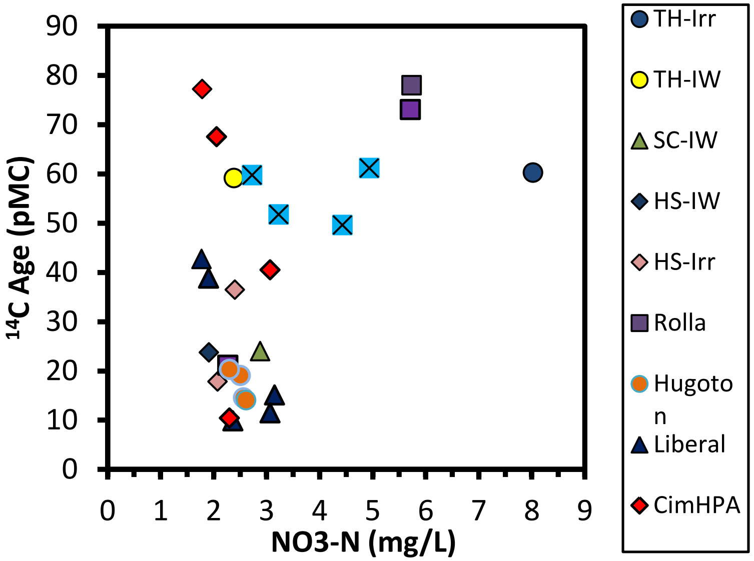


Figure 56—Comparison of radiocarbon age (as percent modern carbon) versus NO_3-N concentration for most of the index well study area. Higher pMC represents younger radiocarbon age waters.

7. Summary of 2015 Accomplishments and Plans for 2016

7.1. 2015 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. Provided initial interpretation of the hydrographs.
- 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. Provided initial interpretation of the hydrographs.
- Drilled three new index wells in GMD1; sensors and telemetry equipment will be added shortly.
- 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.
- 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.
- Continued to develop the theoretical support for the relationship between annual water-level change and reported water use in the HPA.
- 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, GMD personnel, among others.

7.2. *Planned Activities, 2016*

- Continue monitoring and processing of 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, and any other data sets that we can find.
- 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 any other data sets that we can find.
- Assess recovery and pumping for 2015 and 2016 periods.
- Continue to seek new wells to add to the network.
- Drill one or more index wells, most likely in GMDs 3 and/or 4; install sensors and telemetry equipment at each well.
- 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 information that can be acquired from an analysis of the water-level response to changes in barometric pressure.
- Continue assessment of the relationships among climatic indices, radar precipitation data, annual water-level change, and annual water use in the HPA.
- Further develop theoretical support for relationships among annual water-level change, annual water use, and climatic conditions.
- Integrate information from drillers' logs in the vicinity of the Thomas and Scott index wells into interpretation of water-level responses in those areas.

7.3. *Outstanding Issues*

Major unresolved issues include the following:

- The source and areal extent of the inflow, which is in addition to that induced by pumping activity and 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.
- Conditions in the HPA at the Scott County site; understanding is still incomplete but inflow not induced by pumping may also be occurring in that vicinity.
- Relationship between the Dakota aquifer and the HPA in southwestern Kansas.

8. References

Bohling, G. C., Jin, W., and Butler, J. J., Jr., 2011, Kansas Geological Survey barometric response function software user's guide: Kansas Geological Survey, Open-File Report 2011-10, 27 p. Available online at http://www.kgs.ku.edu/HighPlains/OHP/index_program/brf.html (accessed May 13, 2016).

Buchanan, R. C., Wilson, B. B., Buddemeier, R. R., and Butler, J. J., Jr., 2015, The High Plains aquifer, Kansas Geological Survey Public Information Circular 18, 6 pp. Available online at http://www.kgs.ku.edu/Publications/pic18/index.html (accessed May 13, 2016).

Buddemeier, R. W., Stotler, R., Butler, J. J., Jr., Jin, W., Beeler, K., Reboulet, E., Macfarlane, P. A., Kreitzer, S., Whittemore, D. O., Bohling, G., and Wilson, B. B., 2010, High Plains aquifer calibration monitoring well program: Third year progress report: Kansas Geological Survey, Open-File Report 2010-3, 117 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2010/OFR10_3/index.html (accessed May 13, 2016).

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

Butler, J. J., Jr., Stotler, R., Whittemore, D. O., Reboulet, E., Bohling, G. C., and Wilson, B. B, 2012, High Plains aquifer calibration monitoring well program: Fifth year progress report: Kansas Geological Survey, Open-File Report 2012-2, 93 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2012/OFR12_2/index.html (accessed May 13, 2016).

Butler, J. J., Jr., Whittemore, D. O., Bohling, G. C., Reboulet, E., Stotler, R. L., and Wilson, B. B., 2013, High Plains aquifer index well program: 2012 annual report: Kansas Geological Survey Open-File Report 2013-1, 116 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2013/OFR13_1/index.html (accessed May 13, 2016).

Butler, J. J., Jr., Whittemore, D. O., Reboulet, E., Knobbe, S., Wilson, B.B., Stotler, R. L., and Bohling, G. C., 2015, High Plains aquifer index well program: 2014 annual report: Kansas Geological Survey Open-File Report 2015-3, 135 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2015/OFR15_3/index.html (accessed May 13, 2016).

Butler, J. J., Jr., Whittemore, D. O., Reboulet, E., Stotler, R. L., Bohling, G. C., Olson, J. C., and Wilson, B. B., 2014, High Plains aquifer index well program: 2013 annual report: Kansas Geological Survey Open-File Report 2014-1, 90 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2014/OFR14_1/index.html (accessed May 13, 2016).

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

Fross, D., Sophocleous, M. A., Wilson, B. B., and Butler, J. J., Jr., 2012, Kansas High Plains Aquifer Atlas: Kansas Geological Survey, available online at http://www.kgs.ku.edu/HighPlains/HPA_Atlas/index.html (accessed May 13, 2016).

Hayes, M. J., 2016, Comparison of major drought indices: National Drought Mitigation Center, Lincoln, Nebraska, http://drought.unl.edu/Planning/Monitoring/ComparisonofIndicesIntro.aspx (accessed May 13).

Heim, R. R., Jr., 2002, A review of twentieth-century drought indices used in the United States: Bulletin of the American Meteorological Society, v. 83, p. 1,149–1,165.

Katz, B., Stotler, R., Hirmas, D., Ludvigson, G., Smith, J., and Whittemore, D., Geochemical recharge estimation and the effects of a declining water table: Submitted April 2016 to Vadose Zone Journal.

Kruseman, G. P., and de Ridder, N. A., 1990, Analysis and evaluation of pumping test data—ILRI Pub. 47: International Institute for Land Reclamation and Improvement, the Netherlands, 377 p.

Logan, K. E., Brunsell, N. A., Jones, A. R., and Feddema, J. J., 2010, Assessing spatiotemporal variability of drought in the U.S. central plains: Journal of Arid Environments, v. 74, p. 247–255.

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

National Climatic Data Center, 2016, U.S. Palmer drought indices: http://www.ncdc.noaa.gov/oa/climate/research/prelim/drought/palmer.html (accessed May 13).

Stotler, R., Butler, J. J., Jr., Buddemeier, R. W., Bohling, G. C., Comba, S., Jin, W., Reboulet, E., Whittemore, D. O., and Wilson, B. B., 2011, High Plains aquifer calibration monitoring well program: Fourth year progress report: Kansas Geological Survey Open-File Rept. 2011-4, 185 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2011/OFR11_4/index.html (accessed May 13, 2016).

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

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

Whittemore, D. O., Butler, J. J. Jr., Wilson, B. B., and Woods, J., 2015, Using radar precipitation to estimate water-level changes and water use in the High Plains aquifer: Governor's Conference on Future of Water in Kansas, Manhattan, KS, abstract available at http://conferences.k-state.edu/govwater/sessions/concurrent-session-2/ (accessed May 15, 2016).

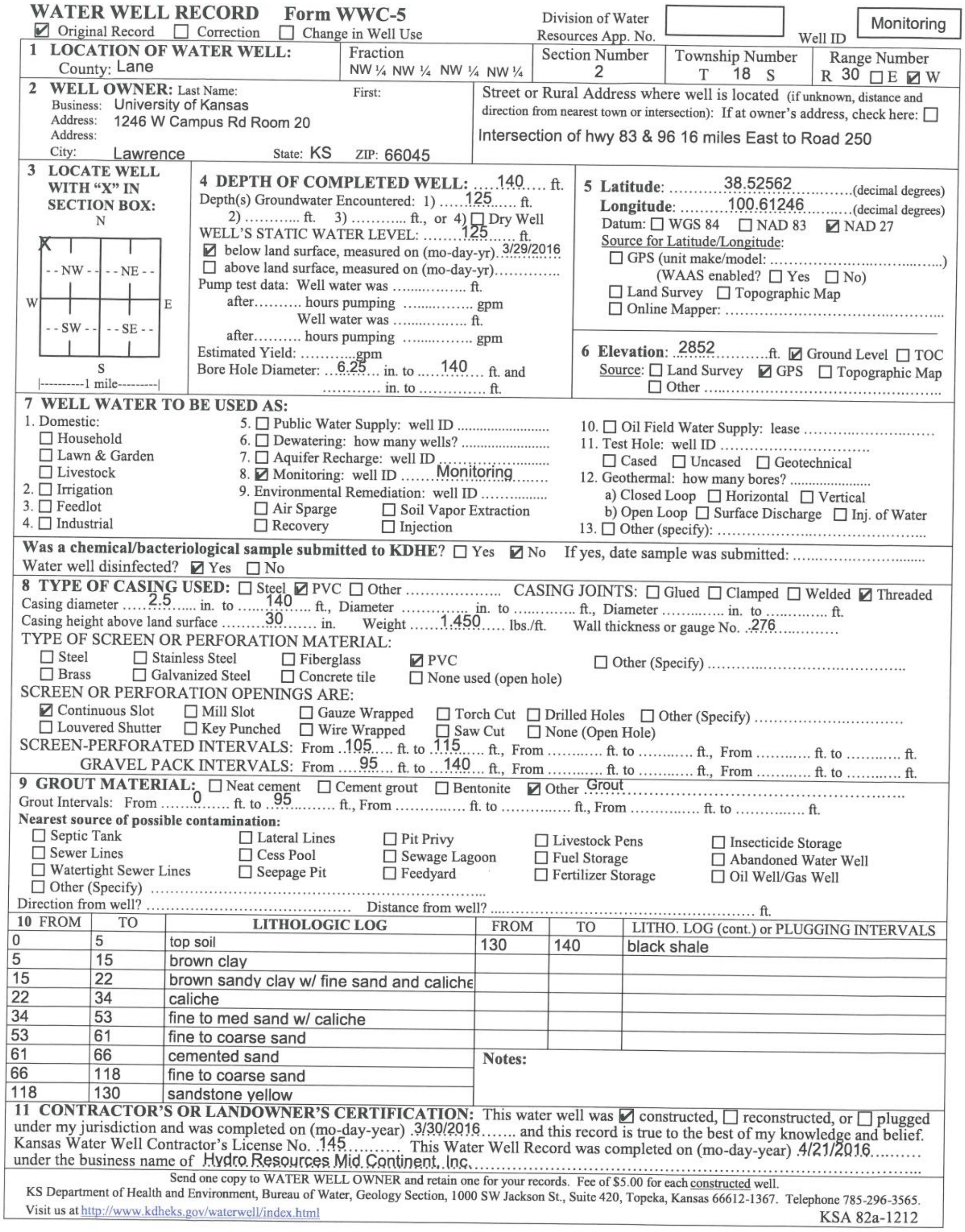
Young, D. P., Buddemeier, R. W., Butler, J. J., Jr., Jin, W., Whittemore, D. O., Reboulet, E., and Wilson, B. B., 2008, High Plains aquifer calibration monitoring well program: Year 2 progress report: Kansas Geological Survey, Open-File Report 2008-29, 54 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2008/OFR08_29/index.html (accessed May 13, 2016).

Young, D. P., Buddemeier, R. W., Whittemore, D. O., and Reboulet, E., 2007, High Plains aquifer calibration monitoring well program: Year 1 progress report on well installation and aquifer response: Kansas Geological Survey, Open-File Report 2007-30, 44 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2007/OFR07_30/index.html (accessed May 13, 2016).

9. Appendix A: WWC-5 Forms for New GMD1 Index Wells and Sheridan-6 Index Wells

9.1. New GMD1 Index Wells

Lane County Index Well



WATER WELL RECORD **Form WWC-5**

☑ Original Record ☐ Correction ☐ Change in Well Use

Division of Water Resources App. No.

Well ID: Monitoring

1 LOCATION OF WATER WELL: County: Lane

Fraction: NW ¼ NW ¼ NW ¼ NW ¼

Section Number: 2

Township Number: T 18 S

Range Number: R 30 ☐ 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: ☐

Intersection of hwy 83 & 96 16 miles East to Road 250

3 LOCATE WELL WITH "X" IN SECTION BOX:

N

X

- - NW - - - - NE - -

W E

- - SW - - - - SE - -

S

|----------1 mile---------|

4 DEPTH OF COMPLETED WELL: 140 ft.

Depth(s) Groundwater Encountered: 1) 125 ft.

2) ………… ft. 3) ………… ft., or 4) ☐ Dry Well

WELL'S STATIC WATER LEVEL: 125 ft.

☑ below land surface, measured on (mo-day-yr) 3/29/2016

☐ 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: 6.25 in. to 140 ft. and

………… in. to ………… ft.

5 Latitude: 38.52562 (decimal degrees)

Longitude: 100.61246 (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: 2852 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 Monitoring
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 140 ft., Diameter ………… in. to ………… ft., Diameter ………… in. to ………… ft.

Casing height above land surface 30 in. Weight 1.450 lbs./ft. Wall thickness or gauge No. .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 105 ft. to 115 ft., From ………… ft. to ………… ft., From ………… ft. to ………… ft.

GRAVEL PACK INTERVALS: From 95 ft. to 140 ft., From ………… ft. to ………… ft., From ………… ft. to ………… ft.

9 GROUT MATERIAL: ☐ Neat cement ☐ Cement grout ☐ Bentonite ☑ Other Grout

Grout Intervals: From 0 ft. to 95 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	5	top soil	130	140	black shale
5	15	brown clay			
15	22	brown sandy clay w/ fine sand and caliche			
22	34	caliche			
34	53	fine to med sand w/ caliche			
53	61	fine to coarse sand			
61	66	cemented sand	**Notes:**		
66	118	fine to coarse sand			
118	130	sandstone yellow			

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) 3/30/2016 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) 4/21/2016 under the business name of Hydro Resources Mid Continent, Inc.

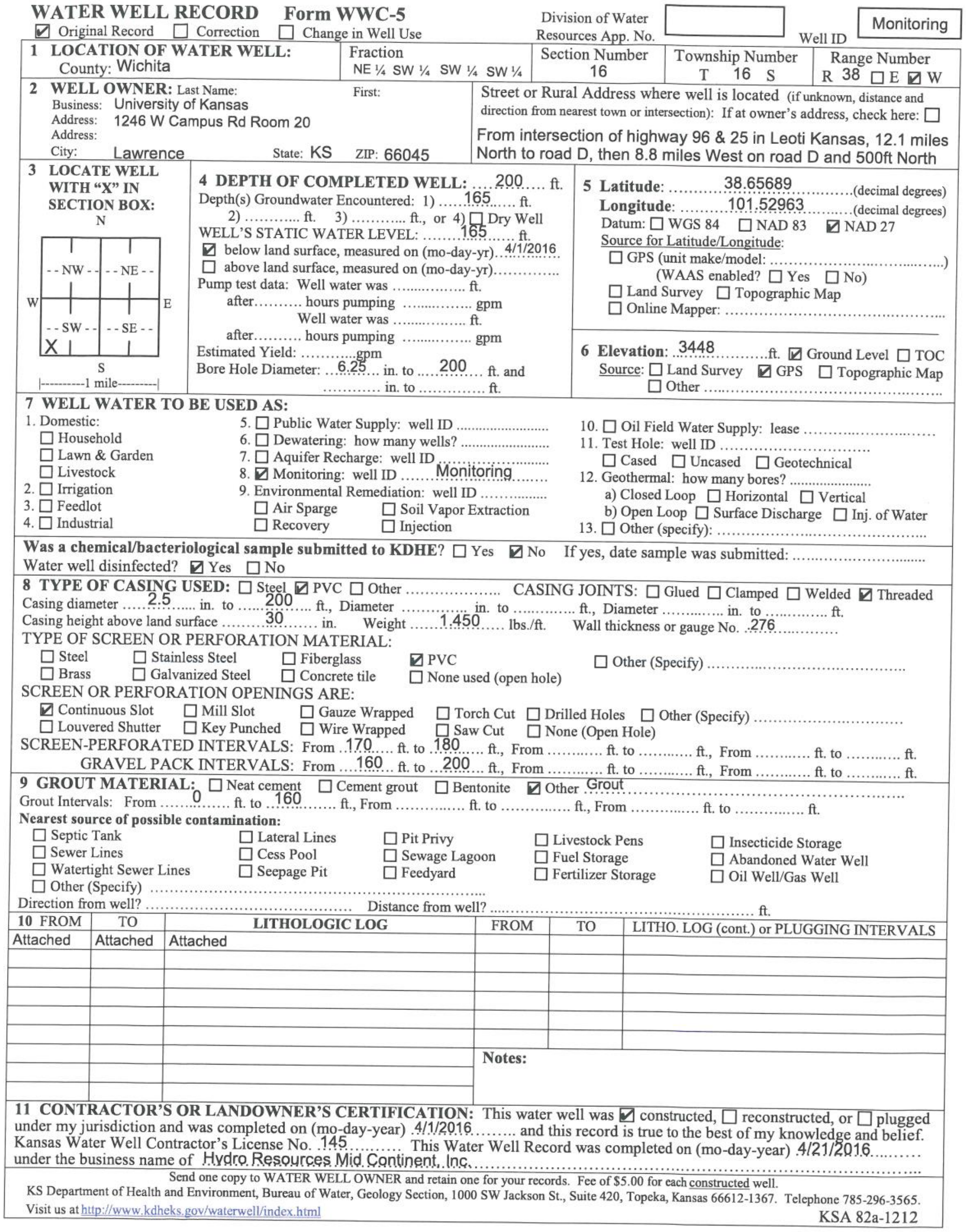
Send one copy to WATER WELL OWNER and retain one for your records. Fee of $5.00 for each constructed well.

