Kansas Geological Survey

High Plains Aquifer Index Well Program: 2013 Annual Report

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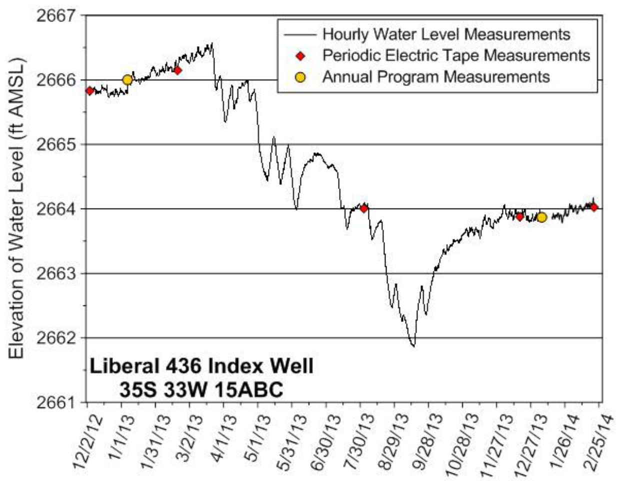

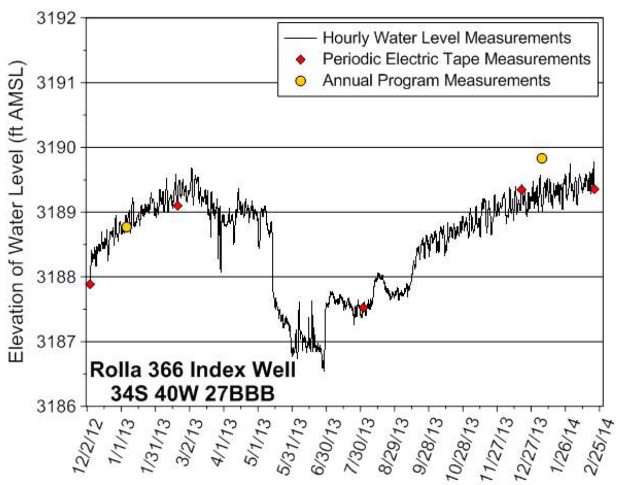

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Acknowledgments

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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 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 Kansas. The Kansas Department of Agriculture, Division of Water Resources (DWR), provides assistance, as do Groundwater Management Districts (GMDs) 1, 3, and 4, 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 that allows 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 current 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 (subunit) 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 six full recovery and pumping seasons and one ongoing recovery season have been obtained at the original three index wells; additional water-level data have been acquired from wells in the vicinity of all three index wells. In late 2012, wells in four monitoring nests (one well from each nest) along the Kansas-Oklahoma state line were added to the network; 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.

This report provides (a) an update of the hydrographs for the original three index wells, the new index wells (wells along the Kansas-Oklahoma border in GMD3), and the expanded network (one well in GMD1 and three wells in the vicinity of the Thomas index well); (b) interpretation of the hydrographs from the original three index wells and discussion of the information conveyed by hydrographs of different forms; (c) a discussion of climatic indices and their relationship to annual water-level changes at the original three index wells and to water use in the vicinity of those wells; and (d) discussion of the results of chemical analyses of groundwater samples obtained from the original index wells and irrigation wells in their vicinity.

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

(1) The annual water-level measurement network alone (even with additional semi-annual observations) does not, in general, produce an adequate dataset to evaluate how management decisions affect water-level changes in the short term (fewer than four to five years);

(2) 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;

(3) 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;

(4) Additional measurements at nearby (local-scale) wells help establish the generality of the conclusions that can be obtained from interpretation of index well hydrographs;

(5) 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;

(6) Continuous monitoring has helped establish the hydrogeologic information conveyed by hydrographs of various forms; and

(7) 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.

The focus of project activities in 2014 will be on the continuation of monitoring at all project wells, continuation of the detailed analyses of hydrographs from all project wells, cooperation with GMD4 on the interpretation of water-level data from monitoring wells in the Sheridan-6 subunit, continued assessment of the subsurface information that can be acquired from an analysis of the water-level response to changes in barometric pressure, further interpretation of geochemical results of analyses of water samples from the vicinity of the index wells, an assessment of the effect of the Dakota aquifer on water levels in the vicinity of the Haskell County index well, further assessment of the relationship between climatic indices and annual water-level changes and water use in the three western GMDs, 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

The index well program (formerly, calibration monitoring well program) is directed at developing improved approaches for measuring and interpreting hydrologic responses at the local (section to township) scale in the Ogallala–High Plains aquifer (henceforth, High Plains aquifer or HPA). 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 Kansas. The Kansas Department of Agriculture, Division of Water Resources (DWR), provides assistance, as do Groundwater Management Districts (GMDs) 1, 3, and 4, 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 (subunit) 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 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.

At the end of 2013, monitoring data (hourly frequency) from six full recovery and pumping seasons and one ongoing recovery season have been obtained. With increasing data, the index well program has demonstrated that (1) the annual water-level measurement network alone does not, in general, produce an adequate dataset to evaluate how management decisions on the sub-unit scale affect water-level changes in the short term (fewer than four to five years); (2) 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; (3) 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; (4) additional measurements at nearby wells help establish the generality of the conclusions that can be obtained from interpretation of index well hydrographs; (5) 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; (6) continuous monitoring has helped establish the hydrogeologic information conveyed by hydrographs of various forms; and (7) 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. In addition, the index well program has motivated the development of methods that use the annual measurement program data to predict the effect of management decisions on a larger scale. The index well network was again enlarged in 2013 to include additional wells at two sites near the Kansas-Oklahoma border. In cooperation with the USGS, telemetry equipment was installed in four wells at those two sites in December 2013. Note that the term "index well" is used here to designate a specially constructed 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) and/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) an update of the hydrographs for the original three index wells, the six new index wells along the Kansas-Oklahoma border in GMD3, and the expanded network (one well in GMD1 and three wells in GMD4); (b) interpretation of the hydrographs from the original three index wells and discussion of the information conveyed by hydrographs of different forms; (c) a discussion of climatic indices and their relationship to annual water-level changes at the original three index wells and to water use in the vicinity of those wells; and (d) discussion of the results of chemical analyses of groundwater samples obtained from the index wells and additional wells in their vicinity.

2. Setting and Experimental Design

The foundation of this project consists of three transducer-equipped wells, designed and sited to function as local 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 current 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" in the vicinity of the 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. 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, Whittemore, and Reboulet, 2013).
2. 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. Monitoring is continuing at three of these additional wells. The commonly adopted view of the HPA as a single unconfined aquifer appears reasonable in the vicinity of the Thomas County site.
3. Scott County expansion—early in 2012, with the assistance of GMD1, two additional "wells of opportunity" in the vicinity of the Scott County index well were equipped with transducers. The commonly adopted view of the HPA as a single unconfined aquifer also appears reasonable in the vicinity of the Scott 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; in May 2013, two pumping wells were shut down by court order. 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. 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 recently published journal article based on that report (Butler, Stotler, Whittemore, and Reboulet, 2013), it is doubtful that large-scale irrigation withdrawals from the High Plains aquifer near the Haskell County site can be sustained at the current pumping rate 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 recharge, at least temporarily, is greater than originally thought. The Scott County site is in GMD1, which is the location of an ongoing 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.

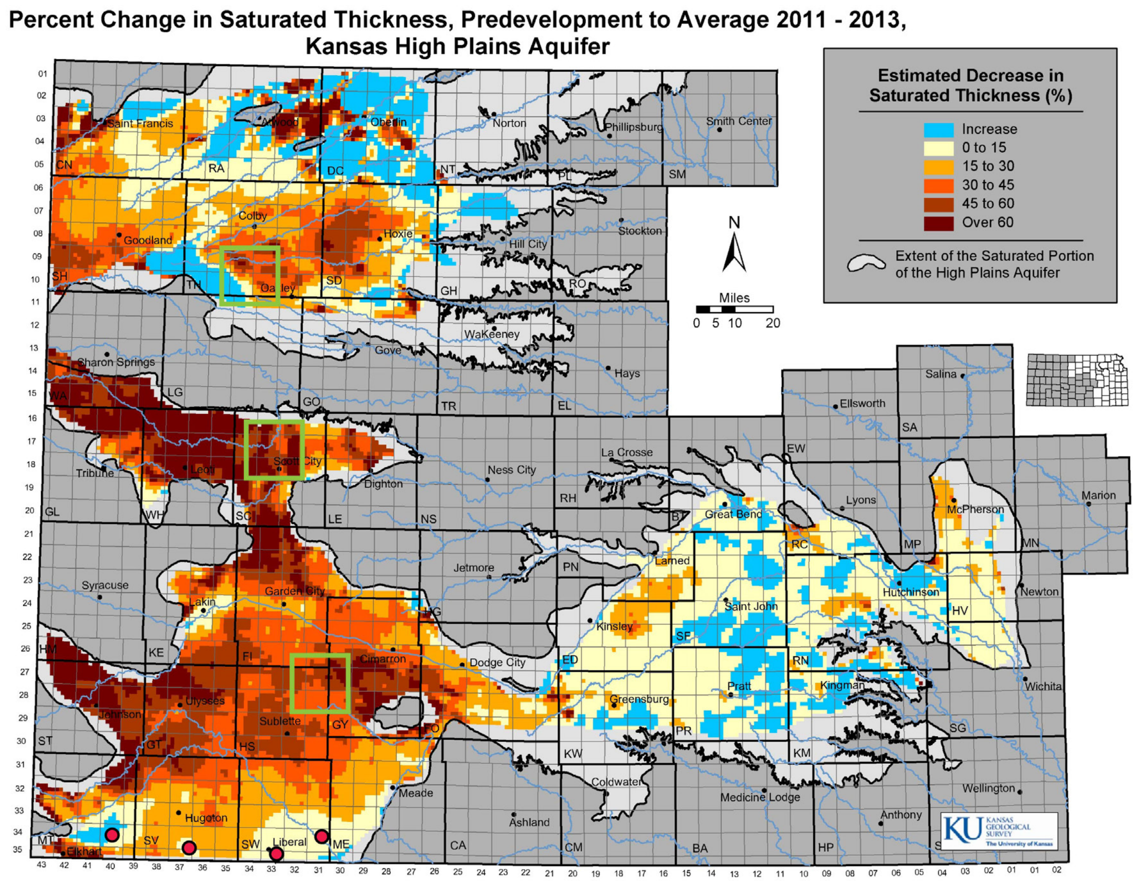

Figure 1—The Kansas portion of the High Plains aquifer, with aquifer and county boundaries shown. Each colored pixel represents one section (1 mi²), coded for the degree of groundwater depletion from the beginning of large-scale development to the average of conditions in 2011–2013. The green boxes are approximately centered on the original index well sites; the filled red circles indicate the locations of the new border index wells. Additional wells (expanded network) are monitored within each of the boxes, the WH-1 well near Leoti in GMD1, which will shortly be replaced, is not shown.

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

Site	2014 WL elev. (ft)[a]	2014 Saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2012 Water Use (ac-ft)		
					1-mi circle	2-mi circle	5-mi circle
Haskell	2,545.5	140.6	433	420–430	1,803	9,706	52,320
Scott	2,829.7	85.5	223	215–225	1,103	3,761	20,091
Thomas	2,968.7	65.3	284	274–284	1,466	3,683	17,494

[a]2014 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 six 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 increase throughout 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 of little significance for assessing 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. Although the recovery extrapolation work has not resulted in reliable estimates of the final recovered water level at the index wells, those efforts, which have been described in previous project reports, have enabled us to identify recovery "signatures." These signatures allow recognition of some of the mechanisms affecting the recovery data even when only relatively short data records are available.

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 in 2012 and 2013. 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 hydrograph from the Thomas County index well is also possible through the GMD4 website (www.gmd4.org).

3.1.1 Haskell County

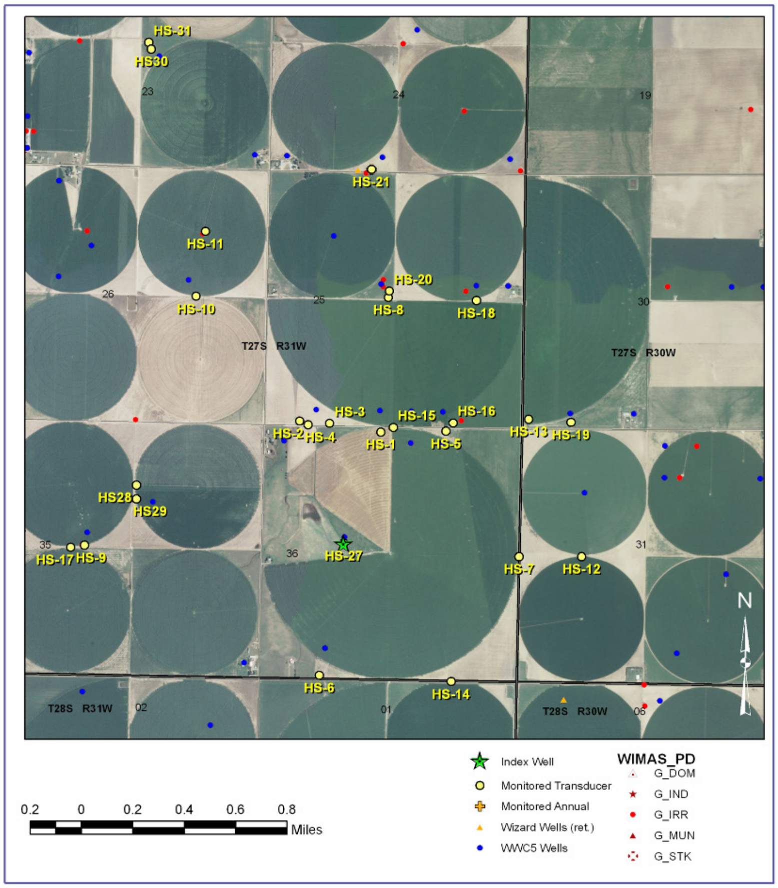

Figure 2—Haskell County site, showing the index well, adjacent monitoring wells, and points of diversion within the area of concentrated DWR studies. Most of the marked wells (yellow circles) are equipped with transducers.

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, the additional wells being monitored by DWR and used by the index well program, and the location of wells with water rights in that area.

3.1.1.1 Hydrograph and General Observations

The complete hydrograph for the Haskell index well is shown in fig. 3, and its general characteristics are summarized in table 2. The confined nature of the aquifer zone in which the index well is screened is illustrated by the greater than 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, most probably as a result of a sensor malfunction. On February 20, the sensor was removed from the well; we anticipate that a functioning sensor will be installed by early spring 2014.

The 2012–13 recovery started on August 18, the last date of pumping for the 2012 irrigation season that had a major impact on the index well, and ended on March 4, 2013, when nearby pumping began. However, as is typical for the Haskell site, few periods during the recovery season were completely free of the influence of pumping. In particular, there was an extended period of pumping during the late fall (October 31, 2012–December 4, 2012), most likely to provide moisture for winter wheat. Similar to previous years, the pumping season started earlier in the vicinity of the Haskell site than at the Scott and Thomas sites, with a break during much of the month of April. The early start of pumping is likely due to a combination of winter wheat irrigation and pre-irrigation of other crops, whereas the break in pumping could be caused by decreased water use during planting of summer crops. The 2013–14 recovery season began on July 29, 2013, and was still continuing at the time of this report (based on February 20, 2014, manual measurement). Other than a 13-day pumping period lasting from August 21 to September 3, 2013, there has been only a minor amount of pumping during the 2013–14 recovery.

Until 2013, the minimum recorded water-level elevation at the Haskell index well declined each year. However, the minimum 2013 water-level elevation was 3.2 ft higher than that in 2012. The most likely explanation is the cessation of pumping early in the 2013 irrigation season at two nearby irrigation wells as a result of a May 21, 2013, court decision (Garetson Brothers versus Kelly and Diana Unruh, District Court of Haskell County Kansas, Case No. 12-CV-09). Water use for 2013 will be available later in 2014 and, as a result of the court decision, is expected to be the lowest during the monitoring period. In 2012, water use within the 2-mile radius surrounding the index well was 9,703 ac-ft, the third highest use year during the monitoring period, and 269 ac-ft above the average for the period (9,442 ac-ft). The 2012 water use was applied on fewer irrigated acres than previous years, resulting in the second highest water use per acre irrigated during the monitoring period (table 2). In 2013, the index well recorded a year-to-year decline in the maximum recovered water level of 8.1 ft, the second largest decline during the monitoring period. Given that the water-level minimum recorded in 2013 was higher than that in 2012, the expectation is that the decline in the maximum recovered water level in 2014 will not exceed the 2013 decline.

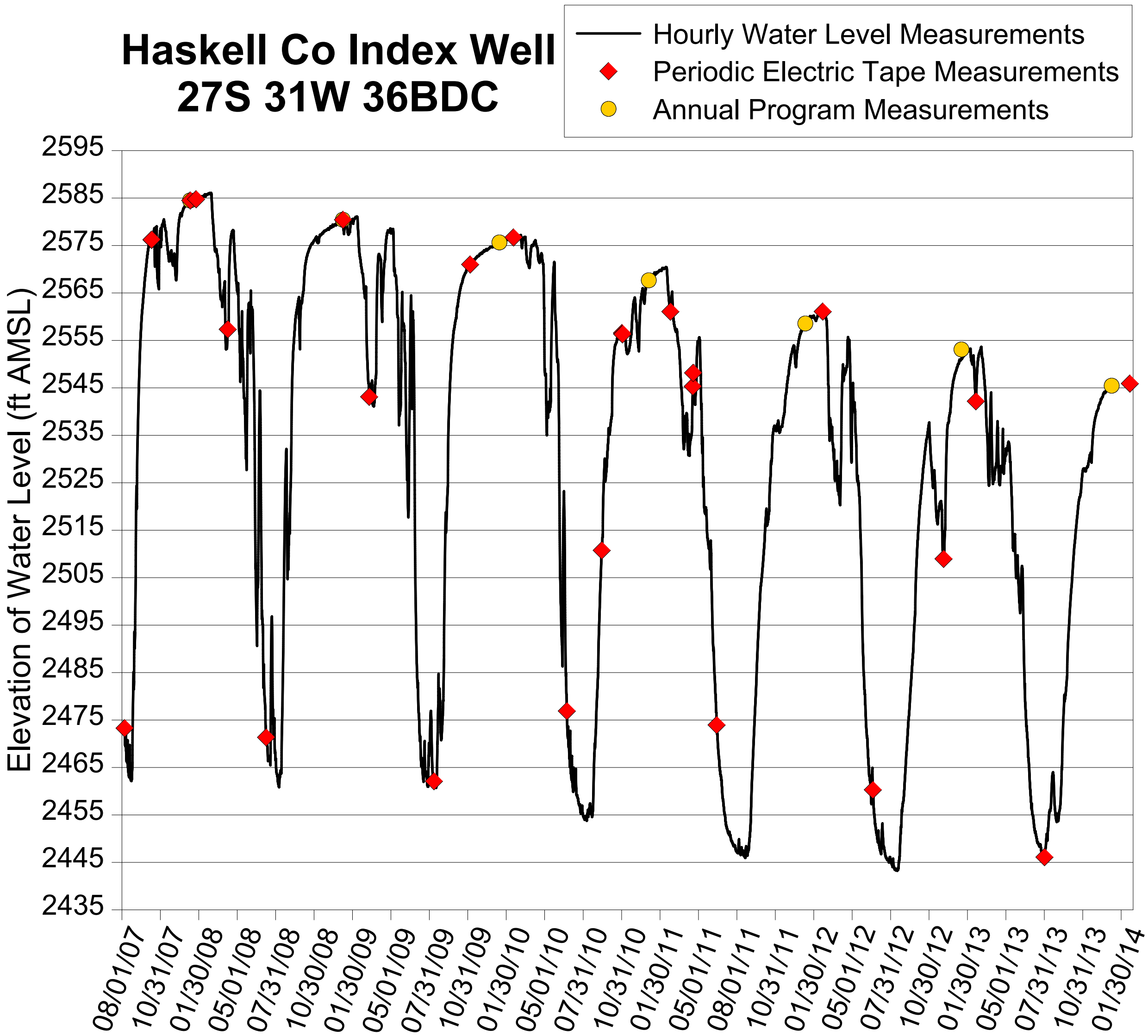

Figure 3—Haskell County index well hydrograph—total data run (continuous measurements) to 1/12/14 (manual measurement obtained 2/20/14). A water-level elevation of 2,445 ft corresponds to a depth to water of 392.85 ft below land surface (lsf); the top of the screen is 420 ft below lsf (elevation of 2,417.85 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.

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

		2007	2008	2009	2010	2011	2012	2013
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
	Date	8/23/07	8/8/08	8/16/09	8/9/10	8/21/11	8/16/12	7/29/13
Maximum Observed Recovery Elevation	Feet	NA	2,586.1	2,581.1	2,577.2	2,570.4	2,561.7	2,553.6
	Date	NA	2/28/08	2/9/09	3/5/10	2/13/11	2/23/12	3/4/13
Apparent Recovery	Feet	NA	124.0	120.3	116.5	116.6	115.8	110.4
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-5.0	-3.9	-6.8	-8.7	-8.1
Recovery Season	Start	NA	8/24/07	8/13/08	8/18/09	8/24/10	8/29/11	8/18/12
	End	NA	2/28/08	2/10/09	3/6/10	2/15/11	2/23/12	3/4/13
	Length (Days)	NA	189.2	181.0	200.2	174.9	178.8	197.9
Pumping During Recovery Season	Days	NA	41.5	20.0	5.2	25.8[a]	28.9	36.3
Length of Pumping Season	Days	NA	166.1	188.5	171.0	193.7	173.4	150.0
2-mi Radius Water Use	Irrigated Acres	6,475	7,755	6,259	6,114	6,107	5,714	NA
	Total Use (ac-ft)	8,764.0	9,931.7	8,720.4	8,972.7	10,560.4	9,706.3	NA
	Irrigation Use Only (ac-ft)	8,762.1	9,929.8	8,718.3	8,970.0	10,556.8	9,703.0	NA
	Use per Irrigated Acre (ft)	1.35	1.28	1.39	1.47	1.73	1.70	NA

[a] Overall, the recovery was not very 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.

3.1.1.2 Measurement Comparisons

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

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/15/2008	2,584.48	NA	Steel tape
	2,584.44[c]	-	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] (NA)	Steel tape
	2,545.94[cf]	-5.28	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.

3.1.2 Scott County

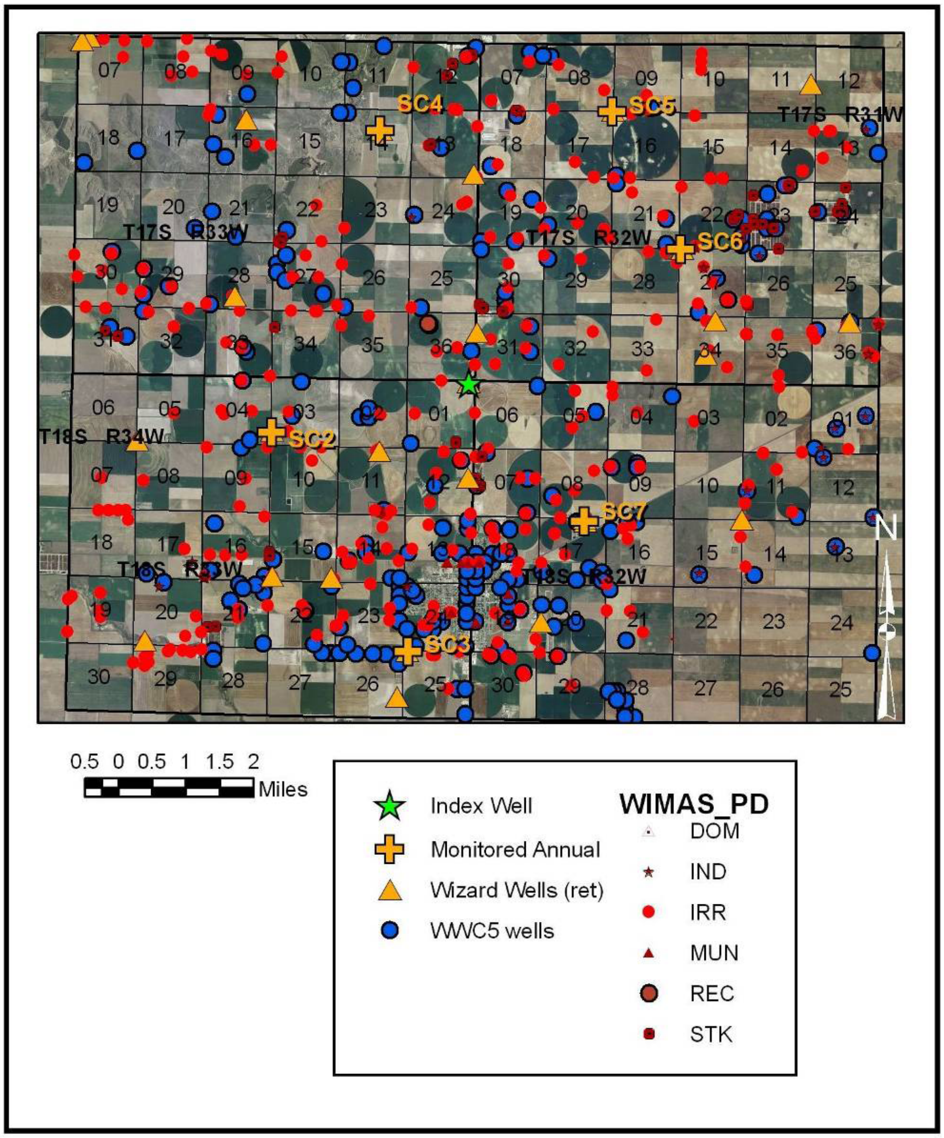

Figure 4a—Scott County site, showing the index well, annual program wells, and nearby points of diversion. GMD1 expansion wells shown in fig. 4b.

Figure 4a is an aerial overview of the Scott County site at a scale that shows the index well, the surrounding network of annual program wells, and the location of wells with water rights in that area. Figure 4b shows the GMD1 expansion wells discussed in Section 3.2.

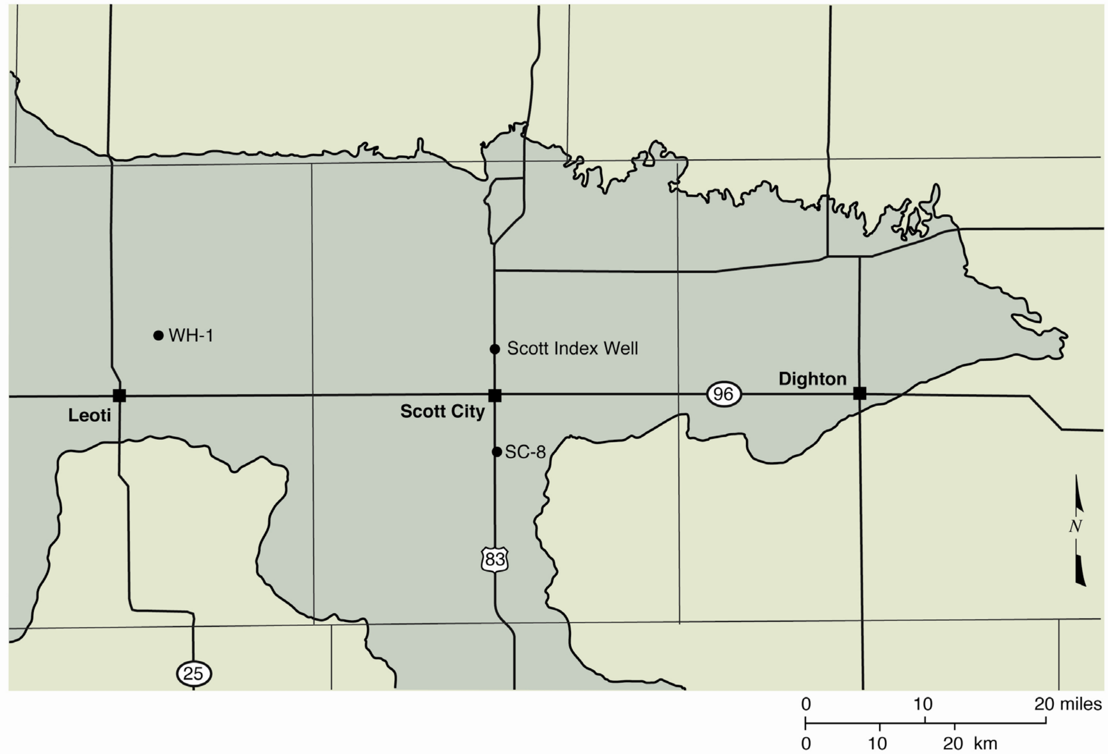

Figure 4b—Scott County index well with the SC-8 and WH-1 expansion wells discussed in Section 3.2. Monitoring at WH-1 ceased on February 19, 2014.

3.1.2.1 Hydrograph and General Observations

The complete hydrograph for the Scott index well is shown in fig. 5 and its general characteristics are summarized in table 4. The unconfined nature of the aquifer zone in which the index well is screened is illustrated by the relatively small change (< 3–4 ft) and rate of change in water level during each pumping and recovery season, despite at least two high-capacity pumping wells within a half-mile of the index well.

The 2012–13 recovery started on September 7, 2012, with sporadic pumping through November 10. After that time, the recovery was nearly linear until pumping for the next irrigation season started on March 11, 2013. Pumping was off and on in the area until late June. After a sudden drop of more than 0.75 ft within 24 hours on June 22–23, pumping appeared to continue at all wells in the vicinity until July 31. Pumping then largely ceased before a final period of widespread pumping from August 21 to September 14. Transducer measurements during the recovery period are noisier than previous years; the source of that higher noise level will be explored in 2014. The recovery was still continuing at the time of this report (February 20, 2014).

Each year, the minimum recorded water-level elevation has declined from the previous year. The lowest water level observed was in 2013; the minimum 2013 water-level elevation was 1.3 ft lower than in 2012, and 4.6 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 2013 and was 1.7 ft below that of 2012 and 5.0 ft below that of 2008. Given the fall pumping that delayed the 2012–13 recovery, the expectation is that the decline in the maximum recovered water level in 2014 will be considerably less than the 2013 decline. Water-use data for 2013 will be available later in 2014. Water use within the 2-mile radius surrounding the index well in 2012 (3,761 ac-ft) was the second highest since the onset of monitoring and 331 ac-ft above the average for the monitoring period (3,430 ac-ft).

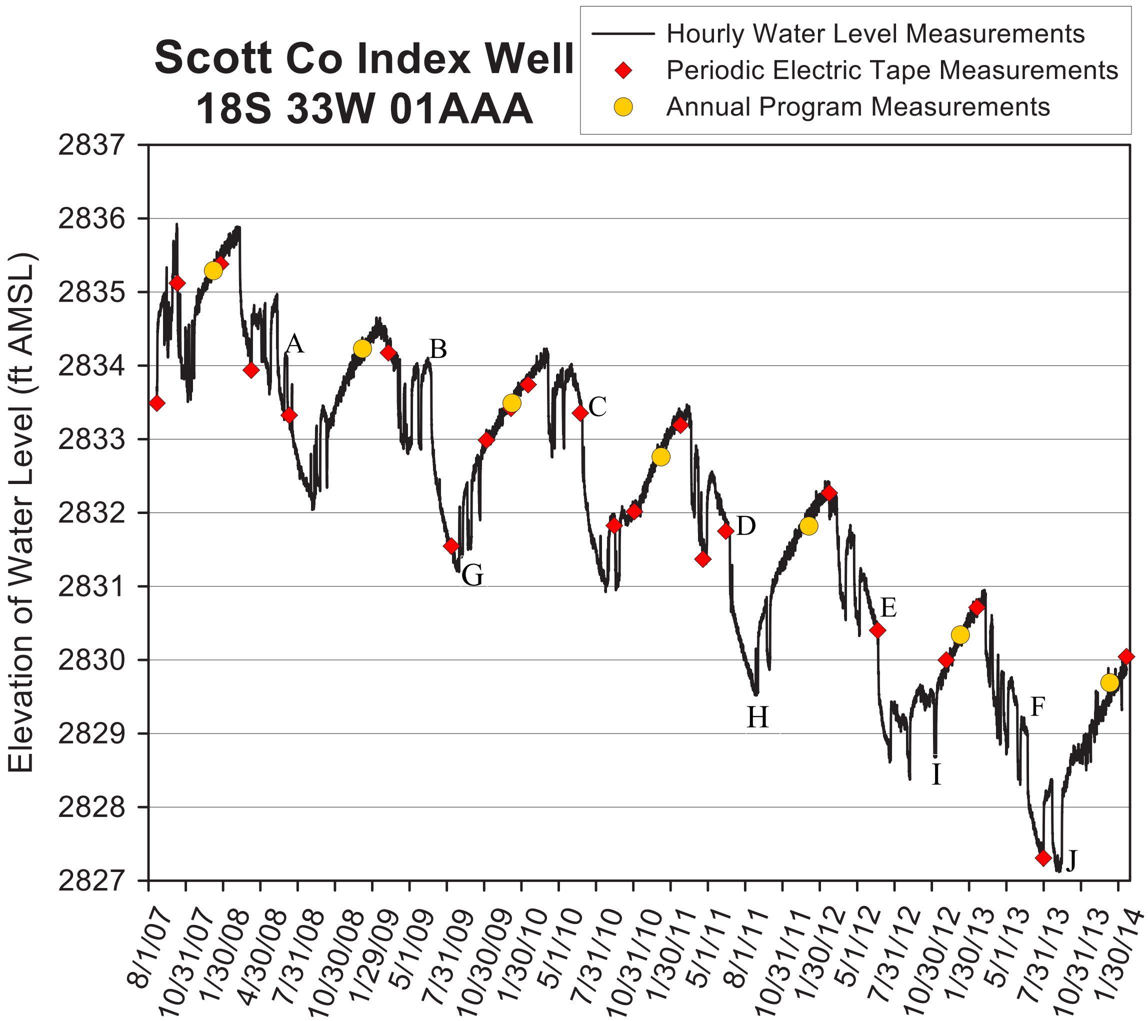

Figure 5—Scott County index well hydrograph—total data run to 2/19/14. A water-level elevation of 2,829 ft corresponds to a depth to water of 138.15 ft below land surface (lsf); the top of the screen is 215 ft below lsf (elevation of 2,752.15 ft) and the bottom of the aquifer is 223 ft below lsf (elevation of 2,744.15 ft). The screen terminates 2 ft below the bottom of the aquifer. A–J defined in text (Section 4.2). Transducer inadvertently dropped 0.29 ft during 2/22/12 download; data adjusted for position change after completion of 2012 annual report.