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

Wichita County Index Well



WATER WELL RECORD **Form WWC-5**

☑ Original Record ☐ Correction ☐ Change in Well Use

Division of Water Resources App. No.

Well ID Monitoring

1 LOCATION OF WATER WELL:
County: Wichita

Fraction: NE ¼ SW ¼ SW ¼ SW ¼

Section Number: 16

Township Number: T 16 S

Range Number: R 38 ☐ 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: ☐

From intersection of highway 96 & 25 in Leoti Kansas, 12.1 miles North to road D, then 8.8 miles West on road D and 500ft North

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

4 DEPTH OF COMPLETED WELL: ....200.... ft.
Depth(s) Groundwater Encountered: 1) ....165..... ft.
2) .... ft. 3) .... ft., or 4) ☐ Dry Well
WELL'S STATIC WATER LEVEL: ....165....... ft.
☑ below land surface, measured on (mo-day-yr)...4/1/2016
☐ 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: ...6.25... in. to .....200...... ft. and
.... in. to .... ft.

5 Latitude: ....38.65689..........(decimal degrees)
Longitude: ....101.52963........(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: ..3448...........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 ....Monitoring.......
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 .....200..... ft., Diameter .... in. to .... ft., Diameter .... in. to .... ft.
Casing height above land surface ....30........ in. Weight ....1.450..... lbs./ft. Wall thickness or gauge No. ..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 ..170..... ft. to ..180........ ft., From .... ft. to .... ft., From .... ft. to .... ft.
GRAVEL PACK INTERVALS: From ....160.. ft. to ..200....... ft., From .... ft. to .... ft., From .... ft. to .... ft.

9 GROUT MATERIAL: ☐ Neat cement ☐ Cement grout ☐ Bentonite ☑ Other Grout ....
Grout Intervals: From ....0...... ft. to ...160........ 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
Attached	Attached	Attached			

Notes:

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) .4/1/2016........ 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) .4/21/2016.......... under the business name of Hydro Resources Mid Continent, Inc...

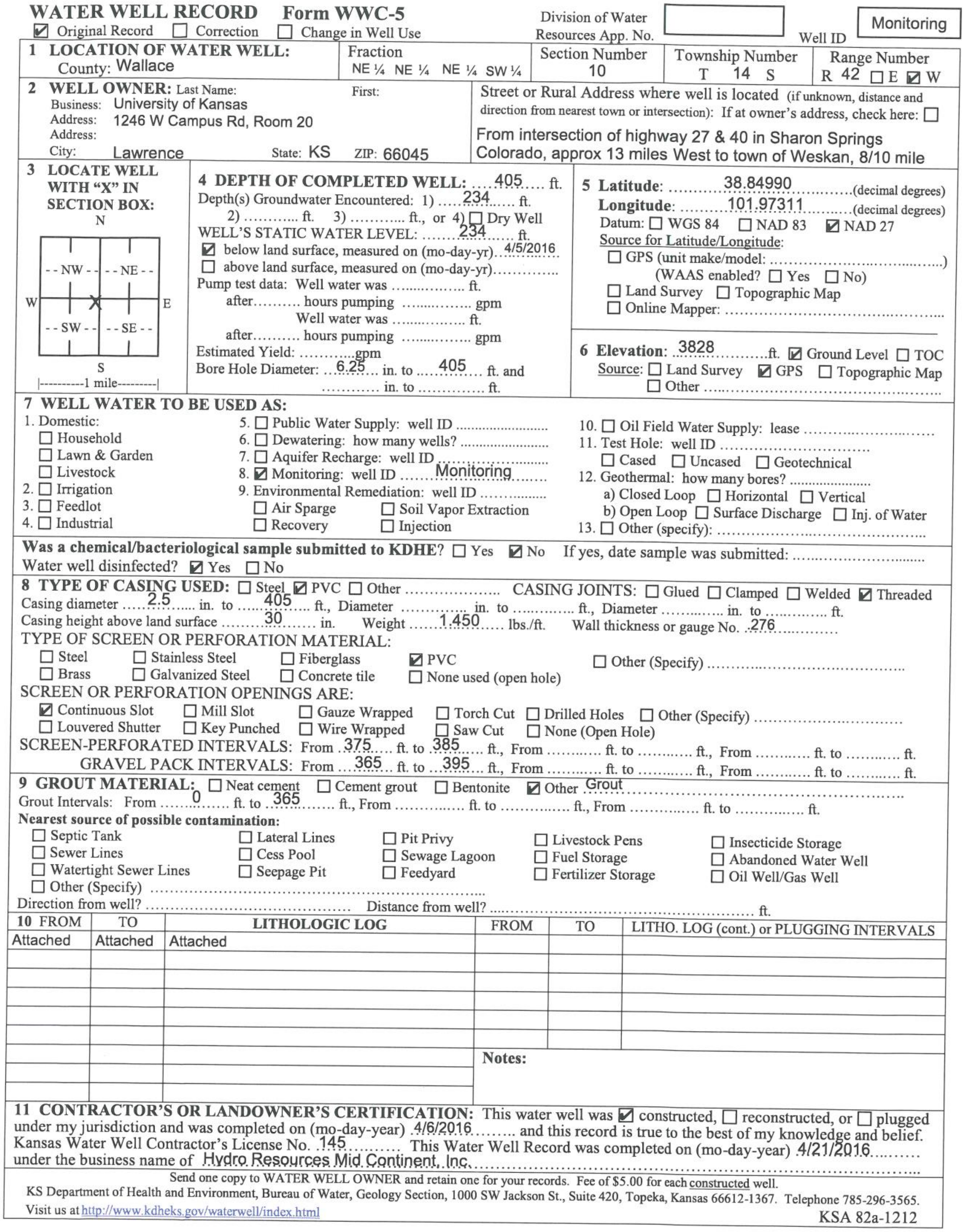
Send one copy to WATER WELL OWNER and retain one for your records. Fee of $5.00 for each constructed well.
KS Department of Health and Environment, Bureau of Water, Geology Section, 1000 SW Jackson St., Suite 420, Topeka, Kansas 66612-1367. Telephone 785-296-3565.
Visit us at http://www.kdheks.gov/waterwell/index.html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

Form	WWC5
Contractor	Hydro Resources Mid Continent, Inc.
Well Owner	
Doc ID	1304626

Litholgy

From	To	LithologicLog
0	3	top soil
3	20	brown sandy clay
20	28	fine to med sand, few clay
28	35	fine sand w/ clay
35	48	fine to med w/ caliche clay streaks
48	61	fine to med sand
61	68	brown clay few cement sand
68	80	fine to coarse sand
80	97	brown sandy clay
97	106	fine sand few clay
106	115	fine to coarse sand
115	123	brown clay few caliche
123	130	fine sand few clay
130	173	fine to coarse sand
173	190	fine to med sand few clay
190	195	yellow soapstone
195	200	black shale

Wallace County Index Well



WATER WELL RECORD Form WWC-5

☑ Original Record ☐ Correction ☐ Change in Well Use

Division of Water Resources App. No.

Well ID: Monitoring

1 LOCATION OF WATER WELL:
County: Wallace
Fraction: NE ¼ NE ¼ NE ¼ SW ¼
Section Number: 10
Township Number: T 14 S
Range Number: R 42 ☐ 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: ☐
From intersection of highway 27 & 40 in Sharon Springs Colorado, approx 13 miles West to town of Weskan, 8/10 mile

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

4 DEPTH OF COMPLETED WELL: 405 ft.
Depth(s) Groundwater Encountered: 1) 234 ft.
2) ………… ft. 3) ………… ft., or 4) ☐ Dry Well
WELL'S STATIC WATER LEVEL: 234 ft.
☑ below land surface, measured on (mo-day-yr) 4/5/2016
☐ 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: 6.25 in. to 405 ft. and
………… in. to ………… ft.

5 Latitude: 38.84990 (decimal degrees)
Longitude: 101.97311 (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: 3828 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 Monitoring
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 405 ft., Diameter ………… in. to ………… ft., Diameter ………… in. to ………… ft.
Casing height above land surface 30 in. Weight 1.450 lbs./ft. Wall thickness or gauge No. .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 375 ft. to 385 ft., From ………… ft. to ………… ft., From ………… ft. to ………… ft.
GRAVEL PACK INTERVALS: From 365 ft. to 395 ft., From ………… ft. to ………… ft., From ………… ft. to ………… ft.

9 GROUT MATERIAL: ☐ Neat cement ☐ Cement grout ☐ Bentonite ☑ Other Grout
Grout Intervals: From 0 ft. to 365 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
Attached	Attached	Attached			

Notes:

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) 4/6/2016 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) 4/21/2016 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

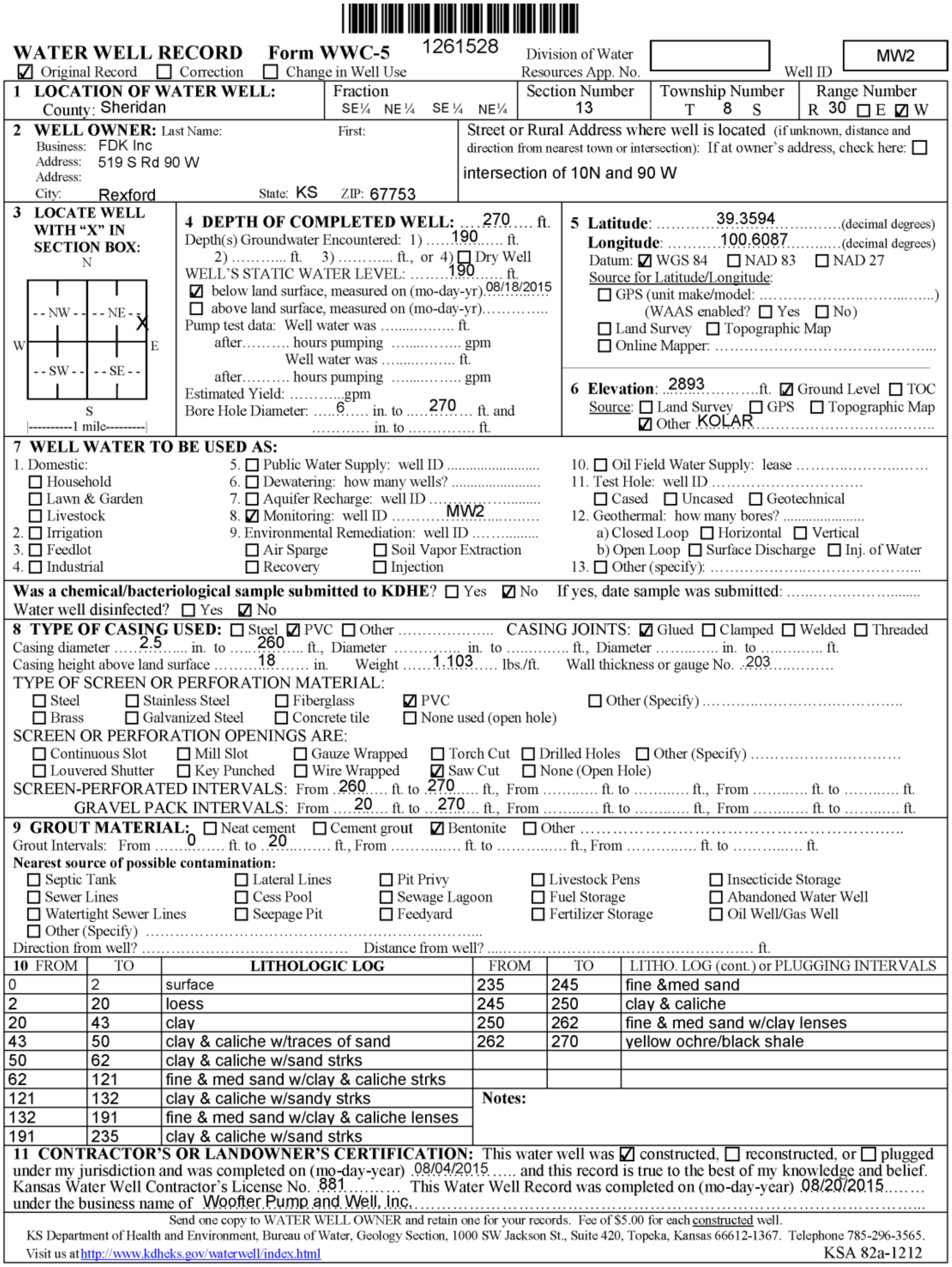
Form	WWC5
Contractor	Hydro Resources Mid Continent, Inc.
Well Owner	
Doc ID	1304644

Litholgy

From	To	LithologicLog
0	5	top soil
5	26	brown clay
26	33	fine to med sand
33	41	brown sandy clay
41	70	fine sand w/ clay
70	78	brown clay w/ fine to med sand ledges
78	106	fine sand w/ clay
106	123	brown sandy clay
123	145	brown sandy clay w/ fine sand
145	163	brown clay
163	180	fine to med sand
180	204	brown sandy clay w/ fine sand
204	241	fine to coarse sand w/ few clay
241	255	brown clay w/ few sand
255	283	fine to coarse sand
283	302	fine to coarse sand w/ few clay
302	354	fine to coarse sand w/ clay streaks
354	362	brown clay
362	394	fine to coarse sand
394	397	gray shale
397	405	black shale

9.2. *Sheridan-6 Index Wells (WWC-5 form for Beckman Index Well not available)*

Baalman Index Well 2



1261528

WATER WELL RECORD Form WWC-5

Division of Water Resources App. No.

Well ID: MW2

☑ Original Record ☐ Correction ☐ Change in Well Use

1 LOCATION OF WATER WELL:
County: Sheridan
Fraction: SE¼ NE¼ SE¼ NE¼
Section Number: 13
Township Number: T 8 S
Range Number: R 30 ☐ E ☑ W

2 WELL OWNER: Last Name: First:
Business: FDK Inc
Address: 519 S Rd 90 W
Address:
City: Rexford State: KS ZIP: 67753

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: ☐
intersection of 10N and 90 W

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

4 DEPTH OF COMPLETED WELL: 270 ft.
Depth(s) Groundwater Encountered: 1) 190 ft.
2) ……….. ft. 3) ……….. ft., or 4) ☐ Dry Well
WELL'S STATIC WATER LEVEL: 190 ft.
☑ below land surface, measured on (mo-day-yr) 08/18/2015
☐ 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: 6 in. to 270 ft. and
………… in. to …………. ft.

5 Latitude: 39.3594 (decimal degrees)
Longitude: 100.6087 (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: 2893 ft. ☑ Ground Level ☐ TOC
Source: ☐ Land Survey ☐ GPS ☐ Topographic Map
☑ Other KOLAR

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 MW2
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 260 ft., Diameter ………… in. to ………… ft., Diameter ………… in. to ………… ft.
Casing height above land surface 18 in. Weight 1.103 lbs./ft. Wall thickness or gauge No. 203
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 260 ft. to 270 ft., From ………. ft. to ………. ft., From ………. ft. to ………. ft.
GRAVEL PACK INTERVALS: From 20 ft. to 270 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 ☐ Sewer Lines ☐ Watertight Sewer Lines
☐ Lateral Lines ☐ Cess Pool ☐ Seepage Pit
☐ Pit Privy ☐ Sewage Lagoon ☐ Feedyard
☐ Livestock Pens ☐ Fuel Storage ☐ Fertilizer Storage
☐ Insecticide Storage ☐ Abandoned Water Well ☐ 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	235	245	fine &med sand
2	20	loess	245	250	clay & caliche
20	43	clay	250	262	fine & med sand w/clay lenses
43	50	clay & caliche w/traces of sand	262	270	yellow ochre/black shale
50	62	clay & caliche w/sand strks			
62	121	fine & med sand w/clay & caliche strks			
121	132	clay & caliche w/sandy strks	**Notes:**		
132	191	fine & med sand w/clay & caliche lenses			
191	235	clay & caliche w/sand strks			

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) 08/04/2015 and this record is true to the best of my knowledge and belief. Kansas Water Well Contractor's License No. 881 This Water Well Record was completed on (mo-day-year) 08/20/2015 under the business name of Woofter Pump and Well, 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

Moss Index Well

WATER WELL RECORD Form WWC-5

Division of Water Resources App. No.

1 LOCATION OF WATER WELL: Fraction ¼ ¼ ¼ SE ¼ | Section Number 25 | Township Number T 7 S | Range Number R 29 ☐E ☒W

Sheridan

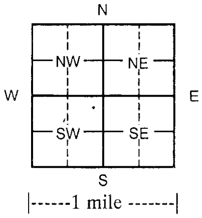
Street/Rural Address of Well Location; if unknown, distance & direction from nearest town or intersection: If at owner's address, check here ☐.

[illegible]

Global Positioning System (GPS) information:
Latitude: (in decimal degrees)
Longitude: (in decimal degrees)
Elevation:
Datum: ☐ WGS 84, ☐ NAD 83, ☐ NAD 27
Collection Method:
☐ GPS unit (Make/Model:)
☐ Digital Map/Photo, ☐ Topographic Map, ☐ Land Survey
Est. Accuracy: ☐ <3 m, ☐ 3-5 m, ☐ 5-15 m, ☐ >15 m

2 WATER WELL OWNER **Ks Ground Water Dist 4**
RR#, St. Address, Box # Northwest Ks GMD No 4
City, State, ZIP Code Colby, Ks 67701

3 LOCATE WELL WITH AN "X" IN SECTION BOX:



4 DEPTH OF COMPLETED WELL 245 ft.
Depth(s) Groundwater Encountered (1) ft. (2) ft. (3) ft.
WELL'S STATIC WATER LEVEL ft. below land surface measured on mo/day/yr
Pump test data: Well water was ft. after hours pumping gpm
EST. YIELD 30 gpm: Well water was ft. after hours pumping gpm
WELL WATER TO BE USED AS: ☐ Public water supply ☐ Geothermal ☐ Injection well
Domestic ☐ Feedlot _Oil field water supply ☐ Dewatering ☐ Other (Specify below)
Irrigation ☐ Industrial ☐ Domestic-lawn & garden ☒ Monitoring well MW # 1
Was a chemical/bacteriological sample submitted to Department? ☐ Yes ☒ No
If yes, mo/day/yr sample was submitted
Water Well Disinfected? ☒ Yes ☐ No

5 TYPE OF CASING USED: ☐ Steel ☒ PVC ☐ Other
CASING JOINTS: ☒ Glued ☐ Clamped ☐ Welded ☐ Threaded
Casing diameter 2.5 in. to 205 ft., Diameter in. to ft., Diameter in. to ft.
Casing height above land surface 48 in., Weight 1.103 lbs./ft. Wall thickness or gauge No. .203
TYPE OF SCREEN OR PERFORATION MATERIAL:
☐ Steel ☐ Stainless Steel ☒ PVC ☐ Other (Specify)
☐ Brass ☐ Galvanized Steel ☐ None used (open hole)
SCREEN OR PERFORATION OPENINGS ARE:
☐ Continuous Slot ☐ Mill slot ☐ Gauze wrapped ☐ Torch cut ☐ Drilled holes ☐ None (open hole)
☐ Louvered shutter ☐ Key punched ☐ Wire wrapped ☒ Saw cut ☐ Other (specify)
SCREEN-PERFORATED INTERVALS: From 205 ft. to 245 ft., From ft. to ft.
From ft. to ft., From ft. to ft.
GRAVEL PACK INTERVALS: From 20 ft. to 245 ft., From ft. to ft.
From ft. to ft., From ft. to ft.

6 GROUT MATERIAL: ☐ Neat cement Cement grout ☒ Bentonite ☐ Other
Grout Intervals From 0 ft. to 20 ft. From ft. to ft. From ft. to ft.
What is the nearest source of possible contamination:
☐ Septic tank ☐ Lateral lines ☐ Pit privy ☐ Livestock pens ☐ Insecticide storage ☐ Other (specify below)
☐ Sewer lines ☐ Cesspool ☐ Sewage lagoon ☐ Fuel storage ☐ Abandoned water well
☐ Watertight sewer lines ☐ Seepage pit ☐ Feedyard ☐ Fertilizer storage ☐ Oil well/gas well None
Direction from well Distance from well

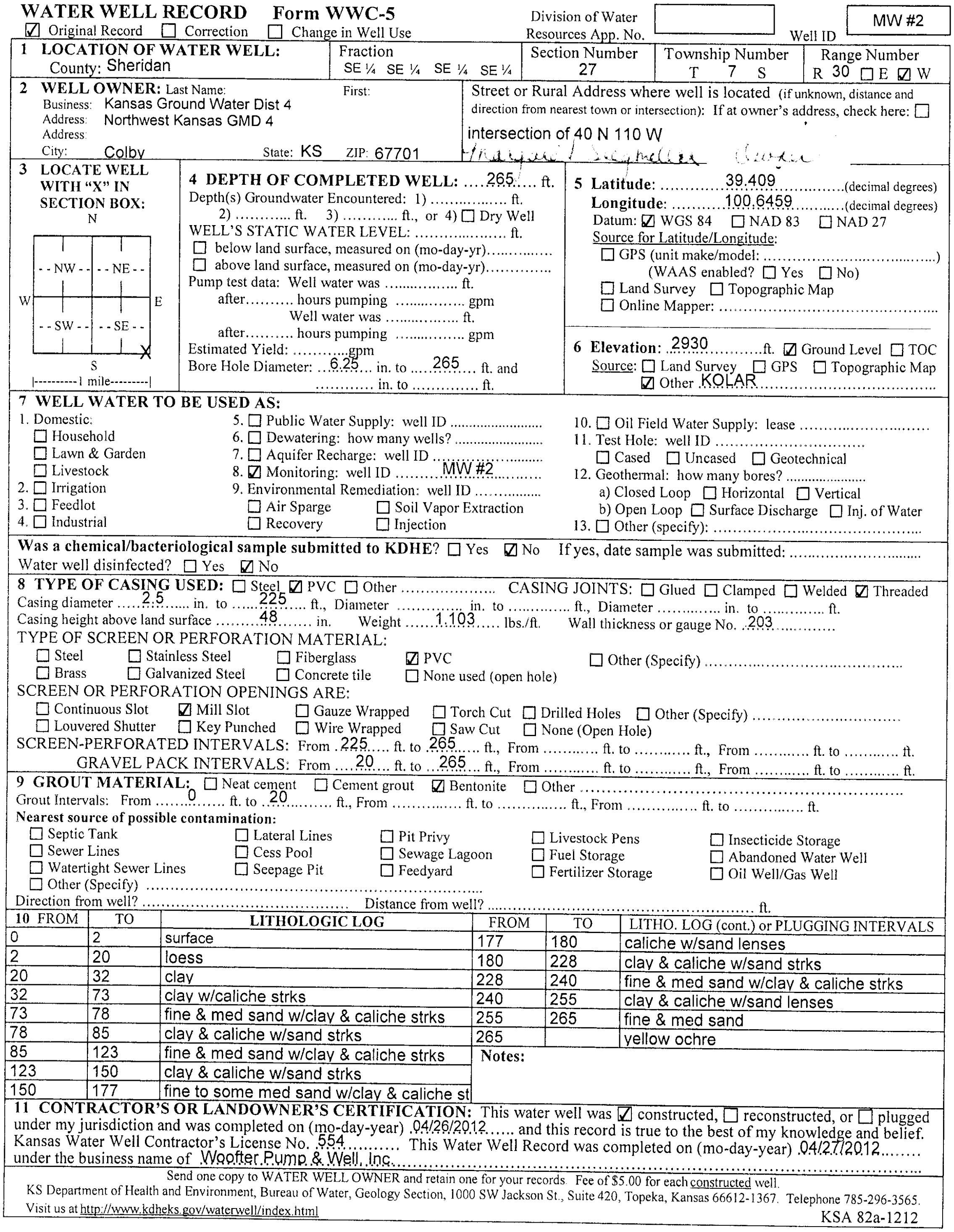
FROM	TO	LITHOLOGIC LOG	FROM	TO	LITHO. LOG (cont.) or PLUGGING INTERVALS
0	2	Surface			Caliche lenses
2	27	Loess	150	163	Clay & calliche w/sand strks
27	54	Clay w/caliche strks	163	172	Fine sd & sdy clay mix w/clay & cal strks
54	68	Fine to med sand w/clay & caliche strks	172	176	Fine & med sd w/clay & caliche strks
68	89	Fine to med sand w/clay strks	176	180	caliche
89	102	Fine sand & sandy clay mix w/clay strks	180	205	Clay & caliche w/sand lenses
102	119	Clay & caliche w/sand lenses	205	223	Fine sd w/caliche strks & clay lenses
119	122	Caliche	223	243	Fine to med sand w/clay & caliche lenses
122	137	Clay & caliche w/sand lenses	243	250	Yellow ochre
137	150	Fine sand & sandy clay mix w/clay &			

7 CONTRACTOR'S OR LANDOWNER'S CERTIFICATION: This water well was constructed, _reconstructed, or ☐ plugged under my jurisdiction and was completed on (mo/day/year) 4-13-2012 And this record is true to the best of my knowledge and belief. Kansas Water Well Contractor's License No. 554 . This Water Well Record was completed on (mo/day/year) under the business name of **Woofter Pump & Well Inc.** by (signature) .

INSTRUCTIONS: Please fill in blanks and check the correct answers. Send three copies (white, blue, pink) to Kansas Department of Health and Environment, Bureau of Water, Geology Section, 1000 SW Jackson St., Suite 420, Topeka, Kansas 66612-1367. Telephone 785-296-5522. Send one to WATER WELL OWNER and retain one for your records. Include fee of $5.00 for each constructed well. Visit us at http://www.kdheks.gov/waterwell/index.html.

KSA 82a-1212 Form provided by Forms-On-A-Disk · (214) 340-9429 · www.FormsOnADisk.com White Copy

Seegmiller Index Well



WATER WELL RECORD **Form WWC-5**

☑ Original Record ☐ Correction ☐ Change in Well Use

Division of Water Resources App. No.

Well ID MW #2

1 LOCATION OF WATER WELL:
County: Sheridan
Fraction SE ¼ SE ¼ SE ¼ SE ¼
Section Number 27
Township Number T 7 S
Range Number R 30 ☐ E ☑ W

2 WELL OWNER: Last Name: First:
Business: Kansas Ground Water Dist 4
Address: Northwest Kansas GMD 4
Address:
City: Colby State: KS ZIP: 67701

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: ☐
intersection of 40 N 110 W
[illegible] / Seegmiller [illegible]

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

4 DEPTH OF COMPLETED WELL: ....265..... ft.
Depth(s) Groundwater Encountered: 1) .... ft.
2) .... ft. 3) .... ft., or 4) ☐ Dry Well
WELL'S STATIC WATER LEVEL: .... ft.
☐ below land surface, measured on (mo-day-yr)..............
☐ 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: ...6.25.... in. to .....265..... ft. and
.... in. to .... ft.

5 Latitude: ....39.409...........(decimal degrees)
Longitude: ....100.6459...........(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: .2930...........ft. ☑ Ground Level ☐ TOC
Source: ☐ Land Survey ☐ GPS ☐ Topographic Map
☑ Other KOLAR....................................

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 ....MW #2..........
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 ......225..... ft., Diameter .... in. to .... ft., Diameter .... in. to .... ft.
Casing height above land surface ....48........ in. Weight ....1.103..... lbs./ft. Wall thickness or gauge No. ..203..............

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 .225..... ft. to .265...... ft., From .... ft. to .... ft., From .... ft. to .... ft.
GRAVEL PACK INTERVALS: From .....20.... ft. to ..265.... 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	177	180	caliche w/sand lenses
2	20	loess	180	228	clay & caliche w/sand strks
20	32	clay	228	240	fine & med sand w/clay & caliche strks
32	73	clay w/caliche strks	240	255	clay & caliche w/sand lenses
73	78	fine & med sand w/clay & caliche strks	255	265	fine & med sand
78	85	clay & caliche w/sand strks	265		yellow ochre
85	123	fine & med sand w/clay & caliche strks	**Notes:**		
123	150	clay & caliche w/sand strks			
150	177	fine to some med sand w/clay & caliche st			

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) .04/26/2012...... and this record is true to the best of my knowledge and belief. Kansas Water Well Contractor's License No. .554.......... This Water Well Record was completed on (mo-day-year) .04/27/2012........ under the business name of Woofter Pump & Well, 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

Steiger Index Well

WATER WELL RECORD **Form WWC-5** Division of Water Resources App. No. ____

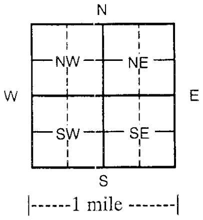
1 LOCATION OF WATER WELL: **Thomas**
Fraction ¼ ¼ ¼ SE ¼
Section Number **26**
Township Number T **8** S
Range Number R **31** ☐E ☒W

Street/Rural Address of Well Location; if unknown, distance & direction from nearest town or intersection: If at owner's address, check here ☐.
[illegible] Steiger - [illegible]

2 WATER WELL OWNER **Kansas Ground Water Dist 4**
RR#, St. Address, Box # Northwest Kansas GMD 4
City, State, ZIP Code Colby, Ks 67701

Global Positioning System (GPS) information:
Latitude: N 39 19.312 (in decimal degrees)
Longitude: W 100 44.761 (in decimal degrees)
Elevation: 29.50
Datum: ☐ WGS 84, ☐ NAD 83, ☐ NAD 27
Collection Method:
☐ GPS unit (Make/Model: ____)
☐ Digital Map/Photo, ☐ Topographic Map, ☐ Land Survey
Est. Accuracy: ☐ <3 m, ☐ 3-5 m, ☐ 5-15 m, ☐ >15 m

3 LOCATE WELL WITH AN "X" IN SECTION BOX:



4 DEPTH OF COMPLETED WELL **185** ft.
Depth(s) Groundwater Encountered (1) ____ ft. (2) ____ ft. (3) ____ ft.
WELL'S STATIC WATER LEVEL ____ ft. below land surface measured on mo/day/yr ____
Pump test data: Well water was ____ ft. after ____ hours pumping ____ gpm
EST. YIELD 30 gpm: Well water was ____ ft. after ____ hours pumping ____ gpm
WELL WATER TO BE USED AS: ☐ Public water supply ☐ Geothermal ☐ Injection well
☒ Domestic ☐ Feedlot _Oil field water supply ☐ Dewatering ☐ Other (Specify below)
Irrigation ☐ Industrial ☐ Domestic-lawn & garden ☒ Monitoring well M.W.#3
Was a chemical/bacteriological sample submitted to Department? ☐ Yes ☒ No
If yes, mo/day/yr sample was submitted ____
Water Well Disinfected? ☒ Yes ☐ No

5 TYPE OF CASING USED: ☐ Steel ☒ PVC ☐ Other ____
CASING JOINTS: ☒ Glued ☐ Clamped ☐ Welded ☐ Threaded
Casing diameter 4 in. to **145** ft., Diameter ____ in. to ____ ft., Diameter ____ in. to ____ ft.
Casing height above land surface 48 in., Weight 2.071 lbs./ft. Wall thickness or gauge No. .237
TYPE OF SCREEN OR PERFORATION MATERIAL:
☐ Steel ☐ Stainless Steel ☒ PVC ☐ Other (Specify) ____
☐ Brass ☐ Galvanized Steel ☐ None used (open hole)
SCREEN OR PERFORATION OPENINGS ARE:
☐ Continuous Slot ☐ Mill slot ☐ Gauze wrapped ☐ Torch cut ☐ Drilled holes ☐ None (open hole)
☐ Louvered shutter ☐ Key punched ☐ Wire wrapped ☒ Saw cut ☐ Other (specify) ____
SCREEN-PERFORATED INTERVALS: From **145** ft. to **185** ft., From ____ ft. to ____ ft.
From ____ ft. to ____ ft., From ____ ft. to ____ ft.
GRAVEL PACK INTERVALS: From **20** ft. to **185** ft., From ____ ft. to ____ ft.
From ____ ft. to ____ ft., From ____ ft. to ____ ft.

6 GROUT MATERIAL: ☐ Neat cement Cement grout ☒ Bentonite ☐ Other ____
Grout Intervals From **0** ft. to **20** ft. From ____ ft. to ____ ft. From ____ ft. to ____ ft.
What is the nearest source of possible contamination:
☐ Septic tank ☐ Lateral lines ☐ Pit privy ☐ Livestock pens ☐ Insecticide storage ☐ Other (specify below)
☐ Sewer lines ☐ Cesspool ☐ Sewage lagoon ☐ Fuel storage ☐ Abandoned water well
☐ Watertight sewer lines ☐ Seepage pit ☐ Feedyard ☐ Fertilizer storage ☐ Oil well/gas well **None**
Direction from well ____ Distance from well ____

FROM	TO	LITHOLOGIC LOG	FROM	TO	LITHO. LOG (cont.) or PLUGGING INTERVALS
0	**2**	**Surface**	**103**	**125**	**Clay & caliche w/sand lenses**
2	**18**	**Loess**	**125**	**138**	**Fine sand w/clay & caliche strks**
18	**26**	**Caliche w/sand lenses**	**138**	**161**	**Clay & caliche w/sandy claly lenses**
26	**38**	**Caliche & clay w/sand strks**	**161**	**177**	**Fine to some med sand w/clay & caliche strks**
38	**43**	**Fine to med sand w/clay & caliche strks**			
43	**60**	**Clay & caliche w/sand strks**	**177**	**190**	**Yellow ochre/black shale**
60	**67**	**Fine to med sand w/clay & caliche strks**			
67	**80**	**Clay & caliche w/sand strks**			
80	**103**	**Fine to some med sand w/clay & caliche strks**			

7 CONTRACTOR'S OR LANDOWNER'S CERTIFICATION: This water well was constructed, reconstructed, or ☐ plugged under my jurisdiction and was completed on (mo/day/year) **4-10-12** And this record is true to the best of my knowledge and belief. Kansas Water Well Contractor's License No. **554**. This Water Well Record was completed on (mo/day/year) ____ under the business name of **Woofter Pump & Well Inc.** by (signature) ____

INSTRUCTIONS: Please fill in blanks and check the correct answers. Send three copies (white, blue, pink) to Kansas Department of Health and Environment, Bureau of Water, Geology Section, 1000 SW Jackson St., Suite 420, Topeka, Kansas 66612-1367. Telephone 785-296-5522. Send one to WATER WELL OWNER and retain one for your records. Include fee of $5.00 for each constructed well. Visit us at http://www.kdheks.gov/waterwell/index.html.

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10. Appendix B

A NEW APPROACH FOR ASSESSING THE FUTURE OF AQUIFERS SUPPORTING IRRIGATED AGRICULTURE

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KEY POINTS:

- Water-balance approach developed to assess prospects for sustainability of heavily stressed aquifers.
- Net inflow (capture) term in water balance is directly estimated from water-level and pumping data.
- Modest pumping reductions can lead to stable water levels over much of High Plains aquifer in Kansas.

ABSTRACT

Aquifers supporting irrigated agriculture are under stress worldwide as a result of large pumping-induced water deficits. To aid in the formulation of more sustainable management plans for such systems, we have developed a water-balance approach for assessing the impact of proposed management actions and the prospects for aquifer sustainability. Application to the High Plains aquifer (HPA) in the state of Kansas in the United States reveals that practically achievable reductions in annual pumping (<22%) would have stabilized areally averaged water levels over much of the Kansas HPA from 1996 to 2013. This demonstrates that modest pumping reductions can have a significant impact and highlights the importance of reliable pumping data for determining the net inflow (capture) component of the water balance. The HPA is similar to many aquifers supporting critically needed agricultural production, so the presented approach should prove of value far beyond the area of this initial application.

INTRODUCTION

Deficits created by imbalances between water inflows and outflows are particularly large in regional aquifers heavily pumped for irrigation, such as the High Plains aquifer (HPA) in the United States (US) and the North China Plain aquifer in China (Aeschbach-Hertig and Gleeson, 2012; Scanlon et al., 2012; Cao et al., 2013). Such aquifers play a critical role in global agricultural production, so water resources planners and managers have increasingly sought guidance from the research community regarding management plans that would lead to more sustainable futures for these heavily stressed systems. For the last half century, the distributed-parameter groundwater flow model has been the preferred tool for assessment of management alternatives. Numerical modeling of regional aquifers, however, is a time- and resource-intensive activity that is not necessarily well suited for timely response to queries from water planners and managers. Moreover, data limitations and conceptual model uncertainties, among other factors, can call into question the reliability of modeling assessments for a particular aquifer (Anderson and Woessner, 1992; Bredehoeft, 2005).

The purpose of this article is to introduce a simple, yet theoretically sound, approach for rapid assessment of an aquifer's future over the short to medium term (years to a few decades) and its prospects for sustainability. The approach, which was motivated by regional correlations between water-level changes and water use for portions of the HPA in the state of Kansas in the central US (Whittemore et al., 2016), is an expression of a fundamental concept in groundwater hydrology, the aquifer water balance, and was specifically developed for application to aquifers for which irrigation is the primary water use. The approach will be demonstrated in the Kansas HPA at the regional and local scales to illustrate the value of the insights that it can provide.