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

		2007	2008	2009	2010	2011	2012	2013
Minimum Water-Level Elevation	Feet	<2,833.4	2,832.0	2,831.2	2,830.9	2,829.5	2,828.7	2,827.4
	Date	8/21/07	9/5/08	8/30/09	8/24/10 and 9/18/10	8/26/11 and 8/29/11	9/7/12	9/10/13
Maximum Observed Recovery Elevation	Feet	NA	2,835.9	2,834.6	2,834.2	2,833.5	2,832.6	2,830.9
	Date	NA	3/4/08	2/17/09	3/26/10 and 4/1/10	3/11/11	2/28/12	3/9/13
Apparent Recovery	Feet	NA	>2.5	2.6	3.0	2.6	3.1	2.2
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-1.3	-0.4	-0.7	-0.9	-1.7
Recovery Season	Start	NA	<8/21/07	9/13/08	8/30/09	8/29/10	9/1/11	9/7/12
	End	NA	3/11/08	4/2/09	4/5/10	3/17/11	3/12/12	3/11/13
	Length (Days)	NA	>203	201.3	217.8	200.2	192.8	185.25
Pumping During Recovery Season	Length (Days)	NA	>48.2	13.7	21.0	12.8	8.7	5
Length of Pumping Season	Days	NA	182.3	150.0	145.7	168.1	186.42	186.8
2-mi Radius Water Use	Irrigated Acres	4,132	3,950	3,923	3,665	4,078	3,734	NA
	Total Use (ac-ft)	3,175.09	4,059.02	2,955.48	3,035.89	3,595.58	3,760.82	NA
	Irrigation Use Only (ac-ft)	3,095.78	4,014.33	2,955.48	3,017.08	3,580.63	3,747.66	NA
	Use per Irrigated Acre (ft)	0.75	1.02	0.75	0.82	0.88	1.00	NA

3.1.2.2 Measurement Comparisons

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

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/7/2008	2,835.29	NA	Steel tape
	2,835.29[c]	-	Transducer
1/6/2009	2,834.23	-1.06 (-1.24)	Steel tape
	2,834.21[c]	-1.08	Transducer
	2,834.95[d]	NA	Transducer
1/7/2010	2,833.49	-0.74 (-0.42)	Steel tape
	2,833.48[c]	-0.73	Transducer
	2,833.55[e]	-1.40	Transducer
1/7/2011	2,832.76	-0.73 (-0.73)	Steel tape
	2,832.86[c]	-0.62	Transducer
	2,832.86[e]	-0.69	Transducer
1/4/2012	2,831.82	-0.94 (-0.90)	Steel tape
	2,831.92[c]	-0.94	Transducer
	2,831.95[e]	-0.91	Transducer
1/9/2013	2,830.34	-1.48 (-1.7)	Steel tape
	2,830.27[c]	-1.65	Transducer
	2,830.25[e]	-1.70	Transducer
1/10/2014	2,829.69	-0.65 (NA)	Steel tape
	2,829.46[c]	-0.81	Transducer
	2,829.50[e]	-0.75	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] Back extrapolated (quadratic best fit) from barometrically corrected values, 1/8/2009–2/18/2009.
[e] Average of values over time interval 0800–1600, corrected for barometric pressure using the KGS barometric pressure correction program.

3.1.3 Thomas County

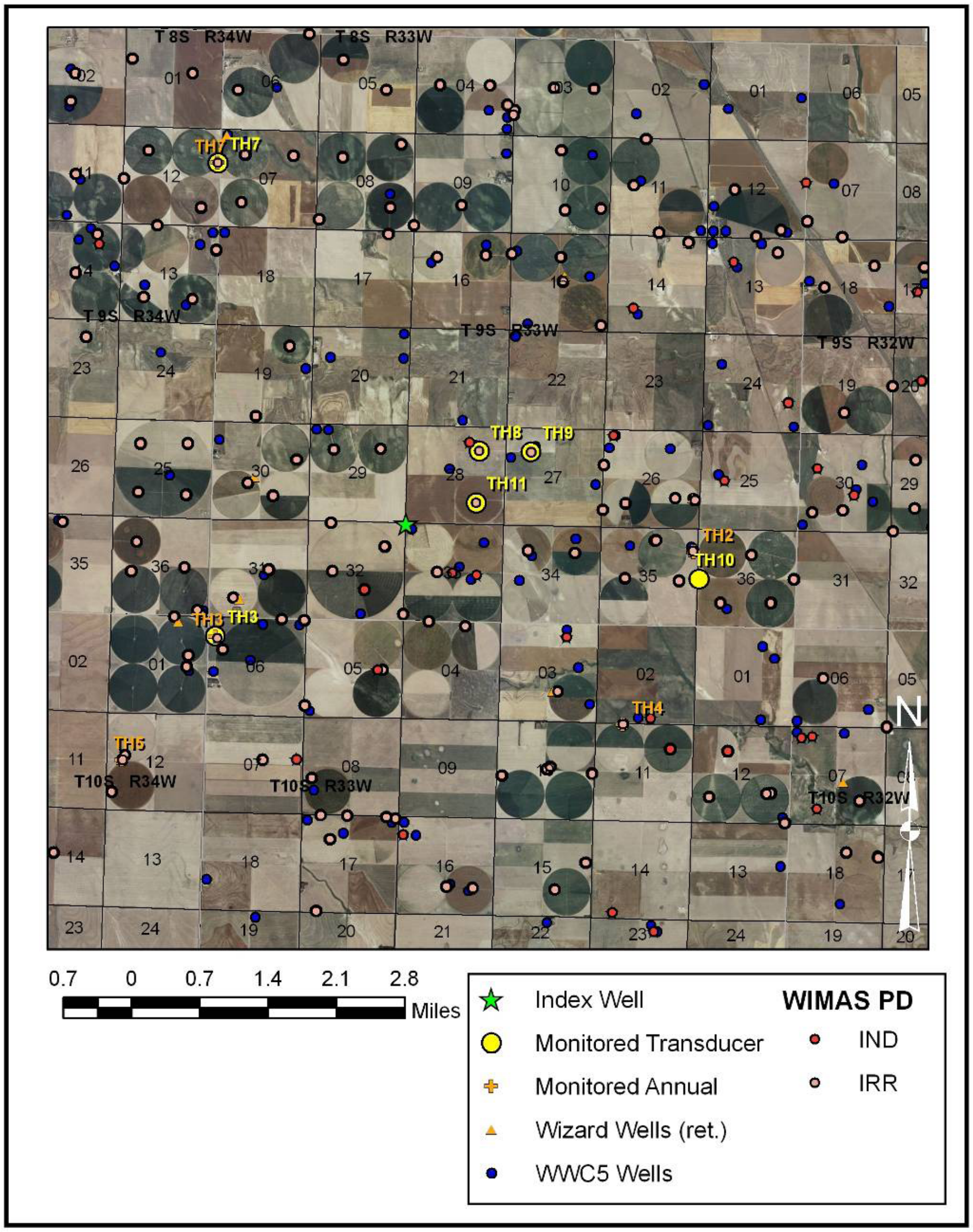

Figure 6—Thomas County site, showing the index well, nearby wells that have been equipped with transducers, surrounding annual program wells, and points of diversion in the area.

Figure 6 is an aerial overview of the Thomas County site at a scale that shows the index well, the additional wells in which transducers have been placed (labeled Monitored Transducer), the surrounding network of annual program wells, and the wells with water rights in that area.

3.1.3.1 Hydrograph and General Observations

The complete hydrograph for the Thomas index well is shown in fig. 7 and its general characteristics are summarized in table 6. The unconfined nature of the aquifer zone in which the index well is screened is illustrated by the relatively small change and rate of change in water level during each pumping and recovery season, despite 10 or more high-capacity pumping wells within a mile of the index well.

The 2012–13 recovery was the second shortest observed during the monitoring period at the Thomas well, beginning on September 17, 2012, and ending on May 9, 2013. However, it was still 42 days longer than the 2010–11 recovery. Although there were periodic short cutoffs at some wells, sustained pumping essentially continued from early May until the end of the pumping season on September 13, 2013. The 2013–14 recovery season was still continuing at the time of this report (February 20, 2014).

Unlike the Haskell index well (until the court-ordered shutdown of two nearby irrigation wells in 2013) 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 2013, which was the lowest recorded over the monitoring period, was 1.8 ft below that of 2012 and 6.1 ft below that of 2010 (the highest recorded minimum water-level elevation during the monitoring period). Water-use data for 2013 will be available later in 2014. In 2012, water use within the 2-mile radius surrounding the index well (3,683 ac-ft) was the highest use year during the monitoring period and 875 ac-ft above the average for the period (2,808 ac-ft). The 2012 water use was applied on only slightly more irrigated acres (<2%) than the average irrigated acres over the monitoring period, so the water use per acre irrigated was the highest for the period (table 6). The maximum observed water level in 2013 was 1.9 ft below that of 2012 and 4.5 ft below that of 2010 (the highest maximum observed water level during the monitoring period). Given that the 2013 minimum water level (recorded on September 11) was the lowest minimum recorded water-level elevation during the monitoring period, the expectation is that, in the absence of a very long recovery period, the maximum observed water level at the end of the 2013–14 recovery will be the lowest value recorded to date at the Thomas index well.

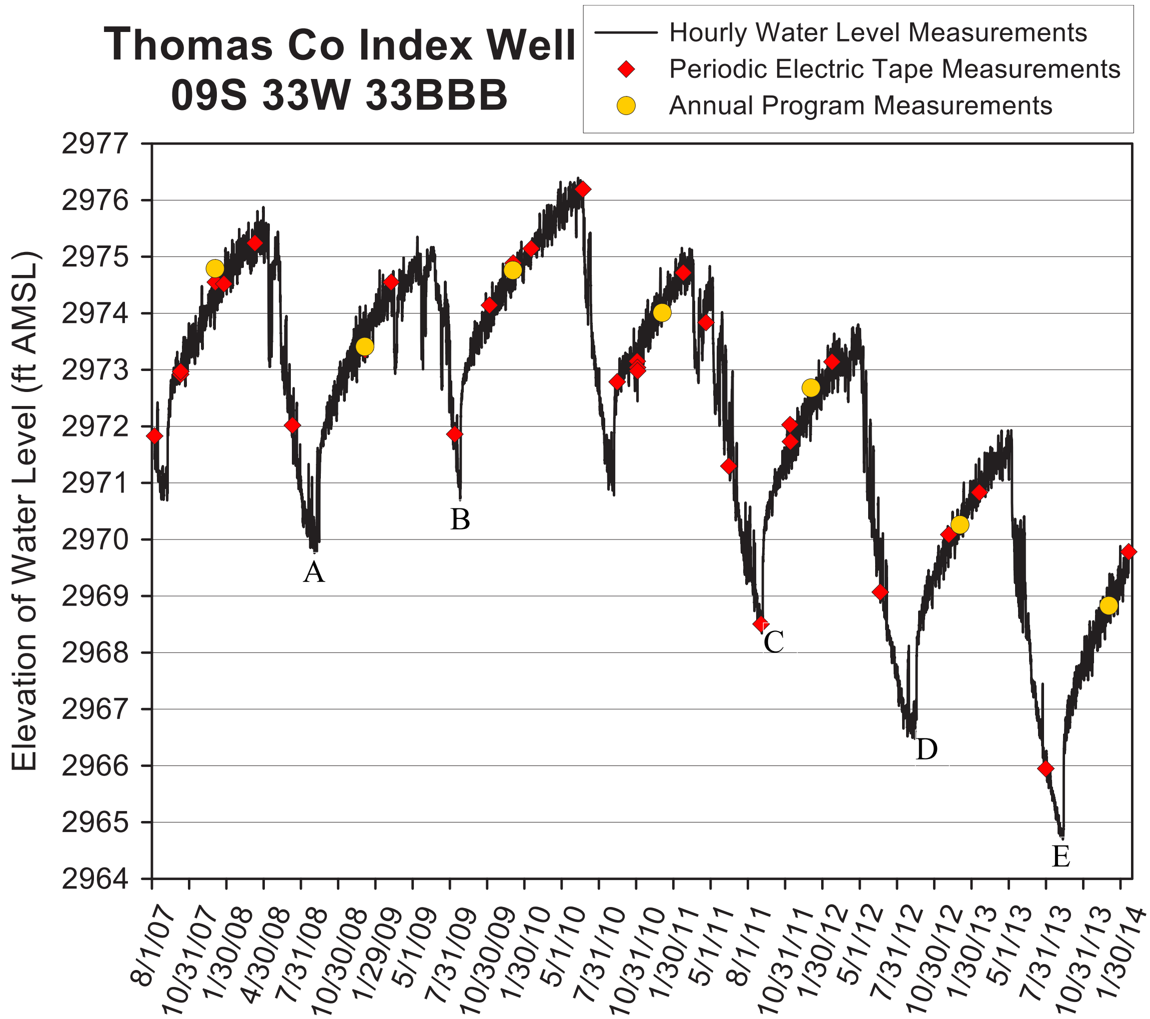

Figure 7—Thomas County index well hydrograph—total data run to 2/19/14. A water-level elevation of 2,968 ft corresponds to a depth to water of 219.56 ft below land surface (lsf); the top of the screen is 274 ft below lsf (elevation of 2,913.56 ft), and the bottom of the aquifer is 284 ft below lsf (elevation of 2,903.56 ft). The screen terminates at the bottom of the aquifer. A–E 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
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
	Date	9/7/07	9/2/08	8/25/09	9/6/10	9/4/11	9/13/12	9/11/13
Maximum Observed Recovery Elevation	Feet	NA	2,975.9	2,975.4	2,976.4	2,975.2	2,973.8	2,971.9
	Date	NA	4/30/08	5/12/09	6/10/10	2/20/11	4/27/12	4/29/13 and 5/7/13
Apparent Recovery	Feet	NA	5.2	5.6	5.7	4.4	5.5	5.4
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-0.5	+1.0	-1.2	-1.4	-1.9
Recovery Season	Start	NA	9/8/07	9/8/08	8/26/09	9/6/2010	9/6/11	9/17/12
	End	NA	5/12/08	6/24/09	6/24/10	3/17/11	5/4/12	5/9/13
	Length (Days)	NA	247.2	289.5	301.38	191.4	241.3	233.7
Pumping During Recovery Season	Length (Days)	NA	5.0	17.0	2.2	18.4	14.0	0[a]
Length of Pumping Season	Days	NA	118.5	63.2	74.6	173.8	135.8	127.0
2-mi Radius Water Use	Irrigated Acres	2,983	3,016	2,958	3,009	3,109	3,070	NA
	Total (ac-ft)	2,868.87	2,825.21	1,917.17	2,256.13	3,298.83	3,683.24	NA
	Use per Irrigated Acre (ft)	0.96	0.94	0.65	0.75	1.06	1.20	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.

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 (NA)	Steel tape
	2,968.73[c]	-1.53	Transducer
	2,968.37[d]	-1.94	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 of opportunity 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 Morton, Stevens, and Seward counties (filled red circles on fig. 1—from right to left (east to west), Cimarron, Liberal, Hugoton, and Rolla sites). These new 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. A barometer will be added to the Cimarron site later in 2014.

Site characteristics and information about all monitored wells are summarized in table 8. In this section, we provide a brief overview and interpretation of the initial hydrographs from each of these wells. A more complete interpretation will be provided in the 2014 annual report after the acquisition of data from two complete pumping seasons and one complete recovery period.

Table 8—Characteristics of the border index wells.

Site	2014 WL elev. (ft)[a]	2014 saturated thickness (ft)	Bedrock depth (estimated ft below land surface)[b]	Screened interval (ft below land surface)[b]	2012 Water Use (ac-ft)		
					1-mi circle	2-mi circle	5-mi circle
Cimarron-210	2,474.33	290.33	345	200–210	81	81	8,593
Liberal-160[c]	2,693.40[d]	448.40	576	140–160	.25	1,280[e]	32,158[e f]
Liberal-436	2,663.87	418.87	576	426–436	.25	1,280[e]	32,158[e f]
Hugoton-313[c]	2,923.40[d]	458.40	635	303–313	591	3,828	43,083[e]
Hugoton-495	2,923.07	458.07	635	485–495	591	3,828	43,083[e]
Rolla-366	3,189.83	213.83	399	356–366	486	2,063	11,622

[a] 2014 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] 2014 WL measurements from hand measurements taken 12/17/2013.

[e] Includes estimates of water use in Oklahoma based on "Permitted" quantities (Liberal: 675 (2-mi circle) and 20,909 (5-mi circle) ac-ft; Hugoton: 17,989 (5-mi circle) ac-ft).

[f] Includes 7,672 ac-ft of non-irrigation water for city of Liberal.

3.2.1.1 Cimarron Site

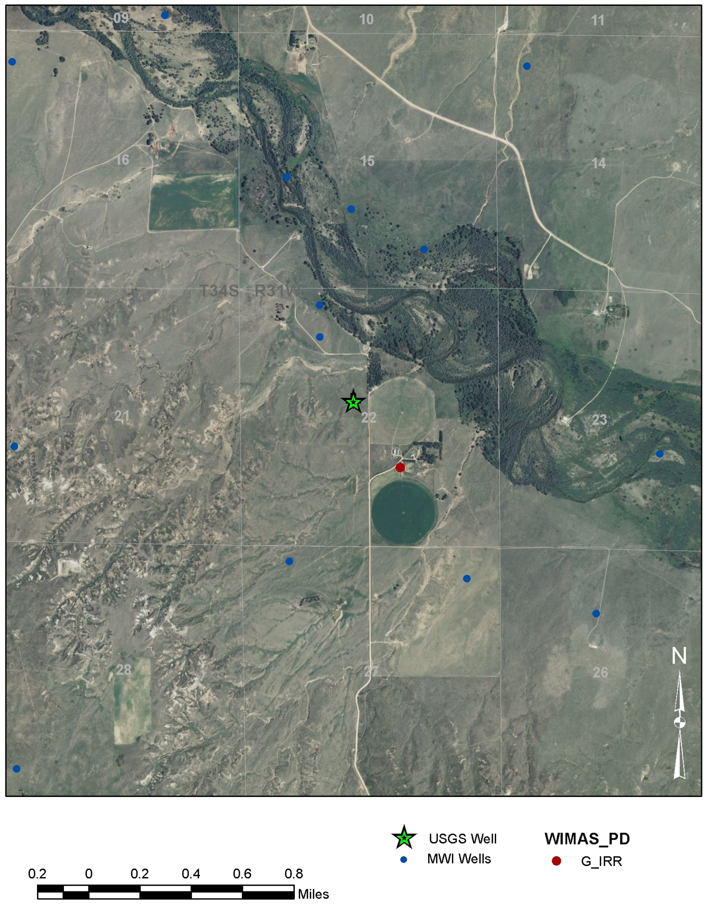

Figure 8—Aerial view of Cimarron site (green star) and points of diversion in the area.