AQUIFER WATER BALANCE

We begin by writing a simple water balance that holds for any area of an aquifer:

$$\text{Water Volume Change} = \text{Net Inflow} - \text{Pumping} \qquad (1)$$

where "Net Inflow" is the difference between the total inflow (recharge plus inter- and intra-unit inflows) and the natural outflow (discharge to streams, evapotranspiration, and inter- and intra-unit outflows), and is equivalent to the "capture" term commonly used in groundwater depletion assessments (Lohman et al., 1972; Konikow and Leake, 2014).

We can rewrite this equation using standard notation:

$$\Delta WL * Area * S_{aq} = I - Q \qquad (2)$$

where ΔWL is the average water-level change over an aquifer area for given time interval, [L]; *Area* is the aquifer area under consideration, [L^2]; S_{aq} is the average specific yield (unconfined) or storativity (confined) for aquifer area, [-]; I is the net inflow to aquifer area for given time interval, [L^3]; and Q is the total pumping in aquifer area for given time interval, [L^3].

Equation (2) should, in theory, hold for any aquifer area and any given time interval. In practice, application is problematic in heavily pumped aquifers because of the difficulty in quantifying individual equation terms for arbitrary spatial scales and time intervals. Those difficulties, however, become much less problematic for the following conditions:

1) Seasonally pumped aquifers considered on an annual time scale – aquifers that are primarily the source of water for irrigation typically have distinct pumping and non-pumping seasons (see figures in Butler et al., 2013). Such seasonally pumped systems appear much more amenable to analysis if considered on annual time scales (Q is more readily quantified on an annual basis because of regulatory reporting requirements) and with ΔWL calculated from measurements taken a few months after cessation of pumping (values from that time are relatively insensitive to variations in the timing of the pumping season).
2) Aquifer areas of a few hundred square kilometers and larger – for areas of this size, little annual variation in S_{aq} would be expected and, given a reasonable density of monitoring wells (> one per 50-60 km^2), the impact of a few anomalous measurements should be relatively small.
3) Depths to water of tens of meters or greater – for areas where the water table is a few tens of meters or more below land surface, relatively little annual variation in recharge would be expected due to the damping of infiltration pulses with depth (Stephens, 1996). Moreover, if evapotranspirative outflows and discharge to streams have largely been captured through

water-level declines, then little variation in I would be expected (Konikow and Leake, 2014).

Given the above conditions, we can simplify equation (2) by considering S_{aq} and I to change little with time:

$$\Delta WL = \frac{I_{ua}}{S_{aq}} - \frac{Q}{Area * S_{aq}} \approx b - aQ \qquad (3)$$

where I_{ua} is net inflow per unit aquifer area [L], a and b are constants (= $1/(Area*S_{aq})$ and I_{ua}/S_{aq}, respectively), and all quantities are defined on an annual basis.

Equation (3) demonstrates that a plot of ΔWL versus Q will be linear when the above conditions hold and reliable water-level and water-use data are available. Moreover, the form of equation (3) reveals that it can be used to estimate S_{aq} and I_{ua} from the slope (a) and intercept (b), respectively, of the best-fit line to that plot. Most importantly, equation (3) can be used to calculate the ΔWL that would be produced by a proposed reduction in Q and, by rearrangement, the Q (Q_{stable}) that would lead to stable areally averaged water levels ($\Delta WL = 0$):

$$Q_{stable} = \frac{b}{a} = I_{ua} * Area \qquad (4)$$

Thus, equation (3) appears to have considerable potential as a tool for rapid assessment of the impact of proposed pumping reductions and the prospects for sustainability. Moreover, the appropriateness of the assumptions underlying equation (3) can always be assessed by checking the linearity of the ΔWL versus Q plot; large temporal variations in S_{aq} and I_{ua} would lead to significant variations in the slope and intercept parameters needed to describe conditions in different years. The potential of this approach is now demonstrated for portions of the HPA in the state of Kansas.

THE HIGH PLAINS AQUIFER IN KANSAS

The HPA is one of the world's largest and most productive aquifer systems, underlying portions of eight states in the High Plains region of the US (Figure 1). The aquifer provides water supplies, primarily for irrigation, that account for over 21% of annual groundwater use (freshwater) in the US (Kenny et al., 2009; McGuire, 2009). Due to this heavy dependence on groundwater, much of the central and southern HPA appears to be on a fundamentally unsustainable path (McGuire, 2014). This is particularly true in western Kansas, where groundwater withdrawals have caused large water-level declines that threaten the viability of the aquifer as a continuing resource for irrigated agriculture (Butler et al., 2013; Buchanan et al., 2015).

Kansas has long placed a high priority on the collection of HPA data. For decades, water levels in wells in the Kansas HPA have been measured annually, typically in early January, three to four months after cessation of irrigation pumping. The measurement network (currently about 1400 wells) was designed so that the wells are distributed approximately uniformly (every ≈40 km^2) across the HPA (Miller et al., 1999; Bohling and Wilson, 2012). In 1996, the Kansas Geological Survey took over responsibility for managing the water-level measurement program. The work reported here uses data from wells that were measured every year from 1996 to 2014. The water-level change for an area for a given year is the areal average of the difference between the depth to water measurement at a well that year and the following.

Since 1978, every non-domestic pumping well in the Kansas HPA has been required to have a water right that specifies the maximum annual water use for that well. A water-use report for each water right must be submitted annually; quality control of the reports began in 1990 and there are penalties for water-right holders who do not submit or knowingly falsify reports. Over time, there has been a gradual transition from less-accurate duration-of-pumping meters to the now-mandatory totalizing flow-rate meters. That transition has proceeded at different rates within the five groundwater management districts (GMDs) overlying the Kansas HPA (see Supporting Information). The water-use data for a given year must be reported by March of the following year; those data are then released, after quality-control checking, by the Division of Water Resources of the Kansas Department of Agriculture by fall of that year.

Regional-Scale Assessment

Whittemore et al. (2016) present regional correlations between average annual water-level change (ΔWL) and annual water use (Q) for select areas of the Kansas HPA for 1996-2012. Equation (3) is applied here to updated and extended forms of these relationships to further understanding of conditions in two of the GMDs for which high-quality ΔWL and Q data are available (assessments for the other GMDs are in Supporting Information). Results in this section and the following are presented as the mean and the 95% confidence interval (henceforth, CI) about it; details of the CI calculations, along with a discussion of uncertainty in the ΔWL and Q values, are provided in Supporting Information.

GMD4 – Semi-arid setting

GMD4 encompasses a 12,623 km^2 region of northwest Kansas (Figure 1) characterized by semi-arid climatic conditions (Fross et al., 2012). Figure 2 is a plot of ΔWL versus Q for 1996-2013. Two features are striking: 1) the strong linearity of the relationship, an indication that the approximations in equation (3) appear appropriate; and 2) the three ΔWL values near zero (±0.03 m), an unexpected occurence for an aquifer undergoing groundwater mining. Q_{stable} is calculated from equation (4) (0.42 x 10^9 m^3 [CI=0.38-0.45 x 10^9 m^3] ignoring 2006 and 2007 ΔWL) and is ~79% of the average Q for 1996-2013 (0.53 x 10^9 m^3). Thus, if the average Q had been 21% less than actual for 1996-2013, water levels in the GMD4 well network would not have changed on average. S_{aq} and I_{ua} are calculated from the parameters of the best-fit line (0.050 [CI=0.040-0.065] and 0.034 m [CI=0.030-0.035], respectively). The major sources of variability in this and the following plots are likely interannual variability in I_{ua} and in the distribution of Q within a year. Figure 2 displays the sensitivity of the relationship to ±20% changes in I_{ua} and S_{aq}; all points (ignoring 2006 and 2007) fall within the ±20% I_{ua} envelope, indicating that I_{ua} changes relatively little between years.

GMD5 – subhumid setting

GMD5 encompasses a 10,120 km^2 region of south-central Kansas (Figure 1) characterized by subhumid climatic conditions (Fross et al., 2012). Figure 3 is a plot of ΔWL versus Q for 1996-2013 with an inset showing five years of continuous water-level monitoring data from a well in western GMD5. Two features are striking: 1) the strong linearity of the relationship for all years but 2007, an indication that the approximations in equation (3) appear appropriate for most of the period; and 2) the number of years for which ΔWL was above (7) or slightly below (3 values within 0.03 m) zero, an indication that the aquifer appears to have been pumped at a near-sustainable level. Q_{stable} is calculated from equation (4) using the best-fit line to the 1996-2006, 2008-2013 data (0.59 x 10^9 m^3 [CI=0.57-0.62 x 10^9 m^3]) and is ~94% of the average Q for 1996-2013 (0.63 x 10^9 m^3). Thus, if the average Q had been 6-7% less than actual for 1996-2013, water levels in GMD5 would not have changed on average. S_{aq} and I_{ua} are calculated from the parameters of the best-fit line (0.035 [CI=0.029-0.044] and 0.059 m [CI=0.056-0.061 m], respectively). Assuming this S_{aq} value is appropriate for 2007, an I_{ua} of 0.083 m is calculated for 2007, which is 41% greater than that of the other years and consistent with the large water-level rises observed across GMD5 that year (Figure 3 inset).

Local-Scale Assessment

Assessments are presented for portions of two counties in GMD2 (McPherson and Harvey) to evaluate the effectiveness of the water-balance approach at smaller scales.

McPherson County

The northern part of GMD2 overlies a 567.1 km^2 area in McPherson County (Figure 1). Figure 4 includes a plot of ΔWL versus Q for 1996-2013 for the GMD2 portion of the county. Two features are striking: 1) the strong linearity of the relationship, an indication that the approximations in equation (3) appear appropriate for most of the period; and 2) the number of years for which ΔWL was above (7) or slightly below (one value within 0.01 m) zero, an indication that the aquifer appears to have been pumped at a near-sustainable level. Q_{stable} is calculated from equation (4) using the best-fit line to the 1996-2013 data (36.9 x 10^6 m^3 [CI=34.7-39.0 x 10^6 m^3]) and is within 6% of the average Q for 1996-2013 (39.0 x 10^6 m^3). Thus, this area has been at near stable water-level conditions (average ΔWL for 1996-2013 was -0.020 m). S_{aq} and I_{ua} are calculated from the parameters of the best-fit line (0.049 [CI=0.038-0.067] and 0.065 m [CI=0.061-0.069 m], respectively). Figure 4 shows that all but two of the points fall within the ±15% I_{ua} envelope, indicating that the variability in I_{ua} is relatively small. The net inflow estimated for the GMD2 portion of McPherson County is slightly greater (<5%) than that estimated for the entire district (0.062 m – see Supporting Information).

Harvey County

An area of 679.1 km^2 of Harvey County lies within GMD2 (Figure 1). Figure 4 includes a plot of ΔWL versus Q for 1996-2013 for the GMD2 portion of the county. Two features are striking: 1) the linearity of the relationship, an indication that the approximations in equation (3) appear appropriate for most of the period; and 2) the number of years for which ΔWL was above (8) or slightly below (one value within 0.02 m) zero, an indication that the aquifer appears to have been pumped at a near-sustainable level. Q_{stable} is calculated from equation (4) using the best-fit line to the 1996-2013 data

(60.2×10^6 m^3 [CI=56.7-63.8 x 10^6 m^3]) and is within 1% of the average Q for 1996-2013 (60.0×10^6 m^3). Thus, this area has been essentially at stable water-level conditions from 1996-2013 (average ΔWL for this period was +0.016 m). S_{aq} and I_{ua} are calculated from the parameters of the best-fit line (0.022 [CI=0.016-0.036] and 0.089 m [CI=0.083-0.094 m], respectively). Figure 4 shows that five of the 18 ΔWL values fall outside of the ±15% I_{ua} envelope. The greater spread observed in this area relative to that observed in McPherson County or over the entire district (see Figure S6 in Supporting Information) could be a product of measurement errors and the small number of wells. However, a more likely explanation is that the net inflow is varying through time as a result of stream-aquifer interactions playing a larger role in the water balance in this portion of GMD2. The net inflow estimated for the GMD2 portion of Harvey County is considerably greater than that estimated for the McPherson County portion of GMD2 (0.065 m) or the entire district (0.062 m – see Supporting Information), and is consistent with greater pumping-induced inflow from streams in this portion of GMD2.

DISCUSSION AND CONCLUSIONS

The strong linearity of the relationships in the ΔWL versus Q plots indicates the assumptions invoked for the simplification in equation (3) appear appropriate for all areas discussed above. The magnitude of I_{ua} in northwest Kansas was considerably larger than what was expected from previous investigations (Hansen, 1991; Republican River Compact Administration, 2003). This larger-than-expected I_{ua} is likely a product of processes brought on by widespread irrigation pumping (irrigation return flow, irrigation-enhanced precipitation recharge, and drainage of dewatered units). However, we cannot yet rule out the possibility that focused natural recharge in ephemeral stream channels and playas is larger than originally estimated and that capture of natural discharge induced by water-level declines is playing the major role. Determination of the factors responsible for the larger-than-expected I_{ua} is critical for assessments of the sustainability of the Kansas HPA. We have shown that practically achievable pumping reductions (<22% and <7%) would have stabilized areally averaged water levels in northwest and south-central Kansas, respectively, from 1996 to 2013. Whether this is a short-term phenomenon or a path to long-term sustainability, however, has yet to be determined. Our use of Q_{stable}, rather than $Q_{sustain}$, is a reflection of this uncertainty, as well as of our uncertainty about the long-term impacts of this level of pumping (van der Gun and Lipponen, 2010).

The temporal variability in I_{ua} was considerably less than expected for the Kansas HPA. Although the large depth to water in GMD4 (January 2014 average of 42.1 m) and capture of virtually all natural discharge may largely explain that behavior in semi-arid northwest Kansas, the near-constant I_{ua} is more surprising in subhumid south-central Kansas. The depth to water in GMD5 (January 2014 average of 10.4 m) appears to have been large enough to dampen temporal variability in I_{ua}. Although stream-aquifer interactions play an important role in portions of GMD5, it appears that increases in inflows are matched, in most years, by corresponding increases in natural outflows (e.g., greater discharge to streams), so I_{ua} changes little. The temporal variability in I_{ua} appears greatest in Harvey County in GMD2, which is consistent with the shallower depth to water (January 2014 average of 7.4 m) and the greater impact of stream-aquifer interactions. Note that I_{ua} does not appear to be a function of Q in any portion of the Kansas HPA. However, in other areas where pumping-induced inflows of surface water make up a sizable component of the aquifer water balance, a dependence on Q may be observed.

The presented approach is not without limitations. In the absence of a dense monitoring network, this approach can be a challenge to apply for areas below several hundred km^2. Further work is needed to assess the monitoring network density appropriate for a given scale of analysis. Temporal variability in S_{aq}, I_{ua}, and timing of the pumping season, as well as pumping outside the irrigation season, can introduce considerable noise into these relationships. However, that noise appears acceptable for assessments of areas above several hundred km^2 for the Kansas HPA well network.

An underlying assumption is that the relationships presented here can be used to assess an aquifer's future over time spans of years to a few decades, with the justification that the recent past should be a reasonable representation of the near- to medium-term future. However, the appropriateness of that assumption in future years is certainly not guaranteed. Fortunately, the relationships themselves will reveal when I_{ua} and/or S_{aq} change with time. For example, if I_{ua} diminishes with time in northwest Kansas as a result of more efficient irrigation practices producing less return flow, future plotted points will fall to the left of the band defined by the 1996-2013 data in Figure 2, enabling changes in this key component of the aquifer water balance to be readily recognized. Thus, one could envision a scenario whereby the relationships are revisited every three to five years so that water managers can adjust pumping with changing conditions.

Finally, data collection in support of aquifer assessments has traditionally involved many activities. This work demonstrates that the primary focus should be on collection of water-level and water-use data. Given the typical sparsity of reliable water-use data, analysts must often resort to estimating pumping from utility records or net irrigation requirements. Greater resources should be devoted to direct measurement of pumping, so deeper insights into an aquifer's future can be obtained.

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REFERENCES

Aeschbach-Hertig, W., and T. Gleeson (2012), Regional strategies for the accelerating global problem of groundwater depletion, *Nature Geoscience*, 5, 853-861, doi: 10.1038/NGEO1617.

Anderson, M.P., and W.W. Woessner (1992), *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*, Academic Press, San Diego, CA, 381 p.

Bohling, G.C., and B.B. Wilson (2012), Statistical and geostatistical analysis of the Kansas High Plains water-table elevations, 2012 measurement campaign, *Kansas Geological Survey Open-File Report 2012-16* (www.kgs.ku.edu/Hydro/Publications/2012/OFR12_16/index.html - accessed January 12, 2016).

Bredehoeft, J. (2005), The conceptualization model problem – surprise, *Hydrogeol. J.*, 13(1), 37-46.

Buchanan, R.C., B.B. Wilson, R.R. Buddemeier, and J.J. Butler, Jr. (2015), The High Plains aquifer, *Kansas Geological Survey Public Information Circular 18* (www.kgs.ku.edu/Publications/pic18/index.html - accessed January 12, 2016).

Butler, J.J., Jr., W. Jin, G.A. Mohammed, and E.C. Reboulet (2011), New insights from well responses to fluctuations in barometric pressure, *Ground Water*, 49(4), 525-533.

Butler, J.J., Jr., R.L. Stotler, D.O. Whittemore, and E.C. Reboulet (2013), Interpretation of water-level changes in the High Plains aquifer in western Kansas, *Groundwater*, 51(2), 180-190.

Cao, G., C. Zheng, B.R. Scanlon, J. Liu, and W. Li (2013), Use of flow modeling to assess sustainability of groundwater resources in the North China Plain, *Water Resour. Res.*, 49, doi: 10.1029/2012WR011899.

Fross, D., M. Sophocleous, B.B. Wilson, and J.J. Butler, Jr. (2012), *Kansas High Plains Aquifer Atlas*, Kansas Geological Survey (http://www.kgs.ku.edu/HighPlains/HPA_Atlas/index.html - January 12, 2016).

Hansen, C.V. (1991), Methods of freshwater storage and potential natural recharge for principal aquifers in Kansas, *U.S. Geological Survey Water-Resources Investigations Report 87-4230*, 100 p.

Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin (2009), Estimated use of water in the United States in 2005, *U. S. Geological Survey Circular 1344*, 51 p.

Konikow, L.F., and S.A. Leake (2014), Depletion and capture: Revisiting "The source of water derived from wells", *Groundwater*, 52(S1), 100-111.

Lohman, S.W., R.R. Bennett, R.H. Brown, H.H. Cooper, Jr., W.J. Drescher, J.G. Ferris, A.I. Johnson, C.L. McGuiness, A.M. Piper, M.I. Rorabaugh, R.W. Stallman, and C.V. Theis (1972), Definitions of selected ground-water terms—Revisions and conceptual refinements, *U.S. Geological Survey Water-Supply Paper 1988*, 21 p.

McGuire, V.L. (2009), Water-level changes in the High Plains aquifer, predevelopment to 2007, 2005-06, and 2006-07, *U. S. Geological Survey Scientific Investigations Report 2009-5019*, 9 p.

McGuire, V.L. (2014), Water-level changes and change in water in storage in the High Plains aquifer, predevelopment to 2013 and 2011-13, *U. S. Geological Survey Scientific Investigations Report 2014-5218*, 14 p.

Miller, R.D., R.C. Buchanan, and L. Brosius (1999), Measuring water levels in Kansas, *Kansas Geological Survey Public Information Circular 12* (www.kgs.ku.edu/Publications/pic12/pic12_1.htm - accessed January 12, 2016).

Republican River Compact Administration (2003), *Ground water model* (www.republicanrivercompact.org/v12p/RRCAModelDocumentation.pdf, accessed January 12, 2016).

Scanlon, B.R., C.C. Faunt, L. Longuevergne, R.C. Reedy, W.M. Alley, V.L. McGuire, and P.B. McMahon (2012), Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley, *Proc. Nat. Acad. Sci. of the USA*, 109 (24), 9320-9325.

Stephens, D.B. (1996), *Vadose Zone Hydrology*, Lewis Pub. Boca Raton, FL, 347 p.

van der Gun, J., and A. Lipponen (2010), Reconciling groundwater storage depletion due to pumping with sustainability, *Sustainability*, 2, 3418-3435.

Whittemore, D.O, J.J. Butler, Jr., and B.B. Wilson (2016), Assessing the major drivers of water-level declines: New insights into the future of heavily stressed aquifers, *Hydrological Sci. Jour.*, 61(1), 134-145, doi: 10.1080/02626667.2014.959958.

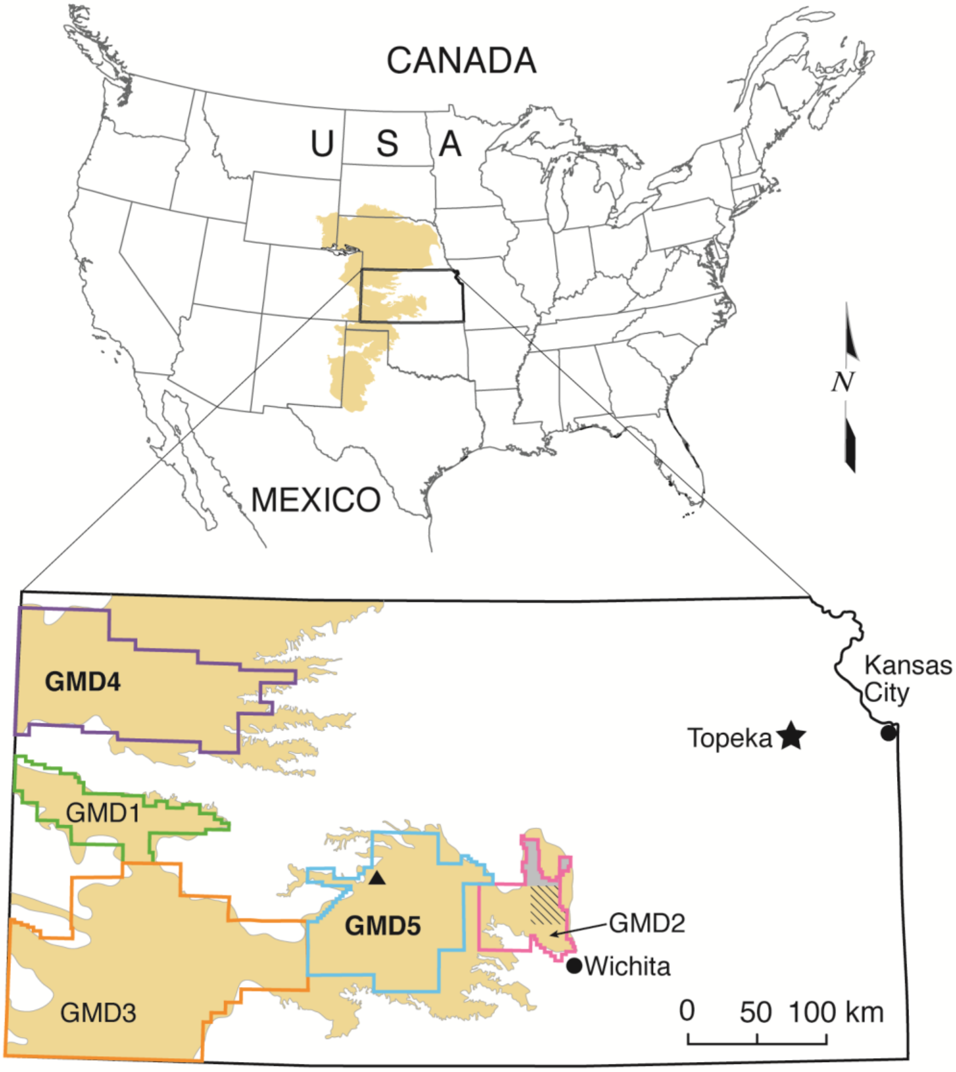

Figure 1 – Location map for the High Plains aquifer (HPA) in the US and Kansas (inset) (after Butler et al., 2013). The boundaries of the five groundwater management districts (GMDs) that overlie most of the Kansas HPA are shown on the inset; the GMDs provide local management of the HPA within the framework of Kansas water laws. The inset also shows the areas of the regional-scale (bolded GMDs) and local-scale (shaded [McPherson County] and cross-hatched [Harvey County] portions of GMD2) assessments discussed here. The triangle in GMD5 marks the location at which the water-level record in the inset of Fig. 3 was obtained.

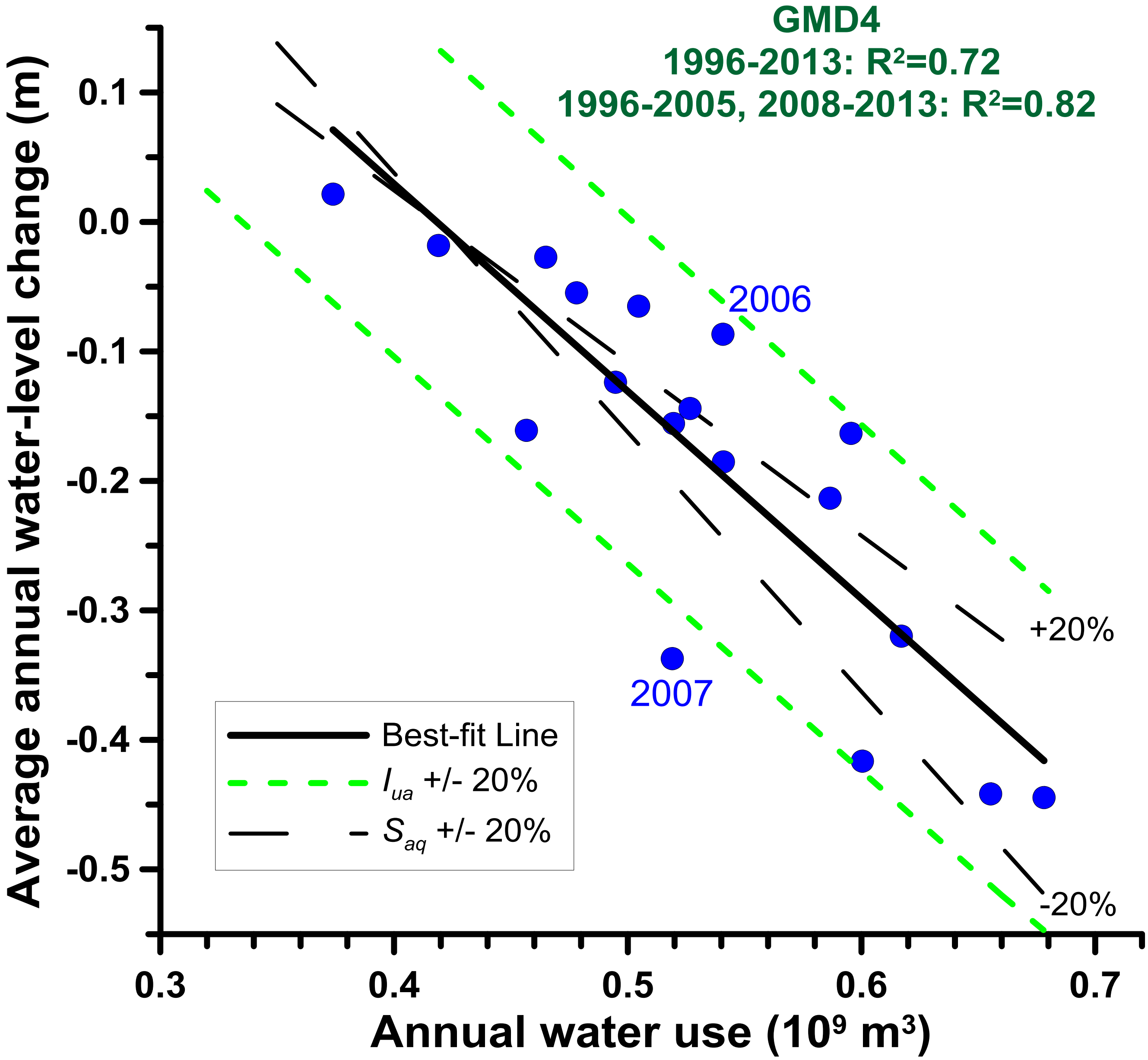

Figure 2 – Average annual water-level change (ΔWL) versus annual water use (Q) plot for GMD4; solid line is best-fit line ($\Delta WL = 0.67 - 1.60Q$, p <0.001) to 1996-2005, 2008-2013 data. ΔWL is the average for the 184 wells measured every year from 1996-2014. Heavy snows delayed the 2007 water-level measurements from early January to late February through early April, so the ΔWL values for 2006 and 2007 are not used in the correlation (see Supporting Information). The small and large dashed lines show the sensitivity to ±20% changes in the estimated net inflow per unit area (I_{ua}) and average specific yield (S_{aq}) values, respectively. Annual water use is the sum of reported use from a maximum of 4,185 pumping wells (well total varies slightly from year to year). Climatic conditions in GMD4 for 1996-2013 were near average (see Supporting Information). The estimated uncertainty in ΔWL is ±0.038 m and that in Q is ±0.09% of plotted value (see Supporting Information).

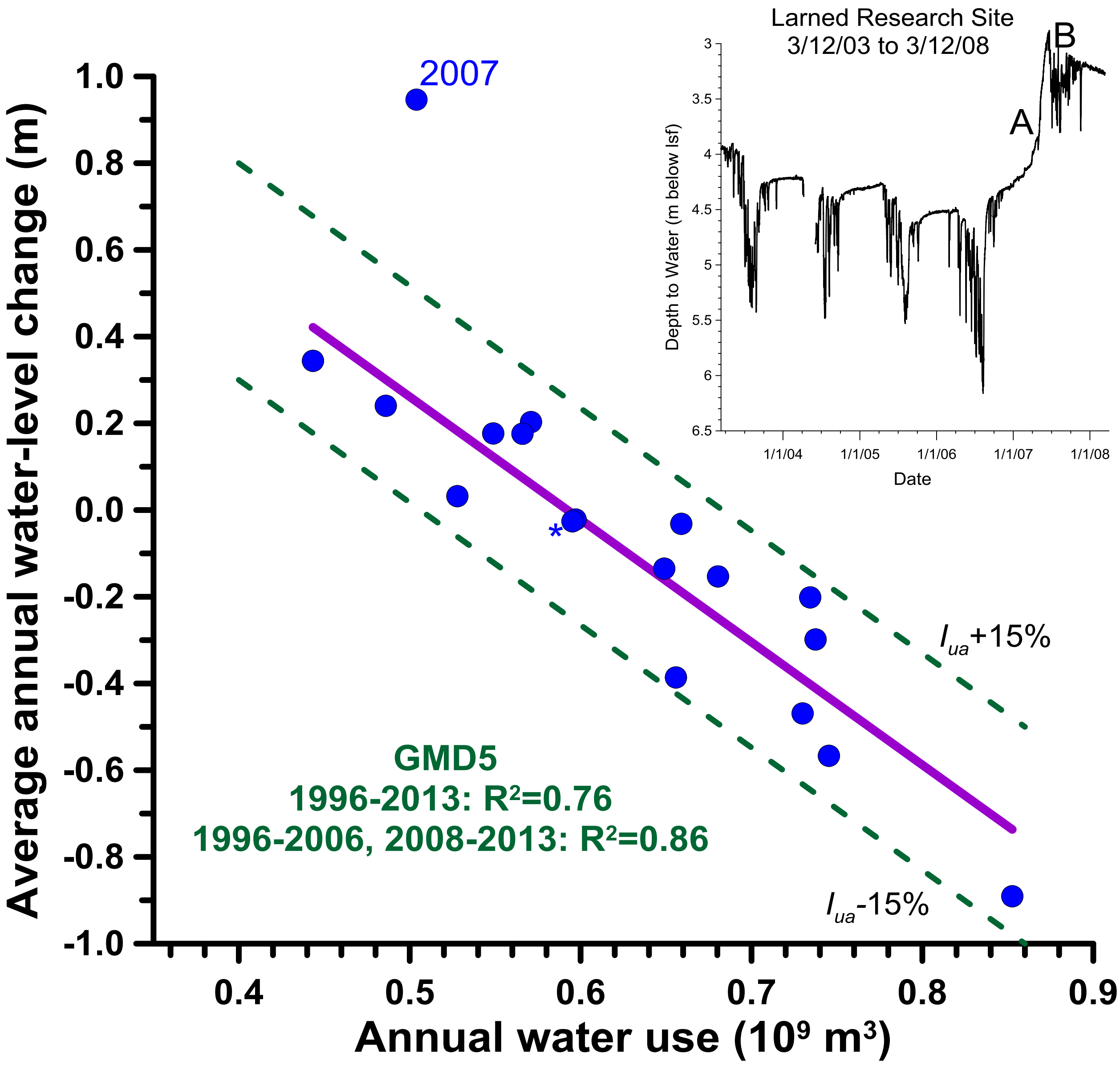

Figure 3 - ΔWL versus Q plot for GMD5; solid line is best-fit line ($\Delta WL = 1.68 - 2.83Q$, p <0.001) to 1996-2006, 2008-2013 data. ΔWL is the average for the 175 wells measured every year from 1996-2014. Inset shows the large precipitation-induced water-level rise (>1.3 m) in the spring of 2007 (A) at an HPA well (triangle on Fig. 1 – 15-minute measurement interval) that occurred prior to the pumping season (B) (Butler et al., 2011). With the exception of the 2007 point, which has been identified as an outlier (see Supporting Information), all plotted points fall within a ±15% I_{ua} envelope of the best-fit line. The * indicates the near coincidence of the 1999 and 2005 values. Annual water use is the sum of reported use from a maximum of 6,355 pumping wells (well total varies slightly from year to year). Climatic conditions in GMD5 for 1996-2013 were slightly wetter than average (see Supporting Information). The estimated uncertainty in ΔWL is ±0.049 m and that in Q is ±0.08% of plotted value (see Supporting Information).

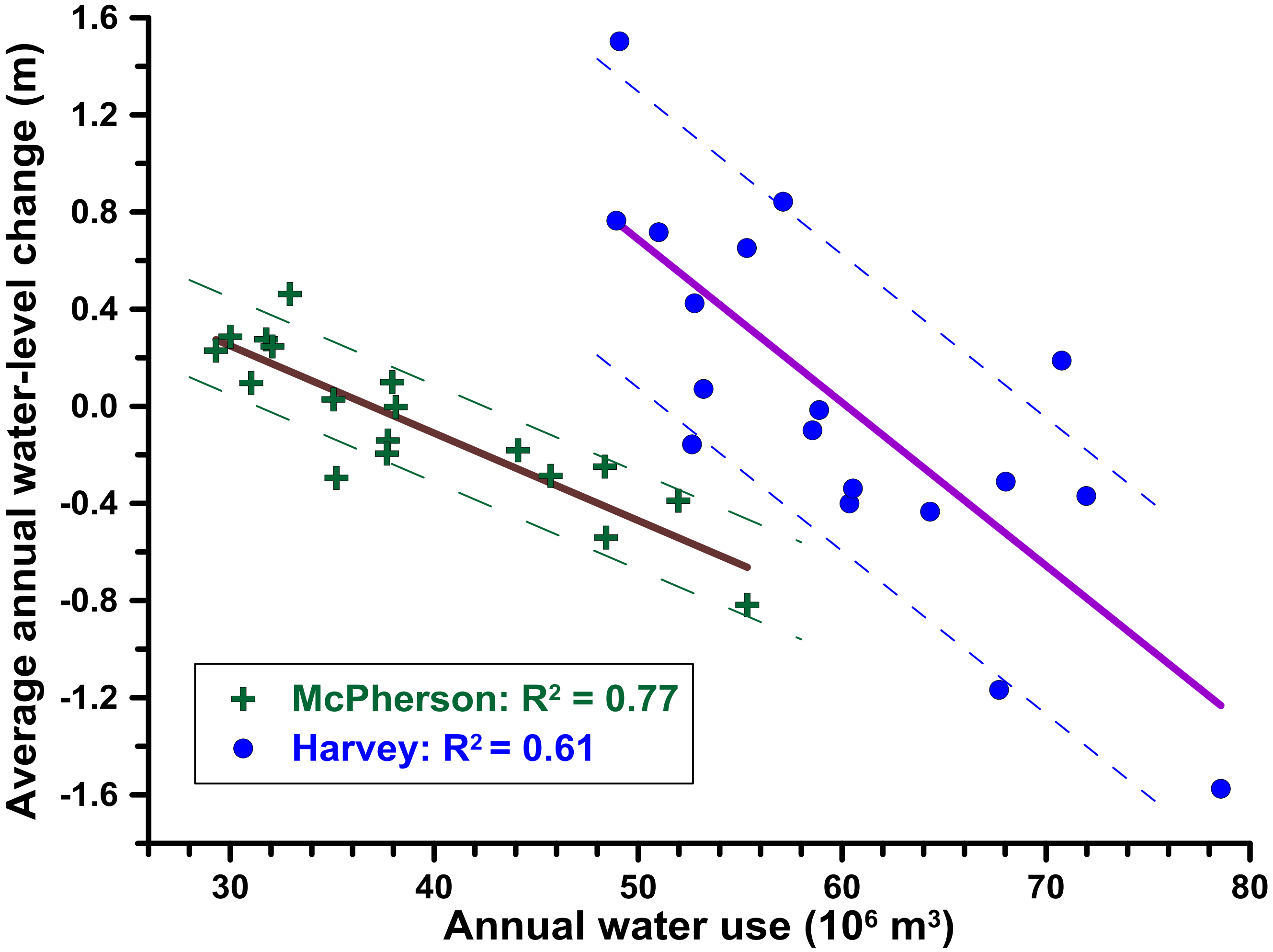

Figure 4 – ΔWL versus Q plots for the portions of McPherson ($\Delta WL = 1.33 - 0.036Q$) and Harvey ($\Delta WL = 4.05 - 0.067Q$) counties in GMD2 for 1996-2013, $p < 0.001$ for both plots. ΔWL is the average for the 10 and 9 wells measured every year from 1996-2014 for McPherson and Harvey counties, respectively. The large and small dashed lines show the sensitivity to ±15% changes in I_{ua} for McPherson and Harvey counties, respectively. All but two McPherson County points fall within a ±15% envelope of the best-fit line and all points fall within a ±27% I_{ua} envelope. All Harvey County points fall within a ±22% I_{ua} envelope of the best-fit line. Annual water use is the sum of reported use from a maximum of 463 and 780 pumping wells for the GMD2 portions of McPherson and Harvey counties, respectively (well total varies slightly from year to year). Climatic conditions in GMD2 for 1996-2013 were slightly wetter than average (see Supporting Information). The estimated uncertainty in ΔWL is ±0.14 m and ±0.21 m for McPherson and Harvey counties, respectively, and that in Q is ±0.3% and ±0.2% for McPherson and Harvey counties, respectively (see Supporting Information).