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 irrigation well. The site includes three wells in the HPA and one in the Permian bedrock; the middle well in the HPA, screened 200–210 ft, has been instrumented (henceforth, Cimarron 210 or Cimarron index well).

3.2.1.1.1 Hydrograph and General Observations

The complete hydrograph for the Cimarron index well is shown in fig. 9, and its general characteristics are summarized in table 9. The unconfined nature of the aquifer zone in which the index well is screened is illustrated by the small change in water level during the pumping season, despite the nearby (<0.3 mile) irrigation well, and the discontinuity of water-level responses during pumping and recovery periods (e.g., break in rate of change at A on fig. 9—see Section 4.3 for further discussion). 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 2013 pumping season began on April 13 and ended on October 5. During the pumping season, the water level is affected by sporadic pumping at the nearby irrigation well and by more regional pumping effects (e.g., decline during period B on fig. 9). The 2013–14 recovery season was still continuing at the time of this report (February 20, 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 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 2014, the water level appears to be recovering to near 2,474.5, a loss of about 1.5 ft in 14 years.

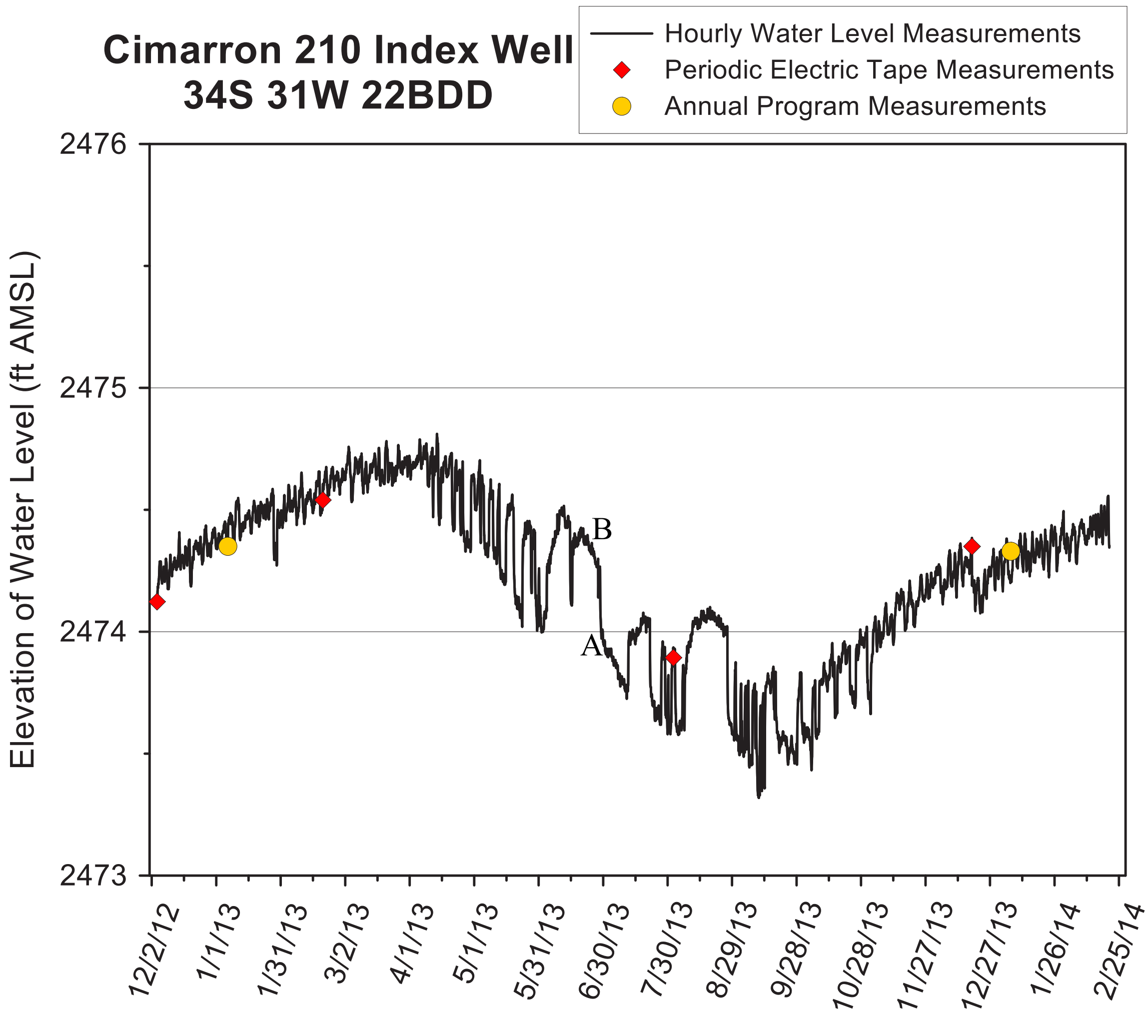

Figure 9—Cimarron 210 index well hydrograph—total data run to 2/20/14. A water-level elevation of 2,474 ft corresponds to a depth to water of 55.0 ft below land surface (lsf); the top of the 10-ft screen is 200 ft below lsf (elevation of 2,219 ft), and the bottom of the aquifer is 345 ft below lsf (elevation 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
Minimum Water-Level Elevation	Feet	2,473.3
	Date	9/10/13
Maximum Observed Recovery Elevation	Feet	2,474.8
	Date	4/13/13
Apparent Recovery	Feet	NA
Annual Change in Maximum Observed Recovery	Feet	NA
Recovery Season	Start	NA
	End	4/13/13
	Length (Days)	NA
Pumping During Recovery Season	Length (Days)	NA
Length of Pumping Season	Days	174.4
2-mi Radius Water Use[a]	Irrigated Acres	NA
	Total (ac-ft)	NA
	Use per Irrigated Acre (ft)	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 (NA)	Steel tape
	2,474.21[c]	-0.20	Transducer
	2,474.28[d]	-0.12	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

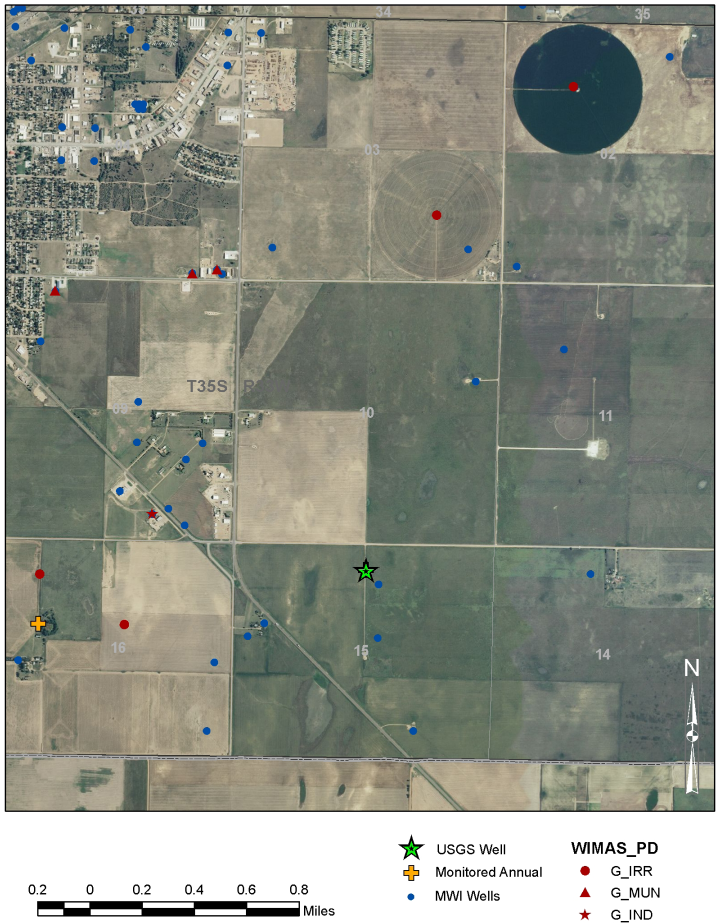

Figure 10—Aerial view of Liberal site (green star), nearby annual program wells, and points of diversion in the area.

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 and the nearby irrigation and municipal wells. 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

The hydrographs for the two Liberal index wells are shown in fig. 11, and the general characteristics are summarized in table 11. The confined nature of the aquifer zone in which Liberal 436 is screened is illustrated by the continuity of the water-level responses during pumping and recovery periods (e.g., drawdown and recovery near A on fig. 11—see Section 4.3 for further discussion) and the relatively small (<0.35 ft) amplitude fluctuations 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 could also be confined as the amplitude of the fluctuations produced by variations in barometric pressure appears to be only slightly larger than that observed in Liberal 436. However, that amplitude could also be produced in an unconfined aquifer given the depth to the water table (126 ft) at the site. The hydraulic conditions in the screened interval at the Liberal 160 well will be clarified in 2014.

The 2013 pumping season began on March 23 and continued through September 15. The very muted response to the pumping season in Liberal 160 indicates that that interval has a very weak hydraulic connection with the heavily stressed portion of the HPA. The elevation difference between water levels in the two wells indicates that the pumping induces downward flow from the shallower interval. The 2013–14 recovery season was still continuing at the time of this report (February 20, 2014). Note that there was a nine-day interruption of continuous monitoring January 5–14, 2014, and a one-hour interruption on January 22, 2014; these interruptions were associated with efforts to install telemetry equipment at the site.

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 monitoring data indicate that the water level in early 2014 at Liberal 436 is recovering to near 2,664, a loss of about 19 ft in 14 years (<1.4 ft/yr), which is consistent with the 20-ft decline over this same time 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 after the 1999 pumping season; the recent data indicate that the water level in early 2014 at Liberal 160 is recovering to an elevation of approximately 2,693.5, a loss of about 12.5 ft in 14 years (<1 ft/yr).

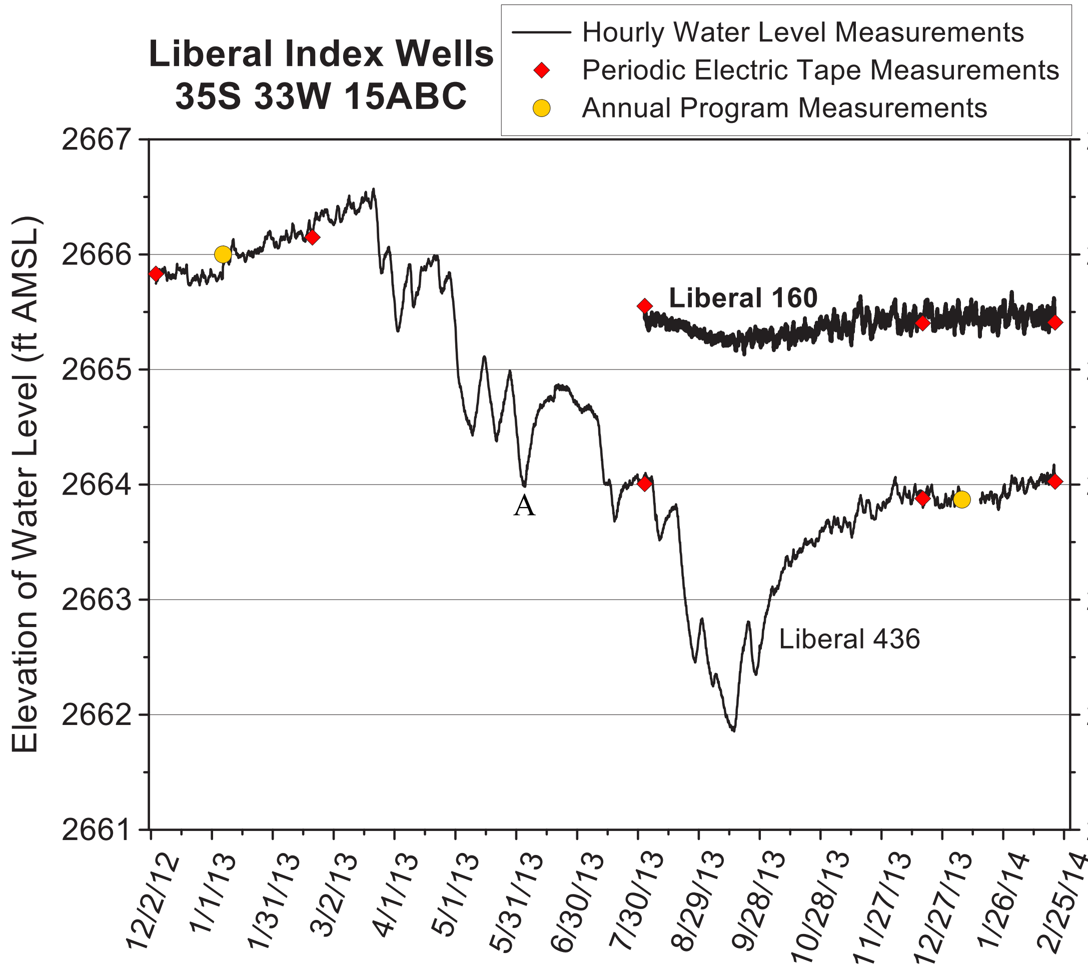

Figure 11—Hydrographs of Liberal index wells—total data run to 2/20/14. The Liberal 436 plot corresponds to the left y-axis; a water-level elevation of 2,664.0 ft corresponds to a depth to water of 156.0 ft below land surface (lsf); the top of the 10-ft screen is 426 ft below lsf (elevation of 2,395 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 126.0 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). A defined in text. Interruption of continuous monitoring at the Liberal 436 index well shortly after the 2014 annual program measurement discussed in text.

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

		2013
Minimum Water-Level Elevation	Feet	2,661.8
	Date	9/15/13
Maximum Observed Recovery Elevation	Feet	2,666.6
	Date	3/21/13
Apparent Recovery	Feet	NA
Annual Change in Maximum Observed Recovery	Feet	NA
Recovery Season	Start	NA
	End	3/22/13
	Length (Days)	NA
Pumping During Recovery Season	Length (Days)	NA
Length of Pumping Season	Days	188.1
2-mi Radius Water Use[a]	Irrigated Acres	NA
	Total (ac-ft)	NA
	Irrigation Use Only (ac-ft)	NA
	Use per Irrigated Acre (ft)	NA

[a]2012 Irrigated Acres—0/359 (KS/OK), Total—1280.06 ac-ft, Irrigation use only—0/675 ac-ft, Use per Irrigated Acre – 0/1.88 ft

3.2.1.2.2 Measurement Comparisons

Table 12—Annual water-level measurement[a] comparison with transducer measurements, Liberal 436 index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/6/2013	2,666.00	NA	Steel tape
	2,665.88[c]	NA	Transducer
	2,665.97[d]	NA	Transducer
1/5/2014	2,663.87	-2.13 (NA)	Steel tape
	2,663.87[c]	-2.01	Transducer
	2,663.90[d]	-2.07	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.

3.2.1.3 Hugoton Site

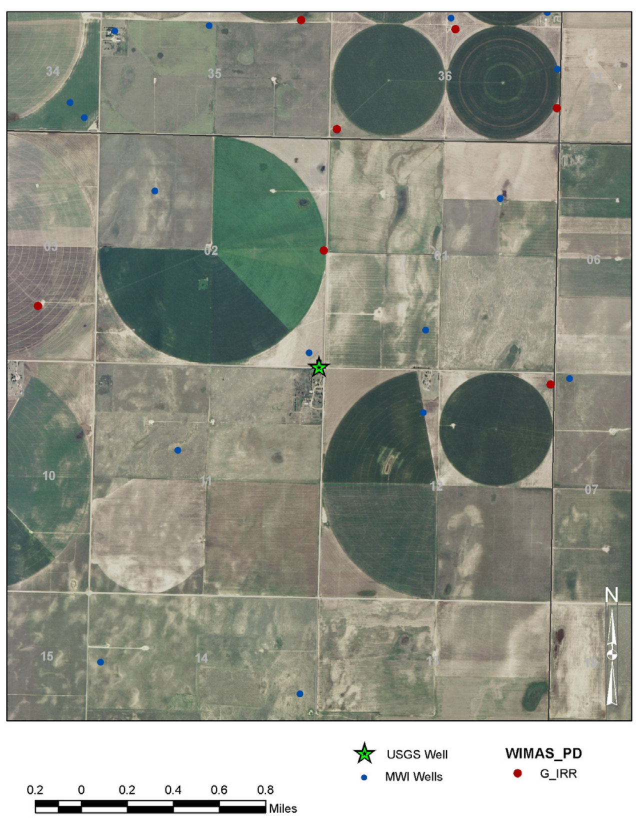

Figure 12—Aerial view of Hugoton site (green star) and points of diversion in the area.

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 and nearby irrigation wells. 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, 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. The 2012 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 2012 water use).