Supporting Information for

A NEW APPROACH FOR ASSESSING THE FUTURE OF AQUIFERS SUPPORTING IRRIGATED AGRICULTURE

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Contents of this file

Introduction

This supporting information provides discussions of uncertainty in ΔWL and Q, data exclusion, confidence-interval calculations, climatic conditions during the analysis period, history of water use metering in the Kansas groundwater management districts (GMDs) that overlie the High Plains aquifer (HPA), and regional scale assessments for the GMDs not discussed in the main text. The figures accompany the discussions of data exclusion (Figure S1), confidence-interval calculations (Figures S2-3), and regional-scale assessments (Figures S4-8).

Text S1 – Uncertainty in ΔWL and Q

ΔWL (Areal Average of Water-Level Changes)

We want to estimate the uncertainty in ΔWL, the average of the annual water-level changes observed in the wells in an area. For each year, ΔWL is computed as the average of the individual water-level differences, δ_{WL} , observed at the *n* wells in an area. The variability of the individual differences can be quantified in terms of the sample standard deviation, $\sigma_{\delta_{WL}}$. Assuming that the individual differences are normally distributed or that *n* is large enough for the central limit theorem to be valid, then the standard deviation of the estimated mean difference, ΔWL, is given by $\sigma_{\Delta WL} = \sigma_{\delta_{WL}} / \sqrt{n}$. This expression is based on the assumption that the individual water-level differences represent an independent random sample of the underlying population. However, we would expect spatial autocorrelation of the δ_{WL} values to reduce the effective number of wells contributing to ΔWL, thus increasing $\sigma_{\Delta WL}$ somewhat [Rehfeldt et al., 1992; Bohling et al., 2012]. Based on semivariogram analysis, we have estimated a correlation length of 10,000 m for the δ_{WL} values in GMD5 and GMD2, and 5000 m for GMD4. These estimates are rough approximations due to the complicating factor of annual variations in the semivariograms. Nevertheless, we have used these correlation lengths to estimate the effective number of wells contributing to the average in each GMD. Essentially, a cluster of wells within one correlation length of each other count as a single effective well [Bohling et al., 2012].

Applying the preceding analysis to the water-level differences for different years will give a time varying sequence of $\sigma_{\Delta WL}$ values. It would be possible to use this entire sequence of values in the regression analysis, weighting the residual for each year by the inverse of the $\sigma_{\Delta WL}$ value for that year, resulting in a chi-squared fit. However, we will simplify the process by taking the average of the annual $\sigma_{\Delta WL}$ values,

$$\bar{\sigma}_{\Delta WL} = \frac{1}{n_y} \sum_{i=1}^{n_y} \sigma_{\Delta WL,i}$$

where n_y is the number of years for the analysis period, as a single estimate of the uncertainty associated with the ΔWL values in each area. The resulting estimates for the areas considered in the main text are as follows:

GMD4 (184 wells, 139 effective wells): 0.038 m
GMD5 (175 wells, 73 effective wells): 0.049 m
McPherson County (10 wells, 5 effective wells): 0.14 m
Harvey County (9 wells, 4.5 effective wells): 0.21 m

Due to the few wells in McPherson and Harvey counties, the number of effective wells for each of those counties has been computed using the ratio of effective number of wells to actual wells estimated for GMD2, the district in which those counties are located (ratio=0.5).

Q (Water Use Estimate)

We want to estimate the uncertainty in the sum, Q, of the reported annual water use, q_i, from the n pumping wells in an area:

$$Q = \sum_{i=1}^{n} q_i$$

Regulations on totalizing flowmeters require that the meters be periodically checked for accuracy and that the reading from a flowmeter be within ±6% of that of the test meter (pers. communication, Lane Letourneau, Water Appropriation Program Manager, Division of Water Resources, Kansas Department of Agriculture, October 19, 2015). This requirement is in the form of a coefficient of variation (CV, standard deviation of an estimate divided by the mean) for the individual flowmeter readings expressed as a percentage. Thus, the ±6% value can be taken to correspond to some multiple of the standard deviation that would scale in the same fashion as the CV under summation.

A simple form of this scaling relationship can be derived by assuming that the “true” or mean value of all the individual reported pumping values is the same ($q_i=q$) for all of the wells. Then, if the standard deviation of the measured q values is σ_q (all the same), the coefficient of variation for each pumping well is

$$CV(q) = \frac{\sigma_q}{q}$$

Assuming the errors in the *q* values are uncorrelated, then the variance in the sum is the sum of the variances:

$$Var(Q) = \sum_{i=1}^{n} Var(q_i) = n\sigma_q^2$$

The expected value of the sum is then

$$E(Q) = nq$$

and the coefficient of variation of the sum is:

$$CV(Q) = \frac{\sqrt{Var(Q)}}{nq} = \frac{\sqrt{n\sigma_q^2}}{nq} = \frac{1}{\sqrt{n}}\frac{\sigma_q}{q} = \frac{1}{\sqrt{n}}CV(q)$$

Through simulation, we have determined that this scaling relationship also holds when the individual q_i values vary. If the CV is the same for all of the q_i values (i.e. their standard deviations vary proportionally with their expected values), then the CV of the sum is $1/\sqrt{n}$ times the CV of the individual values. This translates into the following % uncertainty in the total pumping for the areas considered in the main text:

GMD4 (4,185 pumping wells): 0.09%
GMD5 (6,355 pumping wells): 0.08%
McPherson County (463 pumping wells): 0.3%
Harvey County (780 pumping wells): 0.2%

As long as the number of pumping wells is large, as in all the areas discussed in the main text, the issue of how many standard deviations the ±6% value actually represents is of little importance because the uncertainty in the sum is so small. Note that this analysis assumes that the errors in the individual flowmeters are symmetrically distributed about zero. If the measurements are biased (see assessments of GMDs 1 and 3 in Text S6), then the above analysis will require modification.

References for Text S1

Bohling, G.C., G. Liu, S.J. Knobbe, E.C. Reboulet, D.W. Hyndman, P. Dietrich, and J.J. Butler, Jr. (2012), Geostatistical analysis of centimeter-scale hydraulic conductivity variations at the MADE site, *Water Resour. Res.*, 48, W02525.

Rehfeldt, K.R., J.M. Boggs, and L.W. Gelhar (1992), Field study of dispersion in a heterogeneous aquifer, 3, Geostatistical analysis of hydraulic conductivity, *Water Resour. Res.*, 28(12), 3309-3324.

Text S2 – Data Exclusion

Data were excluded prior to the regression analyses of GMD4 and GMD5. In addition, a data point in the McPherson County dataset, which possibly could have been excluded, was retained. The justification for these decisions is provided in this section.

GMD4

As described in the main text, water levels in wells in the Kansas HPA are measured annually, typically in early January. These measurements are thus separated by about 12 months. Heavy snows (nearly a meter) prevented the measurement of water levels in January 2007; rural roads were impassible and, in some cases, the snow level was above the top of the well. As a result, water levels in 2007 were measured between late February and early April; timing depended on when conditions allowed access to a particular well. The time interval for the 2006 ΔWL value was thus about 14 months and that for the 2007 ΔWL value about 10 months. Given the discrepancy with the 12-month interval characteristic of the remaining values, the 2006 and 2007 ΔWL values were removed prior to the regression analysis (Figure 2).

GMD5

The 2007 ΔWL appeared to be an outlier that should be excluded. An outlier analysis was therefore performed to assess if exclusion was justified. Figure S1 is a plot of the studentized residuals versus year for the regression analysis using all the GMD5 data points. The studentized residuals are jackknife residuals scaled to a unit variance (Venables and Ripley, 1999). A jackknife residual is the difference between the actual Y value at a given data point and that predicted by a regression line fit to the remaining data points, with the point in question withheld. Studentized residuals larger than |2.5| (more than 2.5 standard deviations from the mean) are often identified as outliers (or at least candidates for further investigation). The studentized residual for 2007 is 4.97 and clearly separated from the other residuals in Figure S1. Consequently, the 2007 ΔWL value was removed prior to the regression analysis (Figure 3).

McPherson County

The other potential outlier identified was the 1996 value in the McPherson County dataset (the only point falling below the I_{ua} envelope in the McPherson County plot in Figure 4), with a studentized residual of -2.7. Given the point was just slightly within the outlier "range" and there was no additional justification for exclusion, the value was retained in the regression analysis.

References for Text S2

Venables, W.N., and B.D. Ripley (1999), *Modern Applied Statistics with S-Plus*, Third Edition, Springer-Verlag New York, Inc., 501 pp.

Text S3 – Confidence-Interval Calculations

Confidence intervals were calculated for Q_{stable}, I_{ua}, and S_{aq} (henceforth, derived quantities) for the areas discussed in the main text. Three major issues that arise in the calculation process are described in this section.

Uncertainty in intercept and slope estimates: The residuals from the regressions are approximately normally distributed, so the intercept and slope estimates approximately follow a bivariate normal distribution, with a mean vector given by the estimated coefficients and a 2 x 2 covariance matrix representing the joint uncertainty in the estimates. The diagonal elements of this covariance matrix are the variances of the parameter estimates, given by the squares of the standard error values for the intercept and slope. The off-diagonal elements (both the same) contain the covariance of the parameter estimates, which is proportional to the correlation between the estimates. For all the cases considered here, the intercept and slope estimates are strongly negatively correlated, with a correlation coefficient of -0.98 or -0.99.

Distribution of the derived quantities: The uncertainty in the estimates of the intercept (b) and slope (a) propagate into uncertainty in the derived quantities, $Q_{stable} = b/a$, $I_{ua} = Q_{stable}/Area$, and $S_{aq} = I_{ua}/b$. This uncertainty is assessed through a simulation process. For each regression fit, 10,000 pairs of random samples of b and a are drawn from the appropriate joint distribution (the bivariate normal distribution mentioned above). Figure S2 shows the resulting distribution of (a,b) estimates for the GMD4 regression. For each of these (a,b) pairs, corresponding values of Q_{stable}, I_{ua}, and S_{aq} are computed, resulting in 10,000 samples from the associated distributions of the derived parameters. Figure S3 shows the distribution of Q_{stable} values for GMD4.

Definition of confidence intervals: The Q_{stable}, I_{ua}, and S_{aq} distributions are somewhat asymmetric (Figure S3), so it is more accurate to base 95% confidence intervals on the quantiles of the simulated distributions, rather than on the means and standard deviations of those distributions. Specifically, for this work, the 95% confidence interval for a derived quantity is defined as the interval between the 2.5th and 97.5th percentiles of the distribution (leaving a total of 5% of the distribution in the lower and upper tails). Those two percentiles are marked by the vertical dashed lines in Figure S3. The means and 95% confidence intervals are reported for each of the assessed areas in the main text.

Text S4 – Climatic Conditions During the Analysis Period

Climatic conditions during the analysis period were defined by the standardized precipitation index (SPI); an SPI value of zero indicates average (historic norm; in this case, since 1895) climatic conditions, while values <0 and >0 indicate drier-than-average and wetter-than-average conditions, respectively (McKee et al., 1993). SPI values for various time intervals are available online for Kansas climatic divisions (National Climatic Data Center, 2016). As shown in Whittemore et al. (2016), GMDs 1, 3, and 4 almost entirely lie within Kansas climatic divisions 4, 7, and 3, respectively, and GMDs 2 and 5 largely fall within Kansas climatic division 8. Thus, SPI values for those climatic divisions were used to characterize conditions in the respective GMDs. Whittemore et al. (2016) determined that the most appropriate SPI interval for GMDs 1, 3, and 4 was the nine-month period ending in October, and the most appropriate SPI interval for GMDs 2 and 5 was the 12-month period ending in December. The climatic conditions for the analysis period (1996-2013) were as follows:

GMD1: SPI = 0.12, near average.
GMD2: SPI = 0.46 slightly wet.
GMD3: SPI = 0.08, near average.
GMD4: SPI = 0.01, near average.
GMD5: SPI = 0.46, slightly wet.

References for Text S4

McKee, T. B., N.J. Doesken, and J. Kleist (1993), The relationship of drought frequency and duration to time scales, *Preprints, 8th Conference on Applied Climatology*, 17-22 Jan 1993, Anaheim, CA, 179-184.

National Climatic Data Center (2016), (www7.ncdc.noaa.gov/CDO/CDODivisional Select.jsp - accessed Jan. 13, 2016).

Whittemore, D.O, J.J. Butler, Jr., and B.B. Wilson (2016), Assessing the major drivers of water-level declines: New insights into the future of heavily stressed aquifers, *Hydrological Sci. Jour.*, 61(1), 134-145, doi: 10.1080/02626667.2014.959958.

Text S5 - History of Water Use Metering in the Kansas Groundwater Management Districts

Water use at pumping wells in the Kansas GMDs (Figure 1) has primarily been measured with duration-of-pumping meters (henceforth, duration meters), which record the time of actual use and require an estimated flow rate to convert to water use, and totalizing flow-rate meters (henceforth, totalizing flowmeters), which record the rate of flow and the total flow since installation. Over time, duration meters have largely been replaced by totalizing flowmeters. The use of totalizing flowmeters has varied with time and between the GMDs, as is described in the following paragraphs.

GMD1: Starting January 24, 2003, a totalizing flowmeter had to be installed whenever any part of the diversion works at a non-domestic pumping well was modified. Starting January 1, 2014, every non-domestic well with a water right was required to have a totalizing flowmeter (pers. communication, Kyle Spencer, GMD1 interim manager, June 25, 2015).

GMD2: Starting June 1, 1980, every non-domestic, permanent pumping well in the McPherson Intensive Groundwater Use Control Area (IGUCA) had to be equipped with a totalizing flowmeter. A similar requirement was established for the Burrton IGUCA (within Harvey and Reno counties) on July 15, 1984. Starting on September 1, 1987, every non-domestic permanent well with a new water permit or a well with an existing water right for which a change in place, type of use, or point of diversion was requested after that date was required to have a totalizing flowmeter. Starting July 1, 1995, every non-domestic permanent well for which a certificate of appropriation (the completion of the permitting process) was issued after that date was required to have a totalizing flowmeter. Starting December 31, 2012, all remaining non-domestic wells with water rights were required to have totalizing flowmeters. The implementation is being done in four phases that will end in the spring of 2016. All non-domestic wells with water rights will be equipped with totalizing flowmeters by the start of the 2016 irrigation season (pers. communication, Tim Boese, GMD2 manager, July 7, 2015 and January 18, 2016).

GMD3: Starting January 1, 1993, every non-domestic well with a water right was required to have a totalizing flowmeter. The implementation was done in four phases that ended on July 1, 1996 (pers. communication, Mark Rude, GMD3 manager, June 24, 2015).

GMD4: Starting in 1980, totalizing flowmeters were required on wells for all new water rights and any redrilled wells for existing water rights. In 2006, all wells with water rights were required to have totalizing flowmeters. The transition process was staged so totalizing flowmeters were installed in roughly 25% of the wells without flowmeters prior to use in 2006, 50% in 2007, 75% in 2008 and 100% in 2009. Duration meters had been used extensively in GMD4 prior to that date, but GMD4 personnel had put great effort into educating the irrigation community about the importance of determining accurate flow rates for conversion of duration-of-pumping records into annual water use (pers. communication, Ray Luhman, GMD4 manager, June 24, 2015 and July 13, 2015).

GMD5: Starting in 1993, totalizing flowmeters have been mandatory on all non-domestic wells with water rights (pers. communication, Orrin Feril, GMD5 manager, June 24, 2015).

Text S6 – Regional-Scale Assessments

Assessments are presented here for the GMDs not discussed in the main text. Given the uncertainty in the pumping data for GMDs 1 and 3, confidence intervals are not reported for those GMDs.