3.2.1.3.1 Hydrograph and General Observations

The hydrographs for the two Hugoton index wells are shown in fig. 13 and the general characteristics are summarized in table 13. 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 2013 pumping season began on March 8 with a limited amount of pumping, most likely for winter wheat and pre-irrigation; widespread pumping in the area began on April 5. Widespread pumping continued through August 31, although sporadic pumping occurred in the area until November 5. 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 (80 ft of drawdown at peak of 2013 pumping season) indicate that that interval is more heavily stressed, while the elevation difference indicates that the pumping induces downward flow from the shallower interval. The 2013–14 recovery season was still continuing at the time of this report (February 20, 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 (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 (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 2014 at both wells are recovering to near 2,925, a loss of about 45 ft in 14 years (>3 ft/yr); the water level in the closest annual measurement program well (T. 34 S., R. 37 W., 35 AAD 01) declined 53 ft over this same time period.

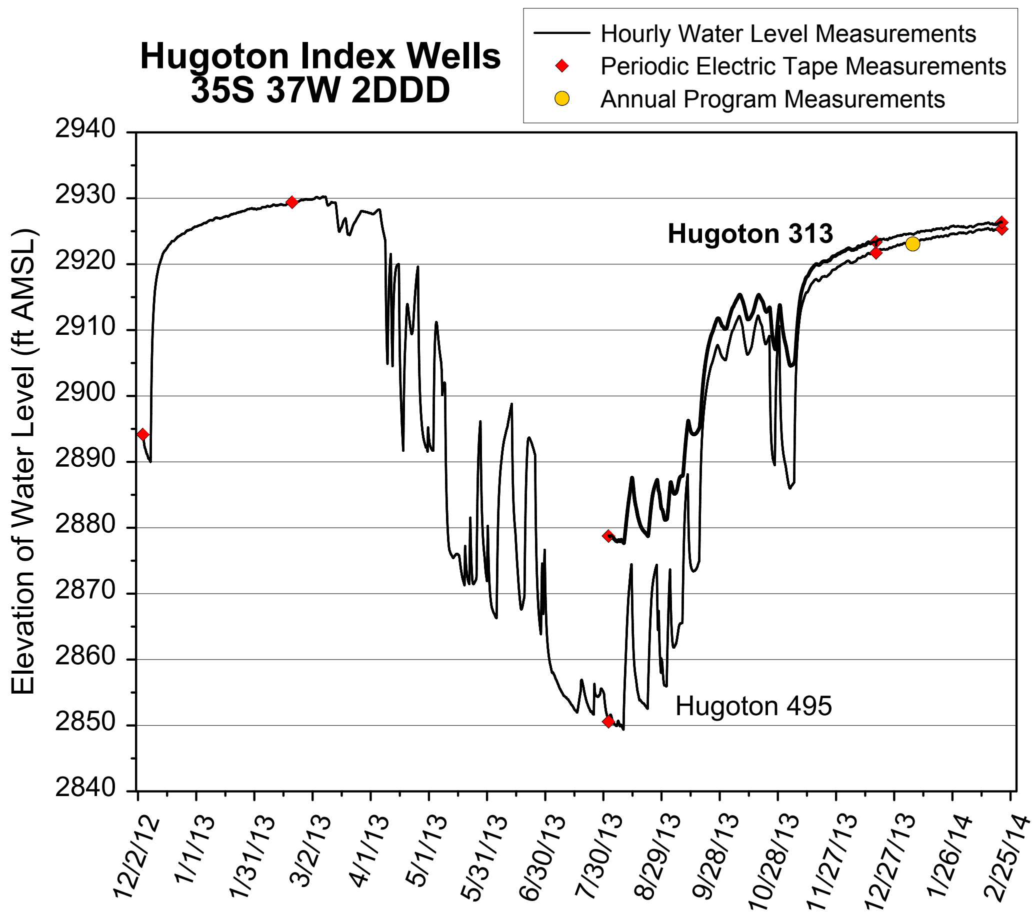

Figure 13—Hydrographs of Hugoton index wells—total data run to 2/20/14. A water-level elevation of 2,930.0 ft corresponds to a depth to water of 170.0 ft below land surface (lsf). For the Hugoton 495 well, the top of the 10-ft screen is 485 ft below lsf (elevation of 2,615 ft). For the Hugoton 313 well, the top of the 10-ft screen is 303 ft below lsf (elevation of 2797 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
Minimum Water-Level Elevation	Feet	2,849.4
	Date	8/9/13
Maximum Observed Recovery Elevation	Feet	2,930.2
	Date	3/7/13
Apparent Recovery	Feet	NA
Annual Change in Maximum Observed Recovery	Feet	NA
Recovery Season	Start	NA
	End	3/8/13
	Length (Days)	NA
Pumping During Recovery Season	Length (Days)	NA
Length of Pumping Season	Days	153.6
2-mi Radius Water Use[a]	Irrigated Acres	NA
	Total (ac-ft)	NA
	Use per Irrigated Acre (ft)	NA

[a]2012 Irrigated Acres—2,700, Total—3,828.39 ac-ft, Use per Irrigated Acre—1.42 ft

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 (NA)	Steel tape
	2,923.18[c]	-3.19	Transducer
	2,923.27[e]	-3.10	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 2013–14 change to be calculated.

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

3.1.1.4 Rolla Site

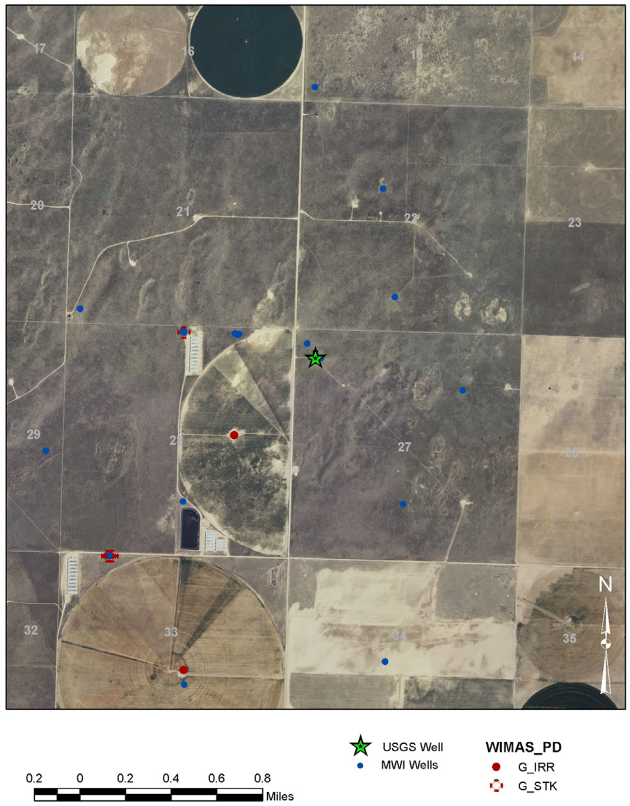

Figure 14—Aerial view of Rolla site (green star) and points of diversion in the area.

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 and the nearby irrigation and stock wells. 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 366 index well).

3.2.1.4.1 Hydrograph and General Observations

The hydrograph for the Rolla index well is shown in fig. 15 and the general characteristics are summarized in table 15. The relatively large (up to 0.7 ft) amplitude fluctuations superimposed on the water levels (particularly evident during recovery periods) 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).

The 2013 pumping season began on March 9 and ended on September 12. The hydrograph indicates that water levels are affected by both local and more regional pumping influences. Early in the irrigation season, pumping appears to have been primarily at wells at some distance from the index well. There was little pumping during much of April, most likely to allow planting of summer crops. A nearby well began pumping on May 13 (A on fig. 15) and continued for the next 46 days. Pumping at more distant wells continued until the end of the irrigation season on September 12. The 2013–14 recovery season was still continuing at the time of this report (February 20, 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 2014 is recovering to near 3,189.5, a loss of about 7.5 ft in 14 years (>0.5 ft/yr); the water level in the closest annual measurement program well (2 miles south—T. 35 S., R. 40 W., 03 BBB 03 and 02 [well redrilled in 2003]) declined 8.9 ft over this same time period.

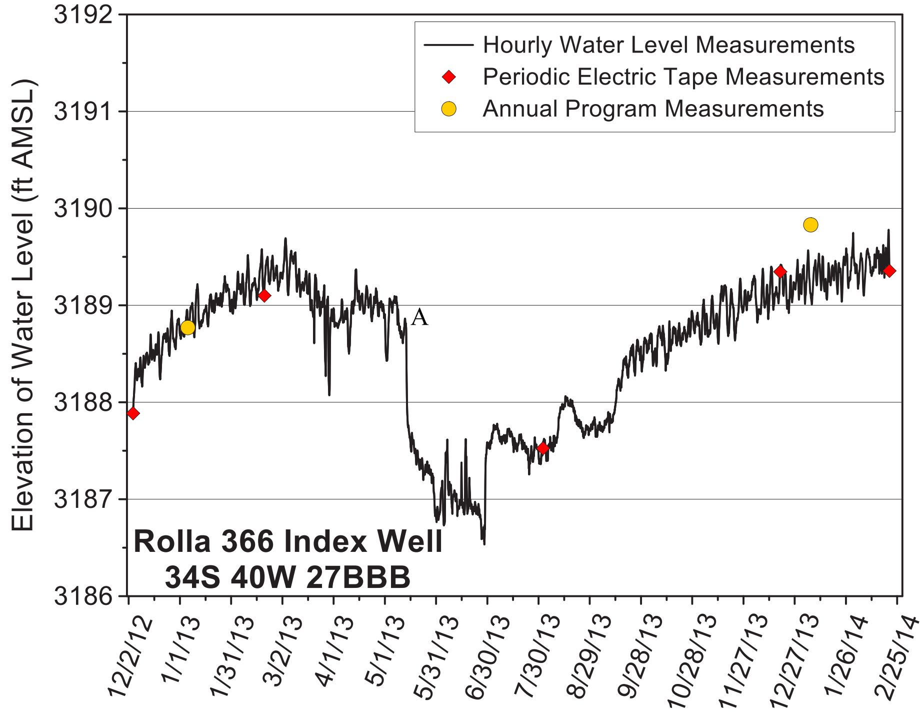

Figure 15—Rolla 366 index well hydrograph—total data run to 2/20/14. A water-level elevation of 3,188 ft corresponds to a depth to water of 187 ft below land surface (lsf). The top of the 10-ft screen is 356 ft below lsf (elevation of 3,019 ft) and the bottom of the aquifer is 399 ft below lsf (elevation of 2,976 ft). A defined in text; suspect 2014 annual program measurement.

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

		2013
Minimum Water-Level Elevation	Feet	3,186.5
	Date	6/28/13
Maximum Observed Recovery Elevation	Feet	3,189.7
	Date	3/3/13
Apparent Recovery	Feet	NA
Annual Change in Maximum Observed Recovery	Feet	NA
Recovery Season	Start	NA
	End	3/9/13
	Length (Days)	NA
Pumping During Recovery Season	Length (Days)	NA
Length of Pumping Season	Days	185.9
2-mi Radius Water Use[a]	Irrigated Acres	NA
	Total (ac-ft)	NA
	Irrigation Use Only (ac-ft)	NA
	Use per Irrigated Acre (ft)	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	3,189.83[e]	+1.06[e] (NA)	Steel tape
	3,189.08[c]	+0.21	Transducer
	3,189.28[d]	+0.46	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.

3.2.2 GMD1 Expansion Wells

Late in 2011, arrangements were made with landowners and GMD1 to install KGS pressure transducers in two old USGS recording wells in the area of the Scott index well (see fig. 4b); the sensors were installed on February 22, 2012. One of the new locations is 6.5 miles south of the Scott index well (henceforth, well SC-8) and the other is 22 miles to the west in Wichita County near Leoti (henceforth, well WH-1). The water columns were short in both SC-8 and WH-1, 16 feet and 10 feet, 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. No further discussion of well WH-1 will be provided in this report; we will seek a replacement well in 2014.

3.2.2.1 SC-8 Site

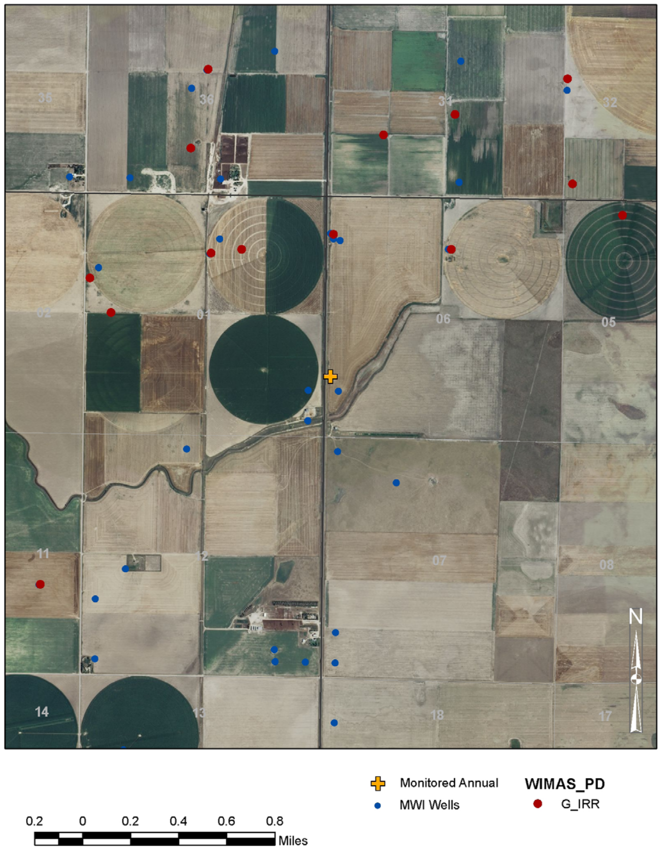

Figure 16—Aerial view of SC-8 site (yellow cross) and points of diversion in the area.

Figure 16 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 and nearby irrigation wells. 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 with the channel). A new irrigation well was installed in the field in which the well is located in the autumn of 2012. However, that field does not appear to have been irrigated during the monitoring period. The fields adjacent to the site on the west appear to be irrigated.

3.2.2.1.1 Hydrograph and General Observations

The complete hydrograph for the SC-8 well is displayed in fig. 17. The approximately two 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. 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, Whittemore, and Reboulet [2013] fig. 5 and related discussion). The relatively large (up to 1.0 ft) amplitude fluctuations super-imposed 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). As noted in the caption of fig.17, the well housing has shifted (tilted) at some point after commencement of monitoring. That shifting may have caused the transducer position and the reference position for manual measurements to change. Thus, little significance can currently be attached to the comparison between transducer and manual measurements. We will explore this issue further in 2014.

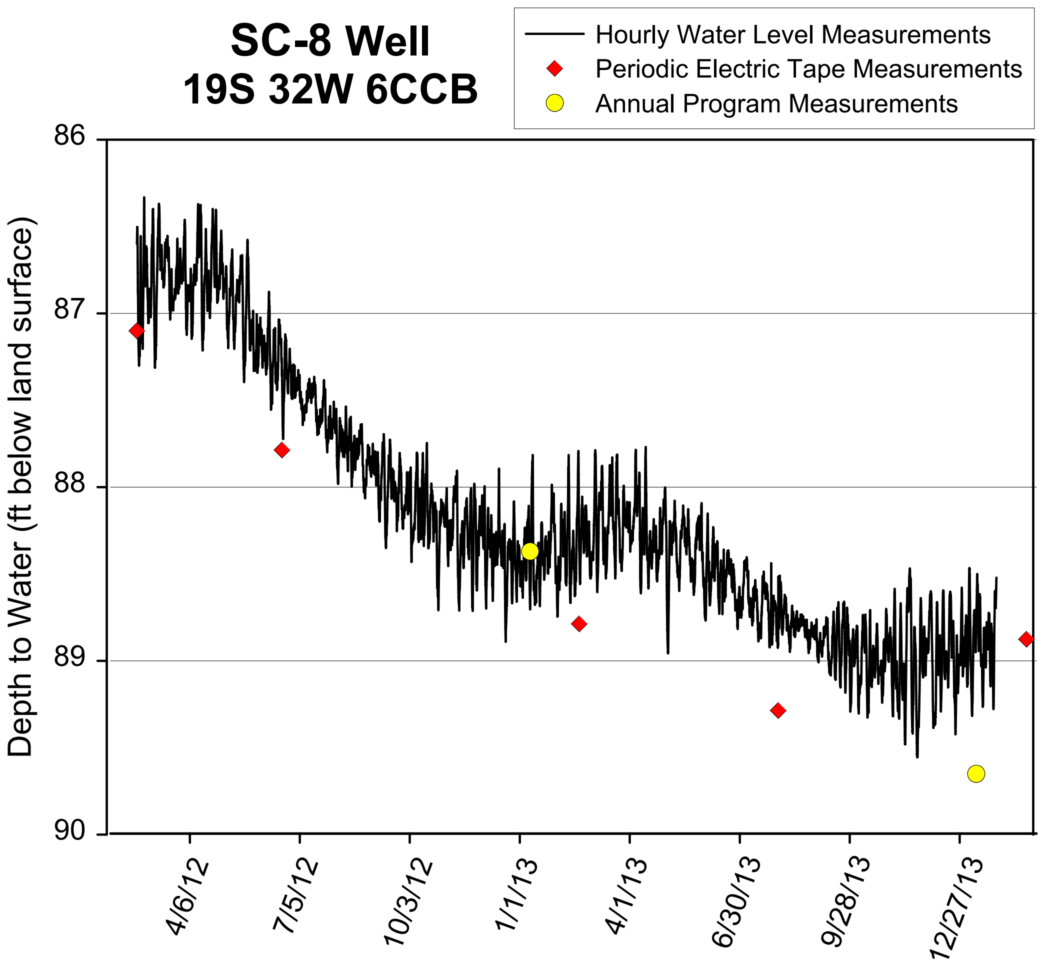

Figure 17—SC-8 well hydrograph—continuous data until sensor stopped on 1/26/14 as a result of a programming error. Well housing position has shifted during monitoring period; this shifting may have affected transducer position and the reference point for manual measurements, leading to a systematic difference between manual measurements and transducer readings. Bottom of well is approximately 102 ft below land surface.

3.2.3 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; and an additional well (TH11) was added to the network in the fall of 2010 (wells labeled “Monitored Transducer” on fig. 6). 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 17 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. Hydrographs from the Thomas index well and these three currently operating expansion wells are given in fig. 18. 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 2014.

Table 17—Installation date and other notes for currently operating Thomas County expansion wells.

Well		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 9/27/13–2/19/14+	Active irrigation well, sensor installed and removed each year by KGS and GMD 4 at land owner's request. Sensor not installed for the 2012–13 recovery. Sensor still in well at time of this report (2/19/14).
TH9	Retired Irrigation	DWR	11/5/09	Sensor removed 11/11 to 11/14/09 for well cap installation; operator error, data gap from 11/23/10 to 2/23/11 and 12/5/12 to 2/18/13. Otherwise operating normally.
TH10	Domestic	DWR	8/12/09	Unexplained break in data 6/22/10–9/15/10, otherwise operating normally.
TH11	Retired Irrigation	KGS	11/3/10	Sensor fitting failed sometime after 11/11/11 download, sensor pulled for repairs and replaced on 6/20/12. Appears to be operating normally.

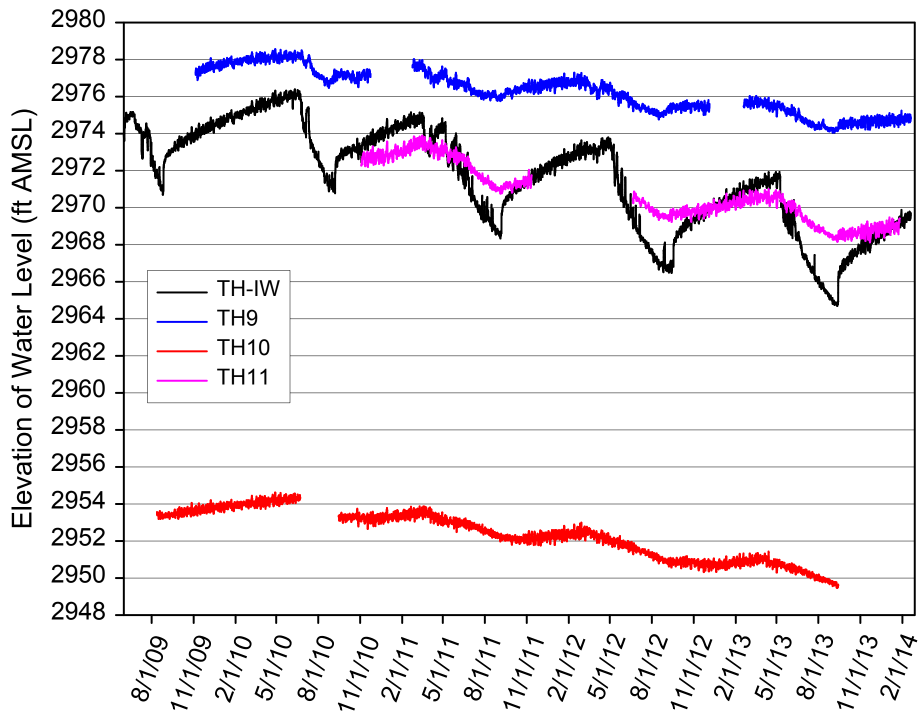

Figure 18—Hydrograph comparison from the Thomas index well and currently continuously operating Thomas expansion wells. The general water-level trend indicates west-to-east groundwater flow.

The hydrograph at well TH9 appears to be responding to many of the same pumping events as the Thomas index well (fig. 19). 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. 6]) in the TH9 hydrograph but are still clearly apparent. 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 2014.

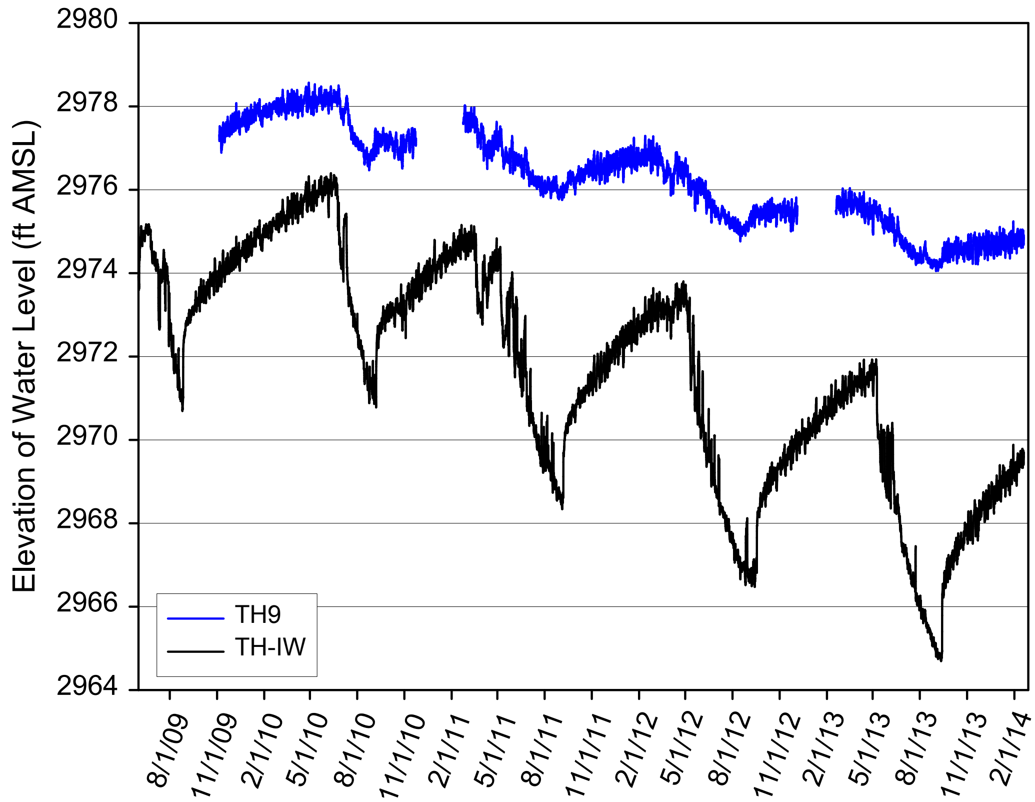

Figure 19—Hydrograph comparison of Thomas index well and expansion well TH9. TH9 is approximately 1.5 miles NE of the index well (0.75 miles north, 1.25 miles east).

The hydrograph at well TH11 also appears to be responding to many of the same pumping events as the Thomas index well (fig. 20), although the responses are again more subdued and smoothed. As with well TH9, 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), makes it difficult to assess if the well has recovered prior to the start of the next irrigation season. A more detailed analysis and interpretation of the well TH11 hydrograph will be pursued in 2014.

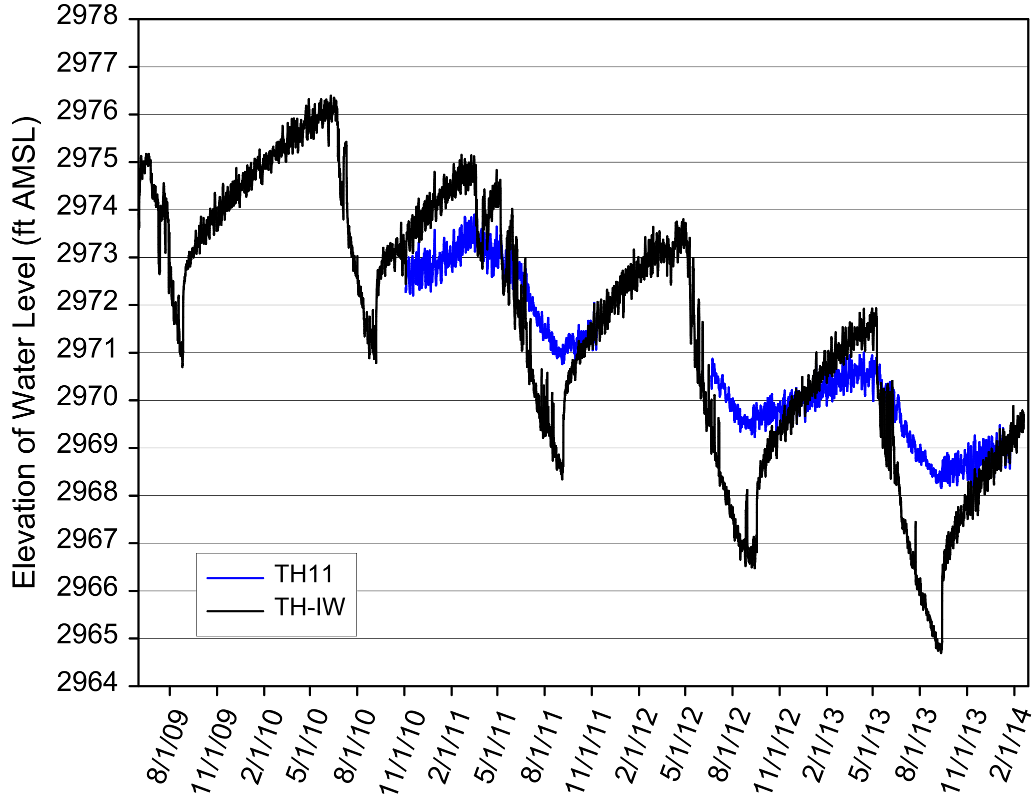

Figure 20—Hydrograph comparison of Thomas index well and expansion well TH11. TH11 is about 0.70 miles ENE of the index well (0.25 miles north, 0.75 miles east).

3.2.4 Haskell County Expansion Wells

In mid-February 2014, 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 the 2014 annual report.

3.2.5 Sheridan-6 Subunit Wells

We are collaborating with GMD4 on the interpretation of the water-level data obtained by GMD4 from the monitoring wells in the Sheridan-6 LEMA area. In 2012, we helped diagnose the source of anomalous fluctuations in the initial water-level data obtained from these monitoring wells. In 2014, we anticipate collaborating with GMD4 on the interpretation of the acquired data.

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 on correcting 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, while the impact of changes in barometric pressure has been shown to be large enough to be of practical significance at one of the original index wells (Thomas County) and at the expansion wells in the vicinity of the Scott and Thomas index wells. Given this finding and the expectation that this impact 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 (> 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 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 from the BRF. That initial work, which will be expanded in 2014, is briefly summarized in this section.

In previous annual reports and other publications by KGS scientists (e.g., Buddemeier et al., 2010; Butler et al., 2011), we have shown that the BRF is a useful time-domain tool for characterizing the relationship between barometric pressure and water levels. This function can be readily determined from water-level and barometric-pressure data using a regression convolution procedure implemented in the Excel-based program developed at the KGS (Bohling et al., 2011). Following on earlier work of Rasmussen and Crawford (1997) and Spane (2002), we have shown how the form of the BRF can be used to develop insights into subsurface conditions (Buddemeier et al., 2010). Based on previous work (Spane, 2002; Butler et al., 2011), it appears more quantitative information about the subsurface can be obtained from an analysis of a BRF calculated from field data using an analytical solution for water-level responses to changes in barometric pressure. For example, the BRF from a well in a confined aquifer can include information about the hydraulic connection between the well and the aquifer, the aquifer storage parameter, the degree of aquifer confinement (Butler et al., 2011), and the viability/existence of an annular seal across the overlying confining unit. The BRF from a well in an unconfined aquifer can provide information about the hydraulic connection between the well and the aquifer and the pneumatic diffusivity of the vadose zone. In both cases, changes in the BRF over time can provide information about changing conditions in the well (e.g., screen clogging leading to a reduction in the hydraulic connection between the well and the aquifer) and the vadose zone (e.g., changes in moisture conditions). In 2012 and 2013, we performed an initial assessment of the information that can be acquired from the BRF of a well in an unconfined aquifer using data from the Scott and Thomas index wells (Butler, Bohling et al., 2013). The Thomas County assessment is presented here.

The solid line in fig. 21 is the BRF determined from the winter 2009 recovery data (1/4/2009–3/9/2009) that was originally presented in the 2009 annual report (Buddemeier et al. [2010] figs. 3–5). The rapid rise to a value of more than 0.95 and then the steady fall toward zero are consistent with an unconfined aquifer overlain by a thick vadose zone that acts to significantly slow the downward transmission of the barometric pressure change at the land surface (Spane, 2002). In this case, it takes more than five days for the full extent of the imposed barometric pressure change to reach the water table (i.e. for the BRF to go to zero). The period before the BRF peak is largely a function of the hydraulic connection between the well and the aquifer (i.e. a function of the near-well hydraulic conductivity), while the period after the peak is largely a function of the speed with which the barometric pressure change is transmitted through the vadose zone (i.e. a function of the pneumatic diffusivity). Thus, a BRF model can be formulated that consists of a slug-test model to incorporate the mechanisms during the pre-peak period and a one-dimensional, vadose-zone pneumatic transmission model for the period after the peak. The summation (superposition) of these two models has been demonstrated by Spane (2002) using the Hvorslev (1951) slug-test model and the vadose-zone model of Weeks (1979). Hydraulic conductivity (K) is the unknown parameter in the Hvorslev model and the pneumatic diffusivity (α) is the unknown parameter in the Weeks model. Thus, the combination of these two models can be fit to the Thomas index well BRF to estimate K and α for that setting. The dashed line in fig. 21 is the best-fit model to the BRF data; the resulting K value (0.1 ft/d), which is quite low for an aquifer, indicates that the hydraulic connection between the well and the aquifer is likely impaired due to insufficient well development; the α value (0.2 ft^2/s) is consistent with estimates obtained by Weeks (1979) for the HPA vadose zone near Lubbock, Texas. We anticipate that the use of field-determined BRFs to estimate K and α will become a common approach in the future. In particular, we believe that this could be a powerful tool to assess changes in near-well K through time (well deterioration) and, perhaps, changing vadose-zone properties due to water-table declines or changing moisture conditions. We will explore the potential of this approach further in 2014 by redeveloping the Scott and Thomas index wells to assess how the BRF-determined K changes with development.

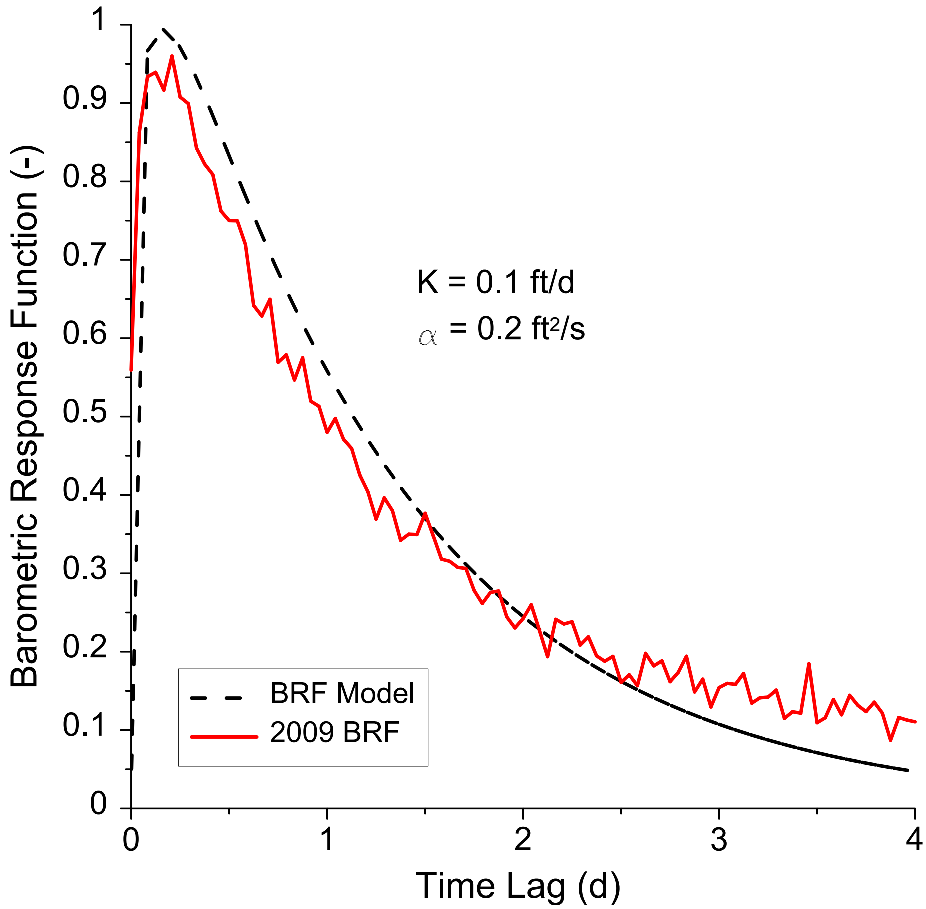

Figure 21—Barometric response function (BRF) calculated for the Thomas index well using winter 2009 recovery data (depth to water varied from 214.6 to 213.1 ft during the time interval used in the analysis) with the best-fit BRF model. BRF model is the summation of the Hvorslev (1951) and Weeks (1979) models as explained in text; K and α defined in text.