GMD1 – semi-arid setting

GMD1 encompasses a 4,734 km^2 region of west-central Kansas (Figure 1) characterized by semi-arid climatic conditions (Fross et al., 2012). Figure S4 is a plot of ΔWL versus Q for 1996-2013. Three features are striking: 1) the lack of correlation when the full 1996-2013 dataset is considered; 2) the tendency for higher reported annual water use for the 1996-2004 period, and 3) the increasing strength of the correlations found for the 2005-2013 and 2009-2013 datasets. These features appear to be produced by the changing quality of the water-use data as totalizing flowmeters replace duration meters (see Text S5). This interpretation is supported by ΔWL versus climatic index plots that have been developed for the

GMDs in Kansas (Whittemore et al., 2016). Figure S5 is a plot of ΔWL versus the standardized precipitation index (SPI), a precipitation-only climatic index (McKee et al., 1993), for GMD1. The correlation between ΔWL and SPI in GMD1 for 1996-2013 is the lowest observed in the Kansas HPA for that period but it is much higher than that for the plot of ΔWL versus Q for the same time period. The strength of the correlation is a reflection of precipitation controlling when the pumps are operating and indicates that there should be a strong correlation between ΔWL and Q when reliable water-use data are available (Whittemore et al., 2016). A comparison between Figures S4 and S5 can provide further insight. Similar water-level changes but a large difference in reported water use are shown on Figure S4 for 1996 and 2009. However, as shown in Figure S5, the climatic conditions for those two years were quite similar (1996 slightly wetter). This is a strong indication that the water use for 1996 appears to have been over reported by about 39% (assuming reported 2009 water use is correct). Similar results can be found from a comparison of 2002 and 2012 (water use appears to have been over reported in 2002 by about 24%) and 2003 with 2010 and 2013 (water use appears to have been over reported in 2003 by about 28%). Thus, the focus here is on data from 2009 and later. Q_{stable} is calculated from the equation of the best-fit line (0.20×10^9 m^3) and appears to be ~80% of the average Q for 2009-2013 (0.25×10^9 m^3). Thus, if the average Q had been 20% less than actual for 2009-2013, water levels in the GMD1 well network would not have changed on average. S_{aq} and I_{ua} are calculated from the parameters of the best-fit line (0.053 and 0.041 m, respectively). The net inflow estimated for GMD1 is about 20% greater than that estimated for the adjacent GMD4 (0.034 m). However, given the questions about the reliability of the GMD1 pumping data, little significance should be attached to that difference; existing estimates of natural recharge for GMD1 are about the same as for GMD4 (Hansen, 1991).

GMD2 – subhumid setting

GMD2 encompasses a 3,543 km^2 region of south-central Kansas (Figure 1) characterized by subhumid climatic conditions (Fross et al., 2012). Figure S6 is a plot of ΔWL versus Q for 1996-2013. Two features are striking: 1) the linearity of the relationship, an indication that the approximations in equation (3) appear appropriate; and 2) the number of years for which ΔWL was above (8) or slightly below (three values within 0.06 m) zero, an indication that the aquifer appears to have been pumped at a near-sustainable level. Q_{stable} is calculated with equation (4) using the best-fit line to the 1996-2013 data (0.22×10^9 m^3 [CI=0.21-0.23 x 10^9 m^3]) and is within 1% of the average Q for 1996-2013 (0.22×10^9 m^3). Thus, GMD2 has been essentially at stable water-level conditions for this period (average ΔWL for 1996-2013 was -0.020 m). S_{aq} and I_{ua} are calculated from the parameters of the best-fit line (0.026 [CI=0.020-0.038] and 0.062 m [CI=0.060-0.066], respectively). Figure S6 shows that most ΔWL values fall within a ±15% I_{ua} envelope about the best-fit line. The net inflow estimated for GMD2 is about 5% greater than that estimated for the adjacent GMD5 (0.059 m). Existing estimates of natural recharge for GMD2 are greater than those for GMD5 (Hansen, 1993).

GMD3 – semi-arid setting

GMD3 encompasses a 21,604 km^2 region of southwest Kansas (Figure 1) characterized by semi-arid climatic conditions (Fross et al., 2012). Figure S7 is a plot of ΔWL versus Q for 1996-2013. Three features are striking: 1) the relatively low correlation when the full 1996-2013 data set is considered; 2) the pre-1998 data for which the reported water use appears high relative to the measured water-level change, and 3) the tendency of the 1998-2013 data to fall into two distinct groups (1998-2004 and 2005-2013) for which much stronger correlations are found than for the 1996-2013 dataset. As in GMD1, these features appear to be produced by the changing quality of the water-use data (see Text S5). Likely explanations are that it took at least two years after completion of the shift to totalizing flowmeters in 1996 before most flowmeters were producing reliable data, and that the flowmeter calibration specifications are questionable for either the 1998-2004 or 2005-2013 periods. These explanations are supported by the ΔWL versus SPI plot for GMD3 (Figure S8). The strength of the correlation between ΔWL and SPI in GMD3 for 1996-2010, 2012-2013 is close to that observed in GMD4 for 1996-2005, 2008-2013 (R^2 of 0.83 [GMD3] versus 0.82 [GMD4]), and is again a reflection of precipitation controlling when the pumps are operating and an indication that there should be a strong correlation between ΔWL and Q when reliable water-use data are available (Whittemore et al., 2016). A comparison between Figures S7 and S8 can provide further insight. Reported water use for 1996 and 1998 is nearly the same in Figure S7 but the ΔWL values differ by over 0.32 m. Figure S8 shows a considerable difference in climatic conditions between those two years (1996 much wetter), so the water use for 1996 appears to have been over reported by a considerable amount. Furthermore, climatic conditions for 1998 and 2005 were quite similar but the reported water use for 2005 is 21% less, despite the larger ΔWL. Similarly, based on climatic conditions and ΔWL, the reported water use for 2012 should have been nearly the same as 2002, and not 13% less. Given the uncertainty in the pre-1998 data and the two groupings for the 1998-2013 data, Q_{stable} is calculated from equation (4) using the best-fit lines to the 1998-2004 (1.98×10^9 m^3) and 2005-2013 (1.39×10^9 m^3) datasets. Q_{stable} for 1998-2004 appears to be approximately 79% of the average Q for that period (2.51×10^9 m^3), while Q_{stable} for 2005-2013 appears to be approximately 58% of the average Q for 2005-2013 (2.41×10^9 m^3). Thus, estimates of the reduction in pumping required to achieve stable water levels vary by approximately a factor of two (21-42%). S_{aq} and I_{ua} are calculated from the parameters of the best-fit lines for the two datasets (0.058 and 0.078 m, respectively, when the estimates from the two datasets are averaged). The net inflow estimated for GMD3 is about 32% greater than that estimated for GMD5, a surprising result given the difference in climatic conditions (semi-arid versus subhumid) and estimated natural recharge (Hansen, 1991). However, the intensity of pumping in GMD3 is about 72% greater than that in GMD5 (water use/area is 0.11 m and 0.064 m for GMDs 3 and 5, respectively, for 2000-2013). Thus, the higher net inflow for GMD3 could be an indication of more irrigation return flow as well as more drainage from the greater volume of dewatered sediments produced by the larger water-level declines in GMD3. This higher net inflow could also be produced by pumping-induced inflow from the underlying Dakota aquifer (Whittemore et al., 2014). However, we cannot rule out that the net inflow (and thus the Q_{stable}) for GMD3 is over estimated as a result of errors in the reported water-use data.

References for Text S6

Fross, D., M. Sophocleous, B.B. Wilson, and J.J. Butler, Jr. (2012), *Kansas High Plains Aquifer Atlas*, Kansas Geological Survey (http://www.kgs.ku.edu/HighPlains/HPA_Atlas/index.html - accessed January 12, 2016).

Hansen, C.V. (1991), Methods of freshwater storage and potential natural recharge for principal aquifers in Kansas, *U. S. Geological Survey Water-Resources Investigations Report 87-4230*, 100 p.

McKee, T. B., N.J. Doesken, and J. Kleist (1993), The relationship of drought frequency and duration to time scales, *Preprints, 8th Conference on Applied Climatology*, 17-22 Jan 1993, Anaheim, CA, 179-184.

Whittemore, D.O, J.J. Butler, Jr., and B.B. Wilson (2016), Assessing the major drivers of water-level declines: New insights into the future of heavily stressed aquifers, *Hydrological Sci. Jour.*, 61(1), 134-145, doi: 10.1080/02626667.2014.959958.

Whittemore, D.O., P.A. Macfarlane, and B.B. Wilson (2014), Water resources of the Dakota aquifer in Kansas, *Kansas Geological Survey Bulletin 260* (www.kgs.ku.edu/Publications/Bulletins/260/index.html - accessed January 12, 2016).

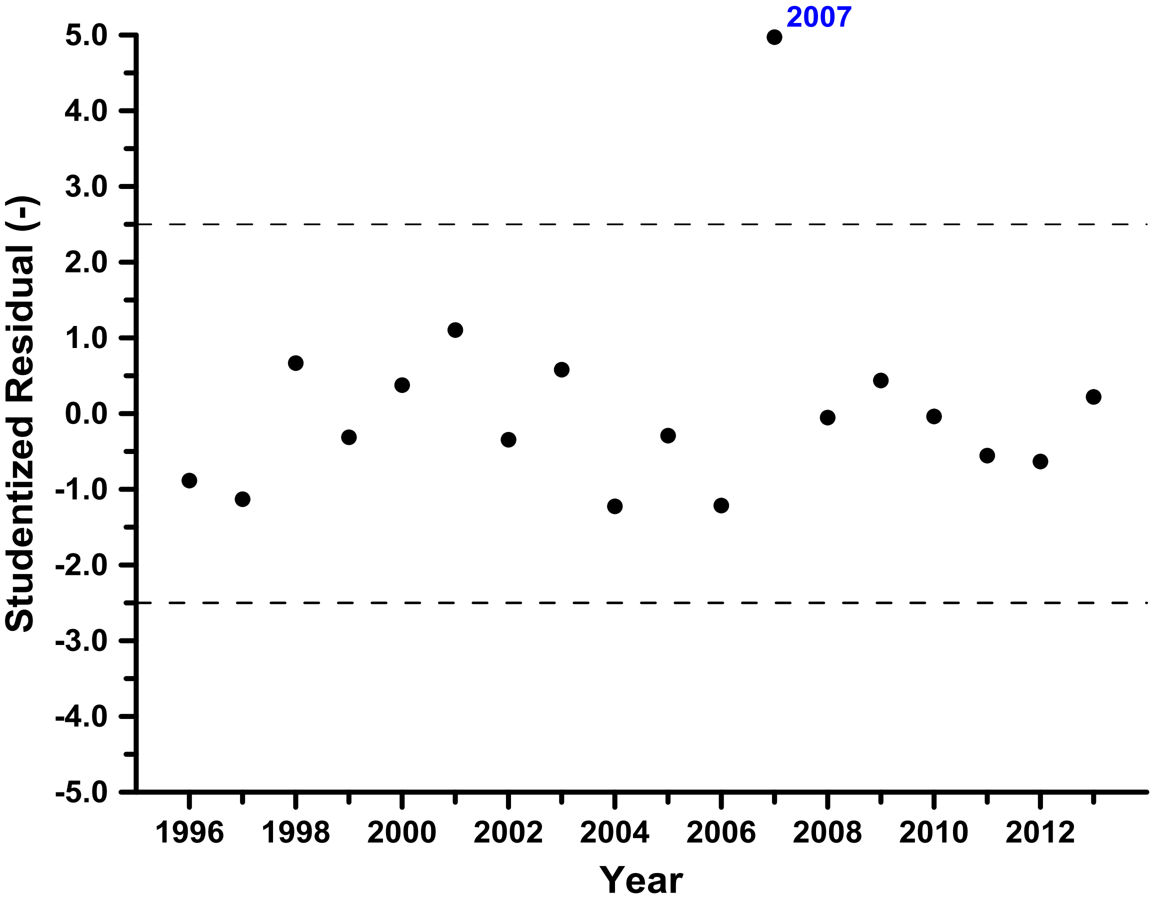

Figure S1. Studentized residuals versus year for regression using all of the GMD5 data. Studentized residuals larger than |2.5| are generally considered outliers (dashed lines indicate ±2.5). The studentized residual for 2007 is 4.97.

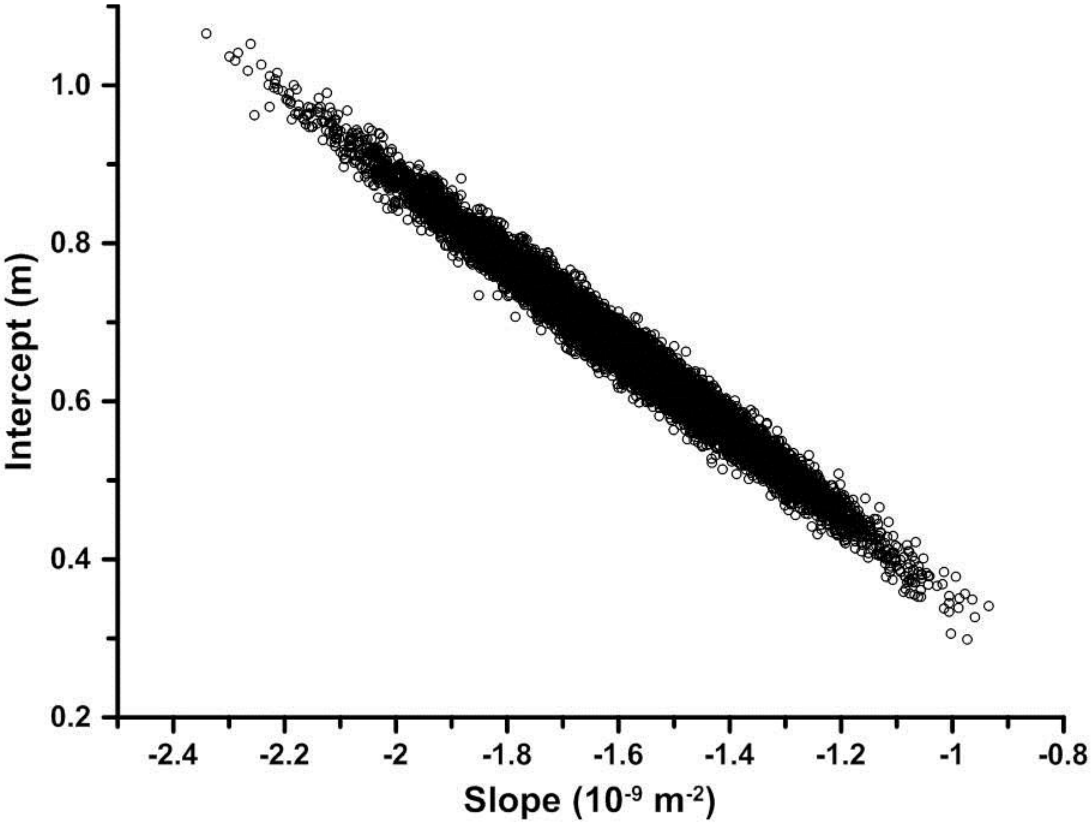

Figure S2. Ten thousand samples drawn from the joint distribution of the intercept and slope estimates for the GMD4 regression. The distribution is a long, narrow ellipse as a consequence of the strong negative correlation between the intercept and slope estimates.

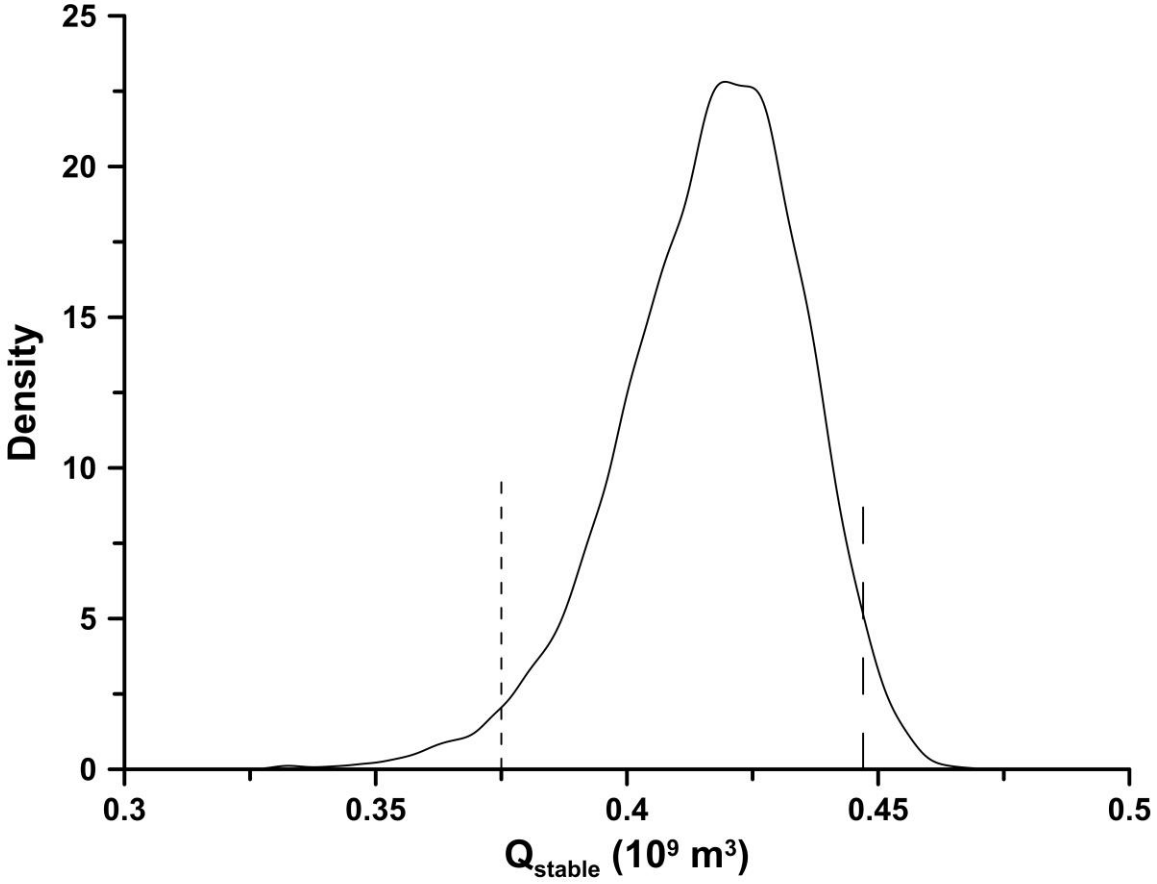

Figure S3. Kernel density estimate of probability density function of Q_{stable} values for GMD4 regression. Plot computed using the Q_{stable} values estimated from the 10,000 slope and intercept values shown in Figure S2. The 2.5% and 97.5% values are marked by the small and large dashed vertical lines, respectively.

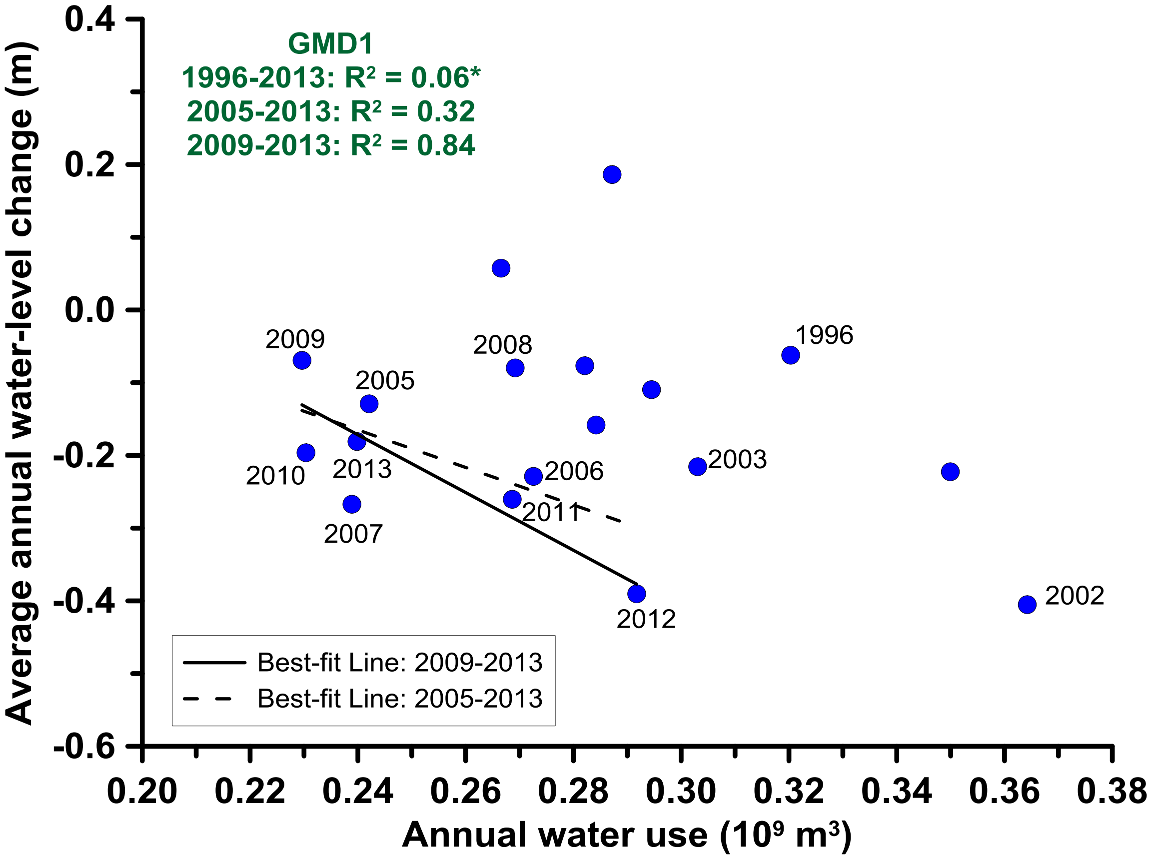

Figure S4. Average annual water-level change (ΔWL) versus annual water use (Q) plot for GMD1; solid line is best-fit line ($\Delta WL = 0.78 - 3.97Q$, $p < 0.01$) to 2009-2013 data, while dashed line is best-fit line ($\Delta WL = 0.45 - 2.58Q$, $p < 0.1$) to 2005-2013 data. ΔWL is the average for the 59 wells measured every year from 1996-2014. Best-fit line for 1996-2013 is not shown (* indicates relationship is not statistically significant). Labelled points are discussed in Text S6. Annual water use is the sum of reported use from a maximum of 3,320 pumping wells (well total varies slightly from year to year). Climatic conditions in GMD1 for 1996-2013 were near average (see Text S4).

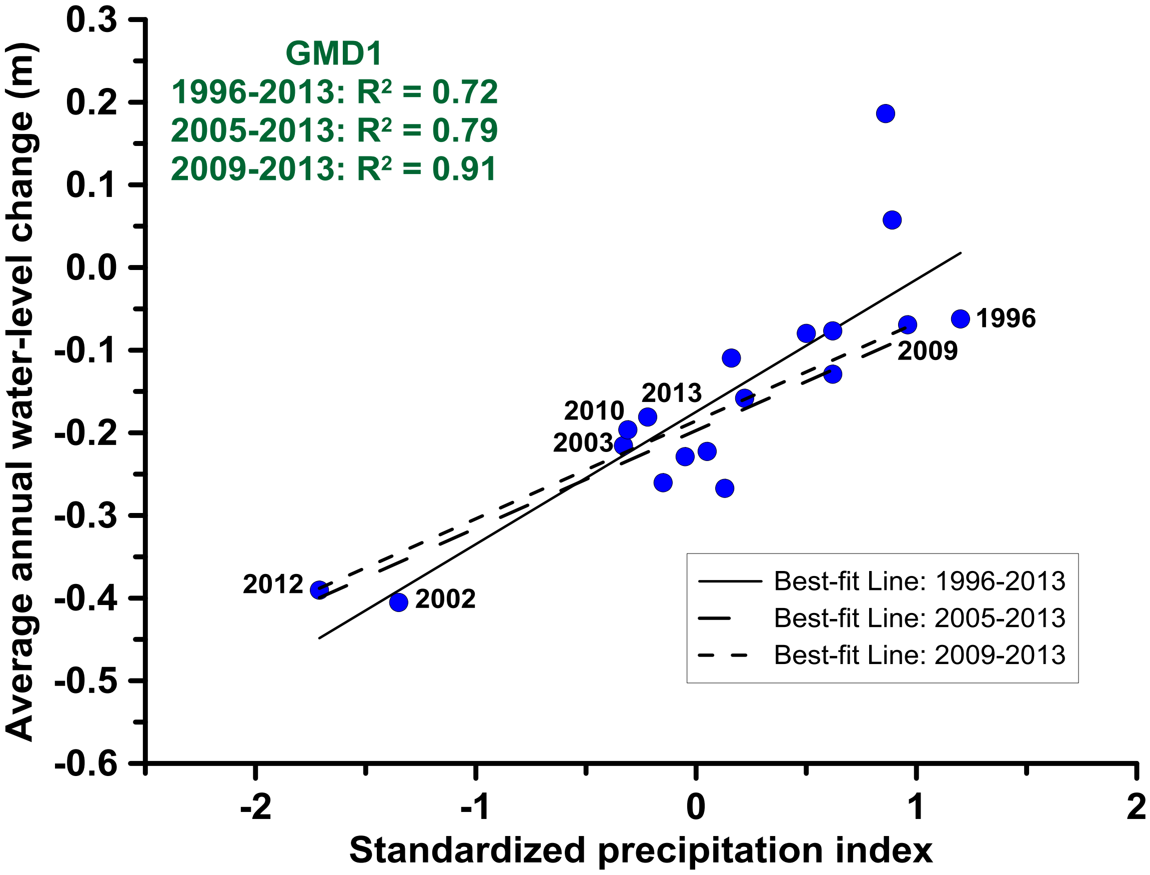

Figure S5. ΔWL versus standardized precipitation index (SPI) plot for GMD1; solid line is best-fit line (ΔWL = -0.17 + 0.16SPI, p <0.001) to 1996-2013 data. Labelled points are discussed in Text S6; SPI is for nine-month period ending in October for Kansas climatic division 4 (see Text S4).

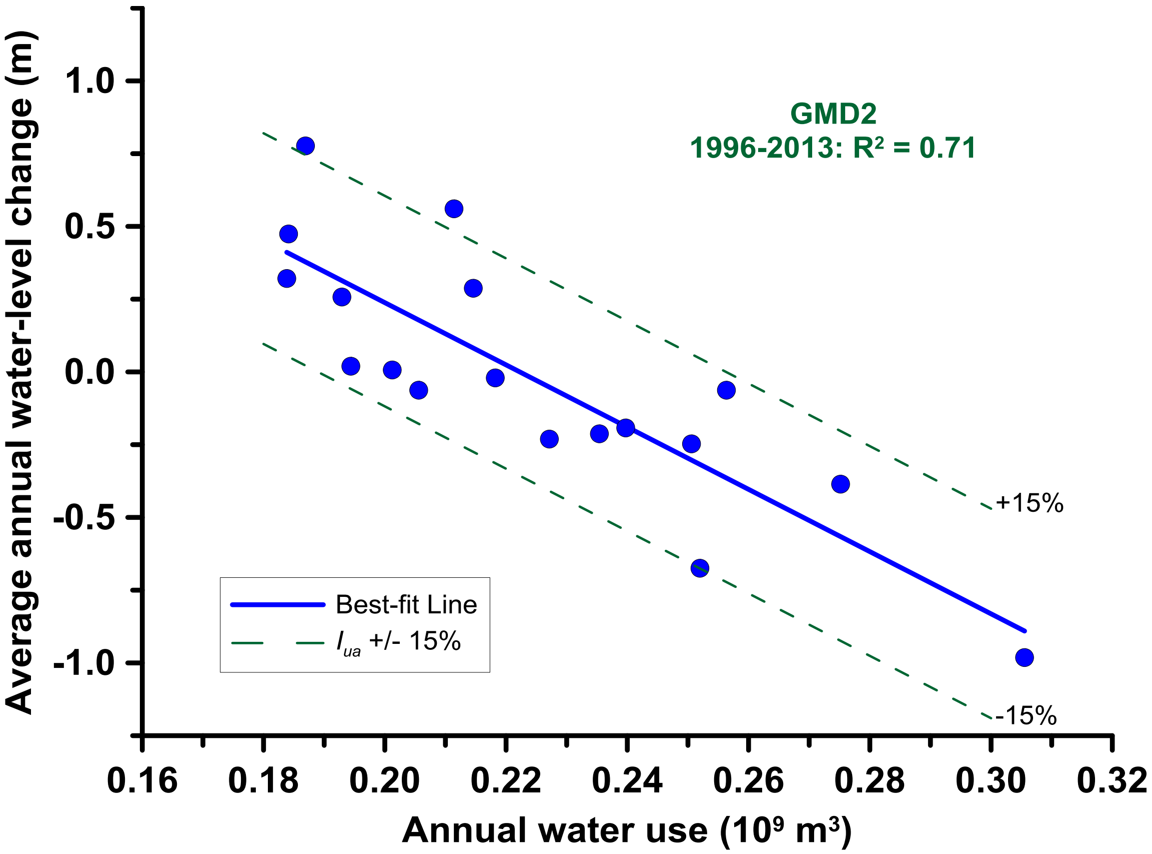

Figure S6. ΔWL versus Q plot for GMD2; solid line is best-fit line ($\Delta WL = 2.38 - 10.69Q$, p <0.001) to 1996-2013 data. ΔWL is the average for the 44 wells measured every year from 1996-2014. The dashed lines show the sensitivity to ±15% changes in the estimated net inflow per unit area (I_{ua}) value; all points fall within a ±18% I_{ua} envelope about the best-fit line. Annual water use is the sum of reported use from a maximum of 3,344 pumping wells (well total varies slightly from year to year). Climatic conditions in GMD2 for 1996-2013 were slightly wetter than average (see Text S4). The estimated uncertainty in ΔWL is ±0.058 m and that in Q is ±0.10% of plotted value (see Text S1).

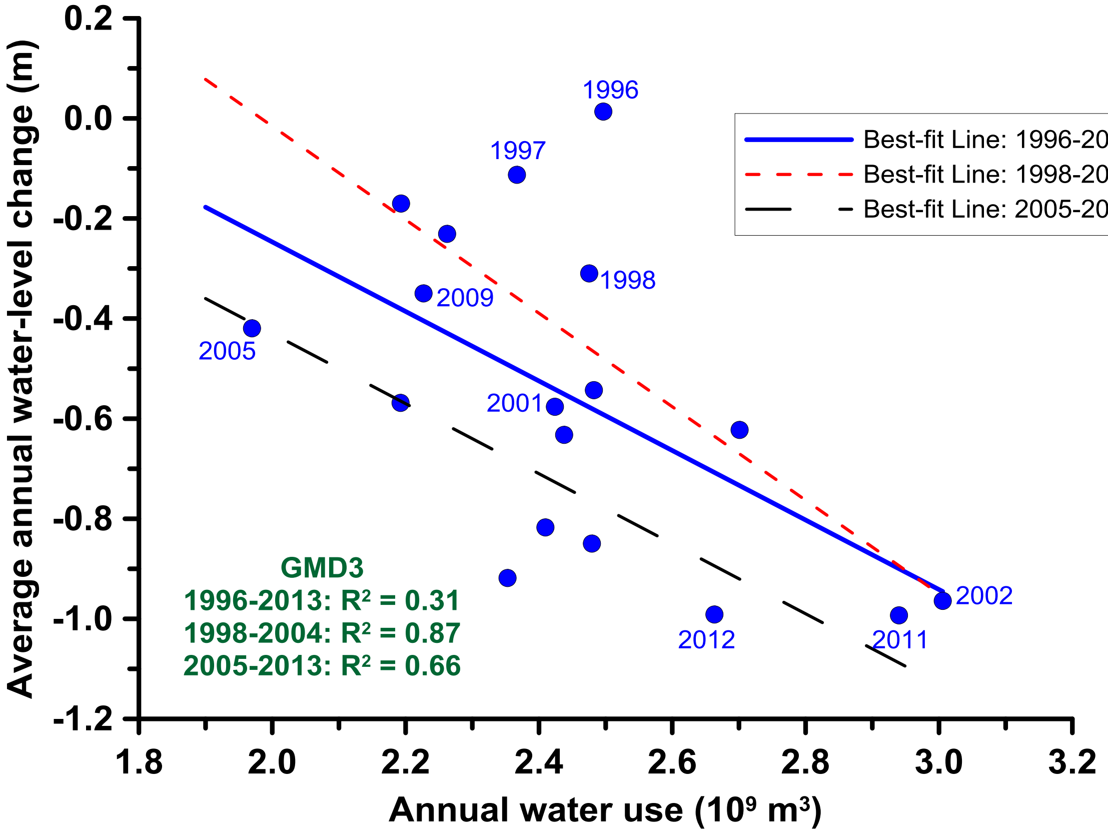

Figure S7. ΔWL versus Q plot for GMD3; solid line is best-fit line ($\Delta WL = 1.14 – 0.69Q$, $p <0.02$) to 1996-2013 data. ΔWL is the average for the 214 wells measured every year from 1996-2014. The small dashed line is best-fit line ($\Delta WL = 1.85 – 0.93Q$, $p <0.01$) to 1998-2004 data, while large dashed line is best-fit line ($\Delta WL = 0.97 – 0.70Q$, $p <0.01$) to 2005-2013 data. Labelled points are discussed in Text S6; 2009 is the only 2005-2013 value to appear above the solid line, while 2001 and 2002 are the only 1998-2004 points to appear below that line. Annual water use is the sum of reported use from a maximum of 14,357 pumping wells (well total varies slightly from year to year). Climatic conditions in GMD3 for 1996-2013 were near average (see Text S4).

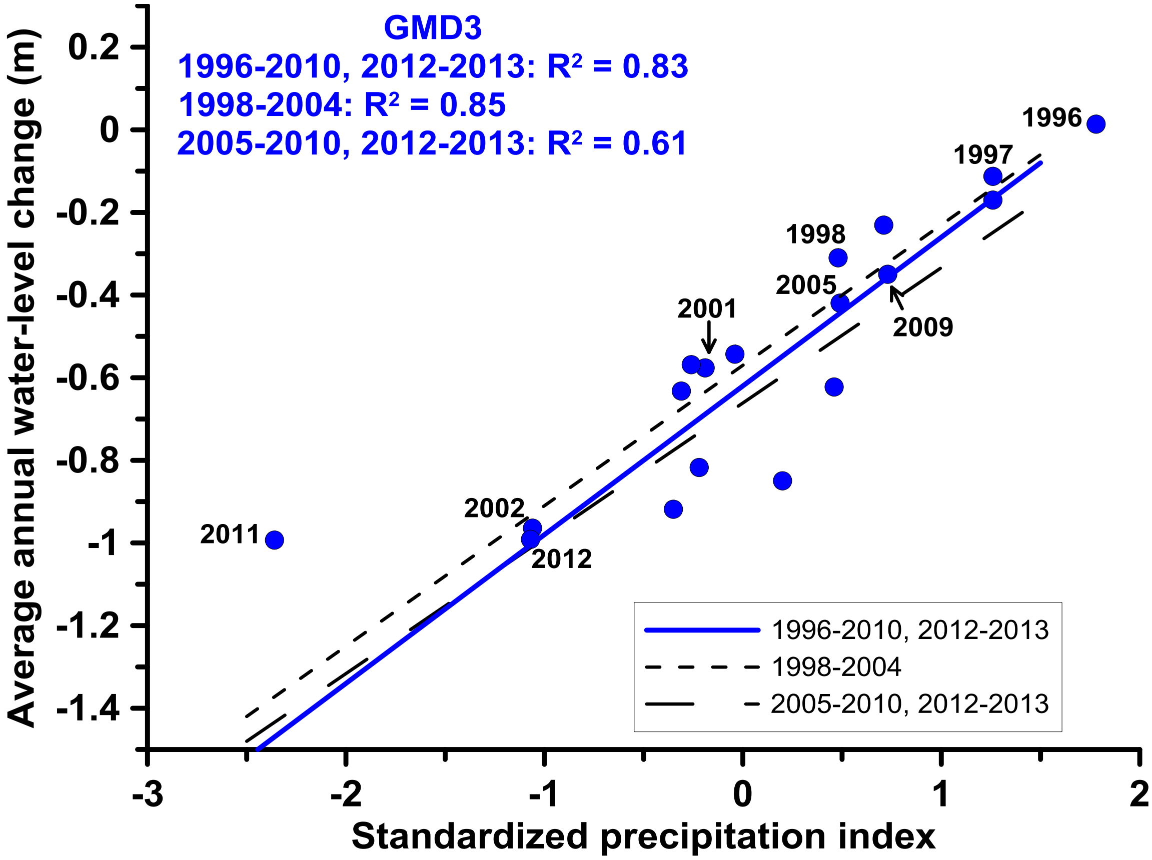

Figure S8. Δ*WL* versus SPI plot for GMD3; solid line is best-fit line (Δ*WL* = -0.62 + 0.36SPI, p <0.001) to 1996-2010, 2012-2013 data. SPI is for nine-month period ending in October for Kansas climatic division 7 (see Text S4); labelled points discussed in Text S6. The severity of the drought in 2011 appears to have caused the water use for that year to deviate from that expected using current pumping practices, so 2011 is not considered in the regressions reported on the plot.