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 three 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; Butler, Whittemore, Bohling et al, 2013) and a 2013 paper in the journal *Groundwater* (Butler, Stotler, Whittemore, and Reboulet, 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 described in the previous paragraph and did not change as a result of data from the 2013 pumping season. 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 39 ft in height at the maximum observed drawdown for 2013 (water column height was likely considerably less in the immediate vicinity of the irrigation wells). This height was similar to that at the maximum observed drawdown in 2011, but 3 ft greater than that in 2012; the increase over 2012 is likely a result of the court-ordered shutdowns described in section 3.1.1. It is currently unknown whether any leakage from the underlying Dakota aquifer will mitigate the rate of decline 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 relatively more water from the Dakota as the HPA becomes depleted in the area of the Haskell index well as discussed in Section 6.

Scott County

The 2013 water-level data helped refine the assessment of conditions in the vicinity of the Scott index well. Figure 22A, 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), and F (2013) on fig. 5. Although these data are relatively "noisy" as a result of pumps cutting on and off, a consistent picture still emerges for all six 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). Before this year, we tentatively interpreted the remaining portions of the plot as being affected by radial flow and aquifer boundaries as shown in fig. 22a. However, the data collected during the 2011 to 2013 pumping seasons have enabled us to reinterpret those portions of the plot. Figure 22b is a plot of drawdown versus the logarithm of duration of pumping for pumping periods beginning at D (2011) and F (2013) on fig. 5 (2012 pumping period data are for shorter interval so not plotted here). The coincidence of the 2011 and 2013 pumping period data indicates that the water-level changes are produced by pumping at the same well at essentially the same rate. In addition, the coincidence and the relatively low noise level of the data reveal a continuous transition from the delayed-drainage period to the large-time response that was original identified as a boundary deviation. The continuous transition, the semilog linear response at large times, and the distance to the nearest pumping well (> 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 estimate its pumping rate, we can obtain estimates of transmissivity and specific yield (drainable porosity) from the data in fig. 22b, 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, Whittemore, and Reboulet, 2013).

The 2009 and 2010 pumping period data in fig. 22a are parallel to but earlier in time than the 2011–2013 data. 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 23 shows the result after 2009 pumping times have been multiplied by 1.56 (* on fig. 23—if the first explanation is valid, the distance to the pumping well in 2009 is 0.8 that of the 2011–2013 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. 23—if first explanation is valid, distance to 2010 pumping well is about 0.9 that of the 2011–2013 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 2009–2013 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 has 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 2014.

The 2012 annual report (Butler, Whittemore, Bohling et al., 2013) presented an assessment of recovery data from two complete recovery seasons (2009–10, 2011–12) and one continuing recovery season (2012–13). Figure 24 presents an update of the recovery assessment with the complete 2012–13 recovery season and the continuing 2013–14 recovery (September 14 was used as the start of recovery for the 2013–14 recovery while November 11 was used as the start of the 2012–13 recovery because of intermittent pumping in September and October). The water use in 2009 and 2012 differed by about 22% (largest use difference during this period); durations of the 2009–10 and 2012–13 pumping periods differed by about 20%. Water-use data for 2013 are not yet available. The interpretation of the similarity of the recovery plots for three complete and one continuing recovery seasons, which hints at the possibility of inflow similar to that at the Thomas index well, will be the focus of further work in 2014.

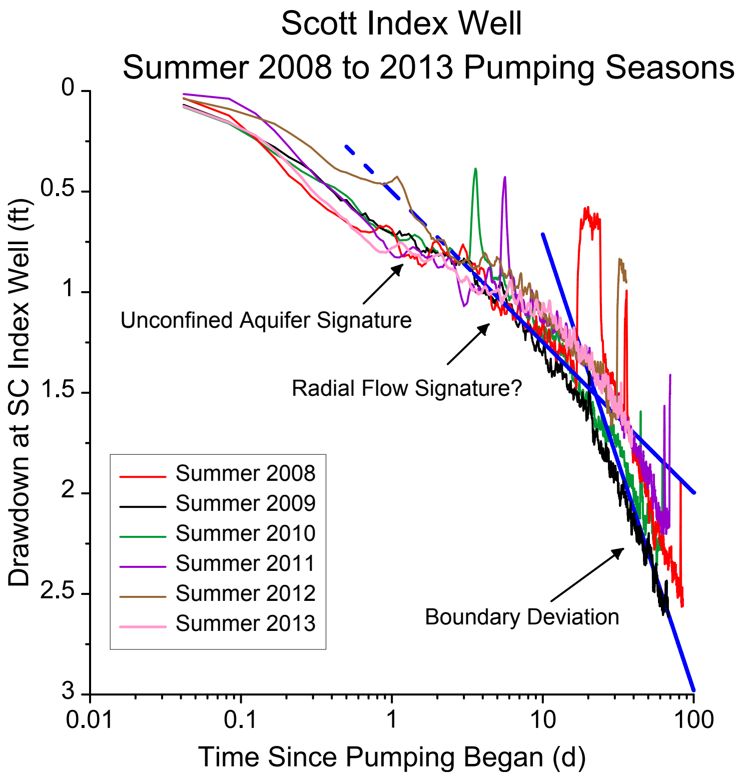

Figure 22a—Drawdown in the Scott index well versus the logarithm of pumping time for pumping periods beginning at points A (2008), B (2009), C (2010), D (2011), E (2012), and F (2013) on fig. 5.

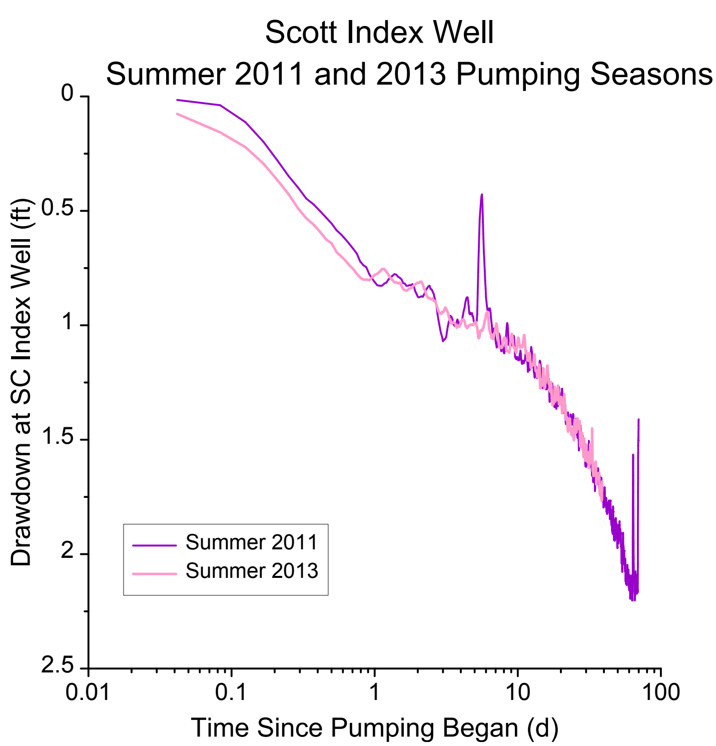

Figure 22b—Drawdown in the Scott index well versus the logarithm of pumping time for 2011 and 2013 pumping periods beginning at points D and F, respectively, on fig. 5.

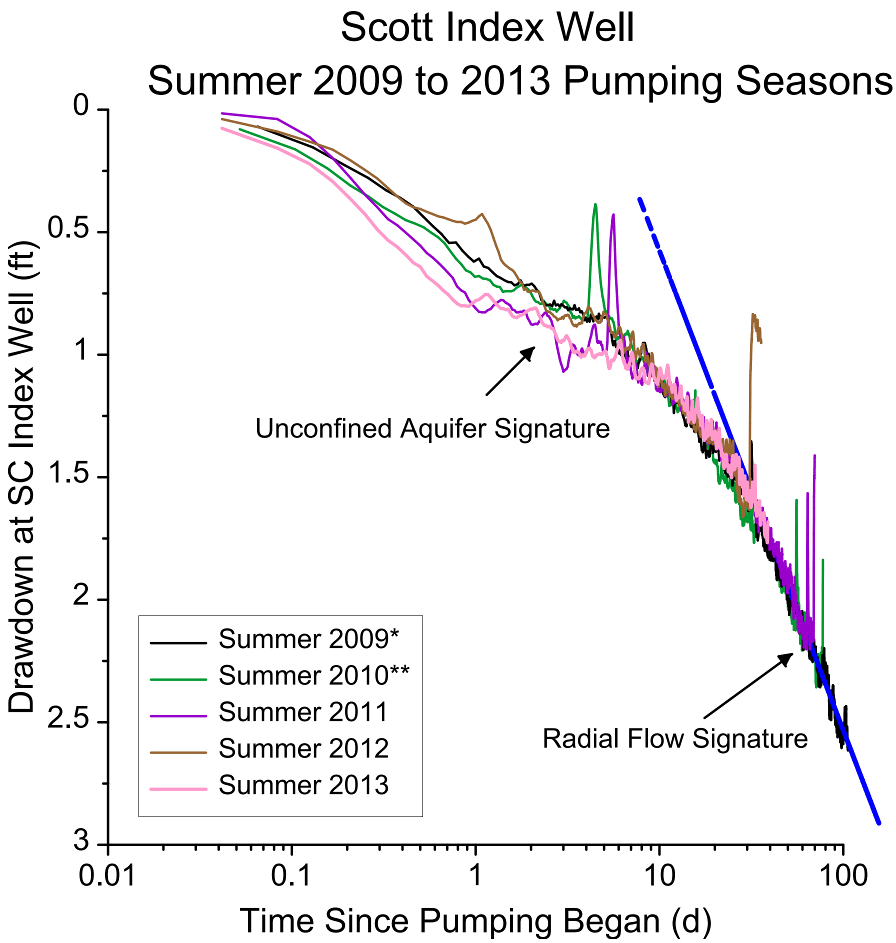

*Figure 23—Drawdown in the Scott index well versus the logarithm of pumping time for pumping seasons beginning at points B (2009), C (2010), D (2011), E (2012), and F (2013) on fig. 5. * and **—pumping times modified as explained in text. 2008 pumping period not plotted because of noise produced by pumping cutoffs and restarts.*

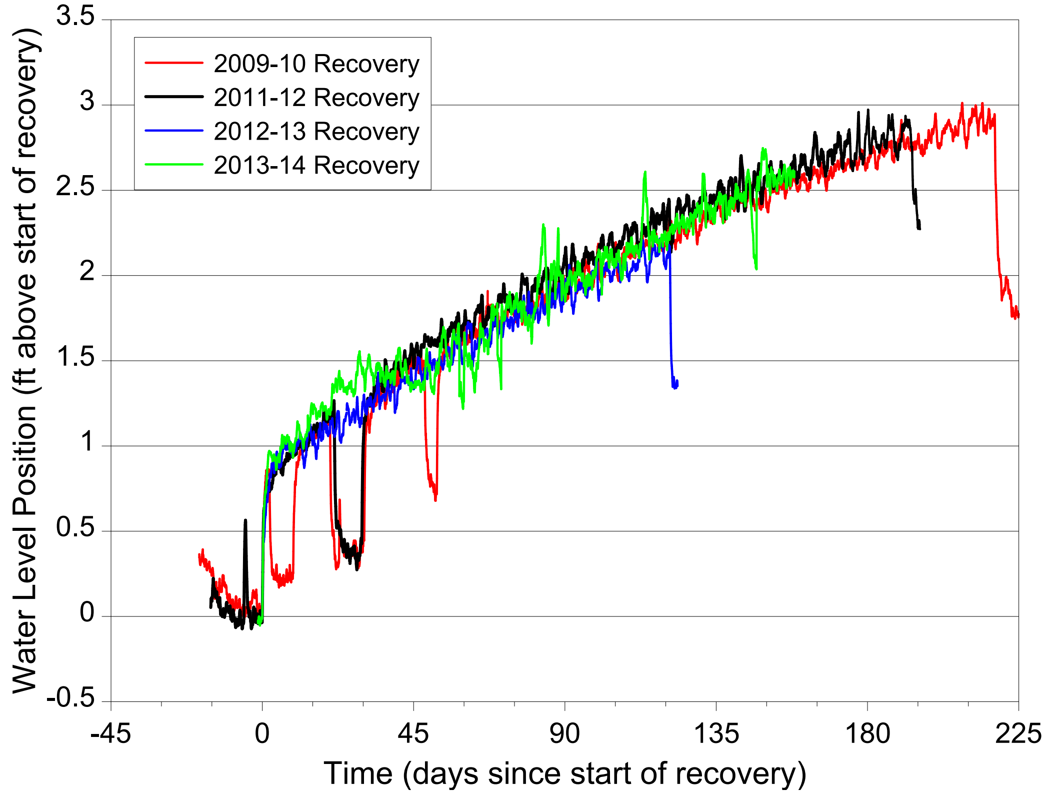

Figure 24—Water levels in the Scott index well for the 2009–10, 2011–12, 2012–13, and 2013–14 recovery periods. Recovery for the 2009–10, 2011–12, 2012–13, and 2013–14 recovery periods calculated from points G, H, I, and J, respectively, on fig. 5.

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 2013 data.

An assessment of three complete and one continuing recovery seasons was presented in the 2012 annual report. Figure 25 presents an update of the recovery assessment with the results for the complete 2008–09, 2009–10, 2011–12, and the 2012–13 recovery seasons and the still continuing 2013–14 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 was essentially the same. The agreement between the superimposed recovery plots on fig. 25 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 must be primarily responsible for the water-level changes during recovery. A similar coincidence is seen when the 2007–08 and 2010–11 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 importance of the inflow into the HPA at the Thomas site can be demonstrated through a simple water-balance calculation using the following equation (Butler, Stotler, Whittemore, and Reboulet, 2013):

$$WU = S_y A_s \Delta s_{is}$$

where WU is the total water use during the irrigation season [L^3], S_y is the specific yield of the unconfined aquifer [-], A_s is the aquifer area [L^2], and Δs_{is} is the annual water-level change [L].

For the first three complete pumping seasons monitored at the Thomas index well, water levels were relatively stable from year to year (fig. 7). The annual withdrawals from the HPA in this vicinity thus appear to be balanced by the inflow. Given the average reported water use for the Thomas site over this period (average of 2008–10 pumping seasons is 2,333 ac-ft for the area with a 2-mile radius centered on the site) and a rate of water-level change of about 3.3 ft /yr estimated from the rate of recovery between days 135 and 270 on fig. 25, the mass balance equation can be used to calculate a S_y of 0.088, which appears plausible for the sediments in the vicinity of the water table at the Thomas site. Although the inflow appears to be balancing the withdrawals over the 2008–10 pumping seasons, it does not with higher rates of pumping. The same mass balance can be performed using the water use for 2011 and 2012 (3,299 ac-ft and 3,683 ac-ft, respectively). In these cases, annual declines in water level of 1.4 ft and 1.9 ft, respectively, are calculated for the Thomas index well, which are consistent with the measured 2011–12 and 2012–13 declines in the maximum observed recovery of 1.4 ft and 1.9 ft, respectively (table 6). The 2012 water use was the largest during the monitoring period and close to the average water use for the decade preceding the monitoring period (3,729 ac-ft); a return to that average use would produce an annual water-level decline exceeding 1.9 ft.

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 the 2011 annual report; further discussion is presented in Section 8 of this report.

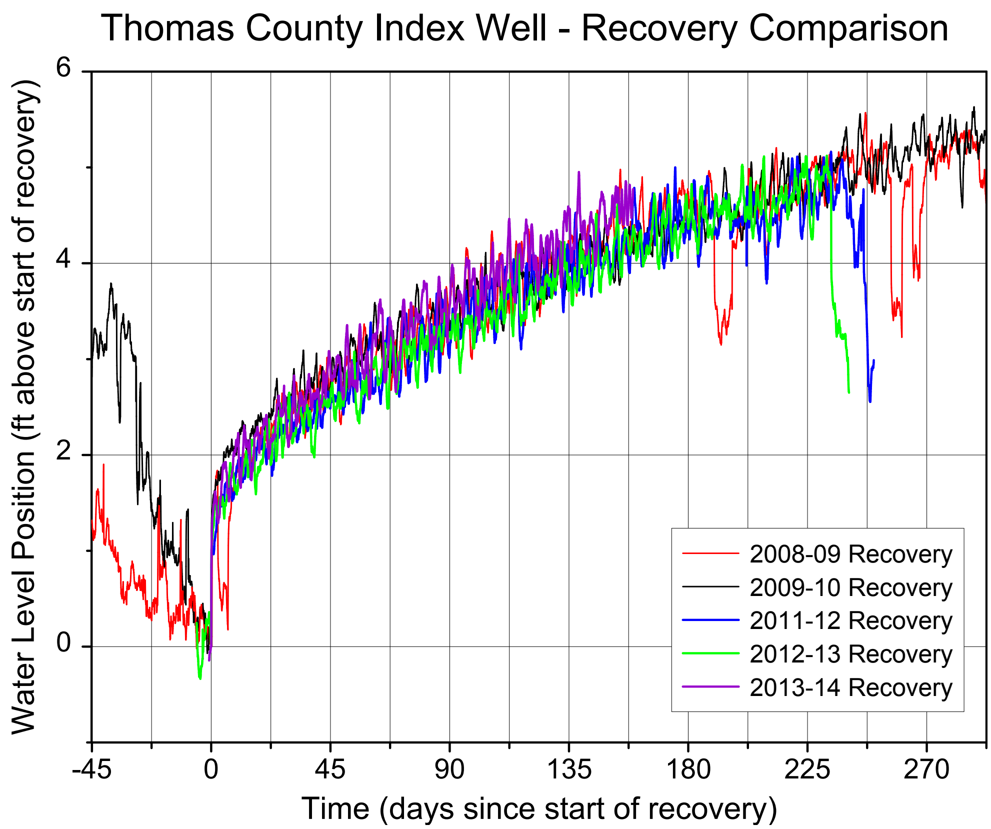

Figure 25—Water levels in the Thomas County index well for the 2008–09, 2009–10, 2011–12, 2012–13, and 2013–14 recovery periods. Recovery for the 2008–09, 2009–10, 2011–12, 2012–13, and 2013–14 recovery periods calculated from points A, B, C, D, and E, respectively, on fig. 7. Recovery period for 2010–11 not included because of pumping during the early portions of that period.

4.3 Identification of Hydraulic Conditions from Hydrograph Inspection

An important objective for the index well program has been to assess what insights about subsurface conditions can be gleaned from a visual inspection of a well hydrograph. In 2013, significant progress was made on assessing the nature of hydraulic conditions (unconfined versus confined) in the screened interval of a well from a hydrograph inspection. That progress will be briefly summarized here.

In western Kansas, portions of the HPA behave as a confined aquifer and portions behave as an unconfined aquifer. When very large pumping-induced drawdown is observed at some distance from the closest pumping well (e.g., figs. 3 and 13), it is clear that the HPA in that vicinity is acting as a confined aquifer. Similarly, when water-level fluctuations of up to a foot are observed during the recovery period when no pumping is occurring (e.g., figs. 7, 15, and 17), it is clear that the HPA in that vicinity is acting as an unconfined aquifer. However, in cases where drawdown during the irrigation season and water-level fluctuations during recovery are relatively small (e.g., figs. 5, 9, and 11), it can be more difficult to assess whether the HPA is confined or unconfined in that vicinity.

One important clue into the hydraulic conditions in the screened interval is provided by how water levels respond to the commencement and cessation of pumping. Figure 26 is an expanded view of the major portion of the 2013 pumping season at the Rolla 366 index well (see fig. 15 for complete record). Note that the rapid drop in water level after the commencement of pumping at a nearby well on May 13 (A) is followed immediately by an abrupt change in the rate of drawdown (B). That pattern is repeated in the reverse direction after the cessation of pumping at the nearby well on June 28; a rapid rise in water level (C) is followed by an abrupt break in the rate of water-level change (D). That pattern of a rapid fall or rise in water level followed immediately by an abrupt break in the rate of water-level change is the hydrograph expression of the typical water-level response to the commencement and cessation, respectively, of pumping in an unconfined aquifer (e.g., fig. 9-2 in Batu [1998]). In unconfined systems, the aquifer initially responds as a confined system in which water is released from compressible storage (storage release characterized by the specific storage parameter). This short initial period is followed by a transition to an unconfined aquifer response, i.e. water is released through pore drainage (storage release characterized by the specific yield parameter). This "dual" storage behavior is clearly observed during pumping-test analyses using log-log or semilog plotting formats. In the linear plotting format of hydrographs, this behavior produces a rapid fall or rise of water level followed immediately by an abrupt break in the rate of water-level change. Upon closer examination of the index well hydrographs, this behavior can be clearly observed in the Scott County index well (fig. 5—see rapid drops and slope breaks following commencement of pumping at D, E, and F) and the Cimarron 210 index well (fig. 9—see abrupt break in rate of water-level change at A), among others. This behavior is particularly well displayed in the recovery plots for the Scott County index well (fig. 24) and the Thomas County index well (fig. 25). When this response is observed at an index well, it is an indication that the aquifer is behaving as an unconfined system between the nearby pumping wells and that index well. As water levels continue to decline, it is possible that the hydraulic connection between the pumping wells and the index well will be impaired by the presence of units of low hydraulic conductivity. In that case, it is likely that the index-well hydrograph will no longer exhibit the unconfined aquifer response to the commencement and cessation of nearby pumping.

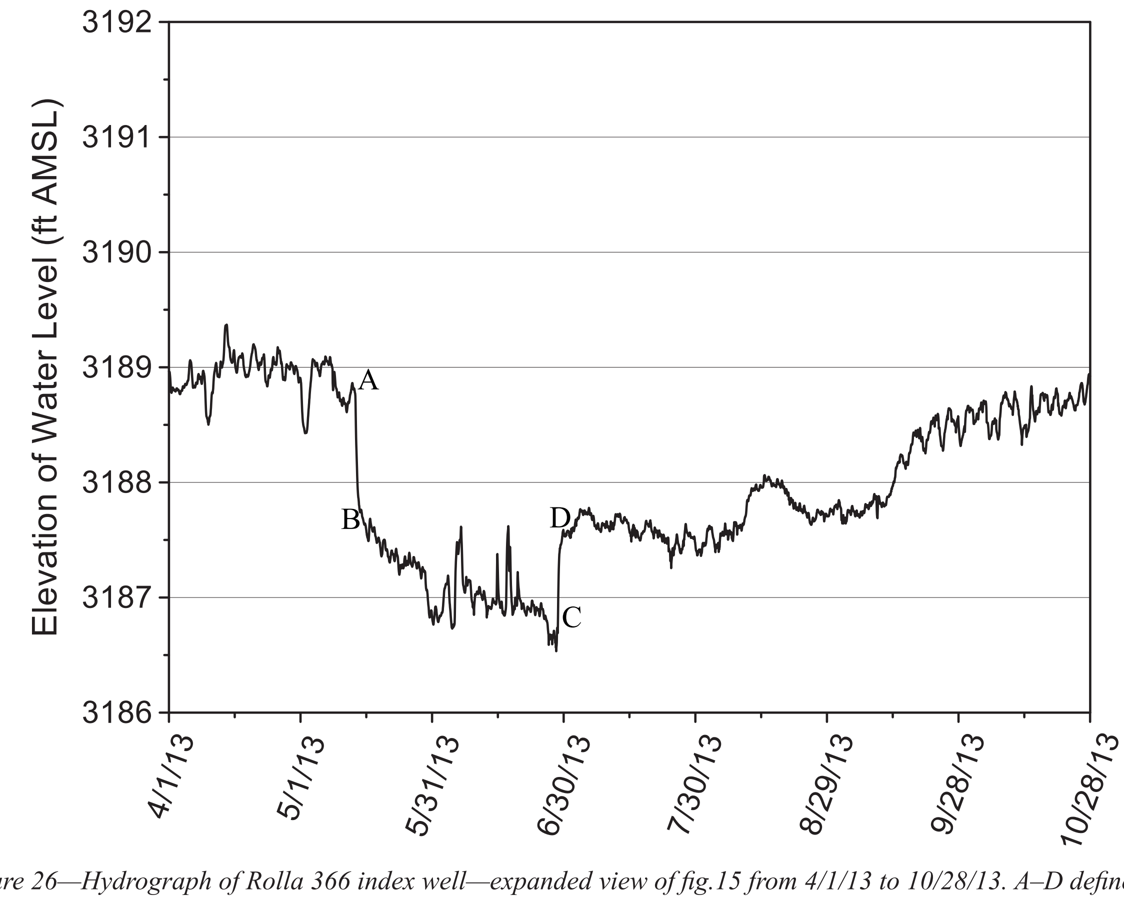

Figure 26—Hydrograph of Rolla 366 index well—expanded view of fig.15 from 4/1/13 to 10/28/13. A–D defined in text.

The hydrograph expression of pumping-induced responses in a confined aquifer is markedly different from that in an unconfined system. Figure 27 is an expanded view of the major portion of the pumping season at the Liberal 436 index well. Note the continuity of the water-level declines over the nine-day period following commencement of pumping at a nearby well on August 18 (interval A–B) and that of the water-level rises over the six-day period following the cessation of pumping at a nearby well on September 15 (interval C–D); a similar continuity in water-level rises occurs following cessation of pumping for the irrigation season on September 26 (E). This continuity of water-level declines or rises in response to commencement or cessation, respectively, of pumping is the hydrograph expression of the typical pumping-induced water-level response in a confined aquifer (e.g., fig. 4.3b of Batu [1998]).

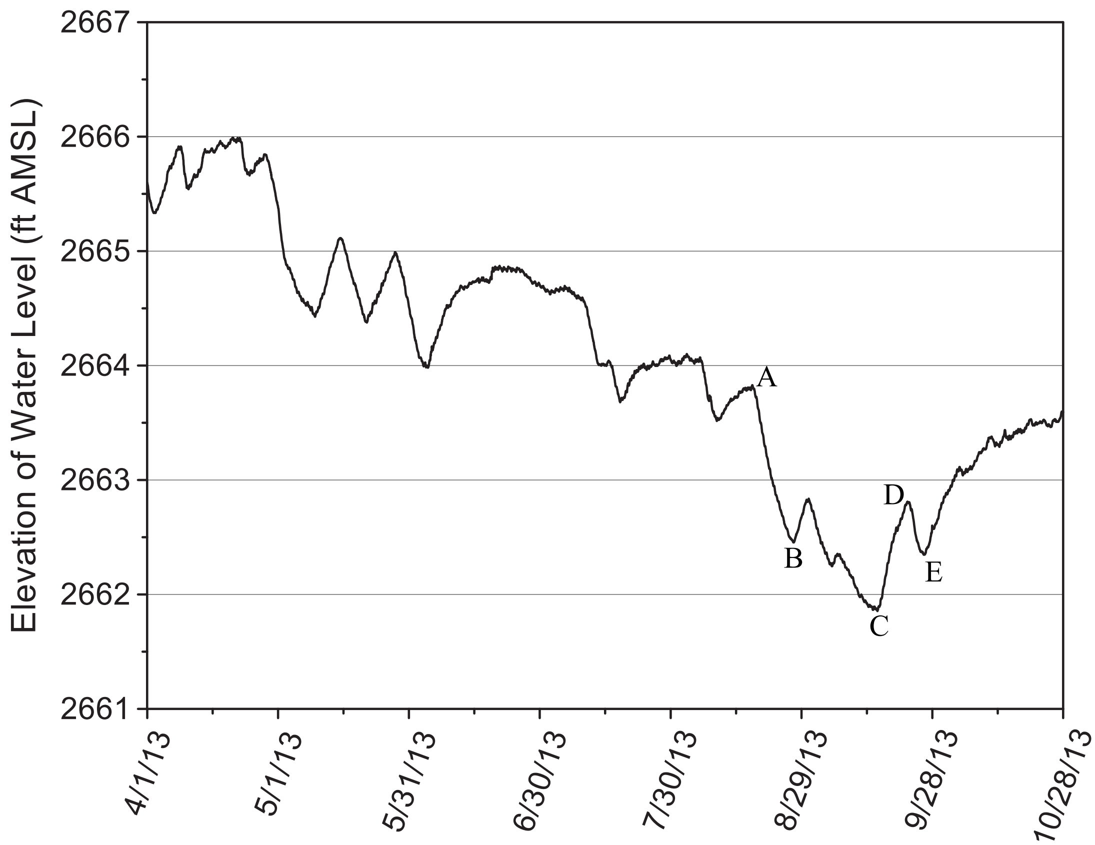

Figure 27—Hydrograph of Liberal 436 index well—expanded view of fig. 11 from 4/1/13 to 10/28/13. A–E defined in text.

Figures 26 and 27 illustrate the end members of the continuum from unconfined to confined conditions. When the hydraulic connection between nearby pumping wells and an index well is affected by intervening intervals of low hydraulic conductivity, interpretation of hydraulic conditions through hydrograph inspection may be difficult. Even in that case, however, important practical insights about subsurface conditions can be gained if the nature of pumping-induced responses at the index well has changed with continued water-level declines. In 2014, we will continue to investigate the insights that can be gained from a hydrograph inspection.

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 by the annual 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 would be valuable for management purposes. This section describes project efforts in that regard.

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, National Drought Mitigation Center; Heim, 2002; Logan et al., 2010; National Climatic Data Center). The PDSI is a monthly index calculated using precipitation, soil moisture, potential evapotranspiration, and other factors important to plant growth (Palmer, 1965). The Palmer Z index is also a monthly index involving procedures related to those used to determine the PDSI, but it was developed to evaluate short-term moisture conditions in crop-producing areas; the PDSI, in comparison, was developed to monitor long-term wet and dry spells. The SPI was developed to quantify precipitation deficits and surpluses for a variety of time scales of relevance for water resources (McKee et al., 1993). An SPI value is normalized by the long-term precipitation record for a particular area (e.g., climatic division).

5.3 Characterization of Climate Since Installation of Index Wells

The index wells were installed in 2007 and provide annual records for complete calendar years from 2008 to the present. The persistent climatic conditions during this period as represented by monthly values of the PDSI changed from near normal in 2008 across the three western climatic divisions (coinciding with GMDs 4, 1, and 3) to wet in 2009 (fig. 28). Wet conditions continued through 2010 and 2011 in northwest Kansas (GMD4), but changed to dry at the end of 2010 in west-central (GMD1) and southwest (GMD3) Kansas. In west-central Kansas, the dry weather persisted until the latter part of 2011, when more rainfall brought the climate to near normal during the winter of 2011–2012. Severe drought started in the summer of 2011 in southwest Kansas and in the summer of 2012 in west-central and northwest Kansas. The long-term condition of drought continued until the end of 2013 in the three western climatic divisions, with some recovery towards normal conditions during the fall of 2013 in southwest Kansas.

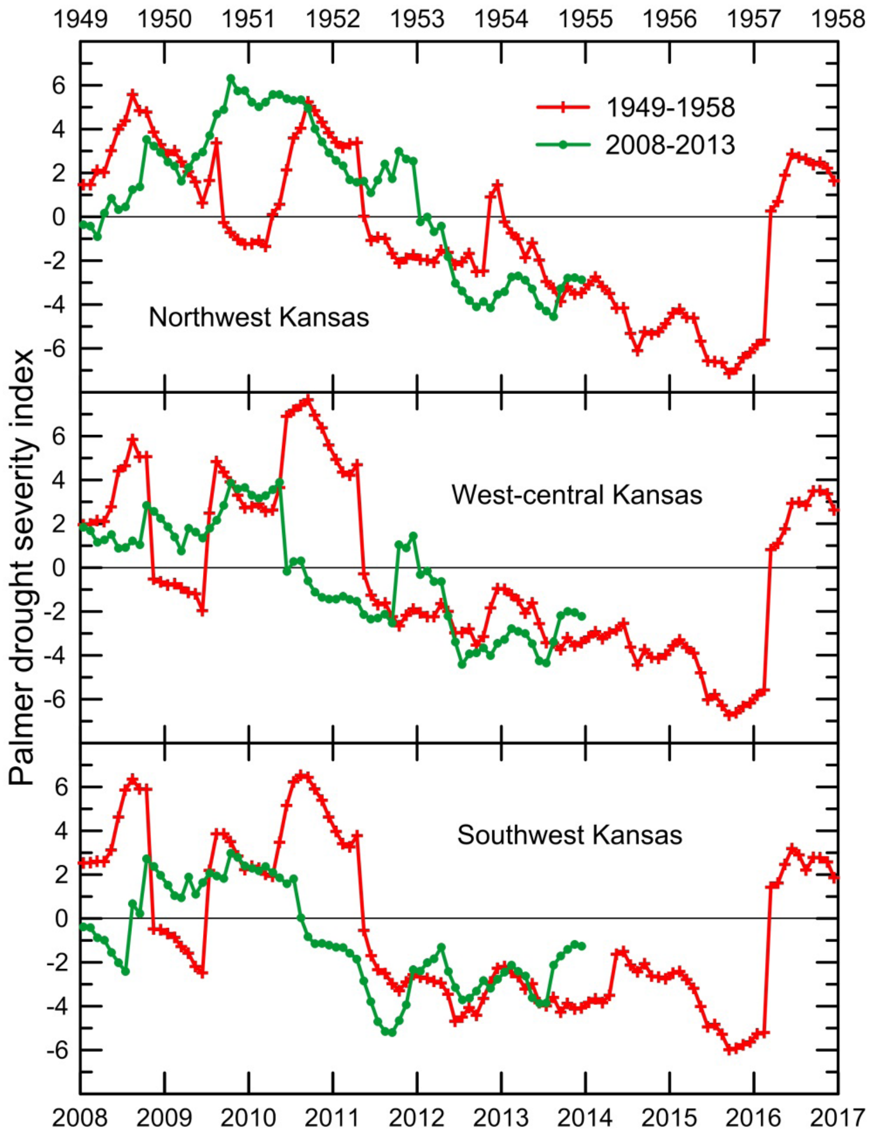

Figure 28—Comparison of monthly values of the Palmer Drought Severity Index (PDSI) for the three western climatic divisions of Kansas during 1949 to 1958 with 2008 through 2013. The monthly values are plotted as the middle of the month.

Figure 28 also includes comparison of the monthly PDSI values during 1949 to 1958, which included the drought of the 1950s, with those for 2008 through 2013. The years of 1949 through early 1952 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. Portions of the drought in 2012 and 2013 in northwest and west-central Kansas and from 2011 through 2013 in southwest Kansas were either comparable to or worse than the drought of 1952–1954.

Shorter term representations of drought are shown by the average of the monthly Palmer Z index values for the growing season (the six months of April–September) in fig. 29 and by the 9-month October SPI (the value that correlates well with water-level change in GMDs 1, 3, and 4 as discussed later) in fig. 30. The Palmer Z index indicates that the growing season drought of 2011 in southwest Kansas was more severe than that for 1952, the first year of the 1950s drought period (fig. 29). The dry conditions for the growing season in 2012 in northwest and west-central Kansas were worse than, and in southwest Kansas about the same as, those for the second year of the 1950s drought (1953). The conditions were not as dry during the growing season of 2013 as the third year of the 1950s drought (1954) in the three western climatic divisions.

Based on the 9-month SPI for October, the drought of 2011 and 2012 in southwest Kansas was comparable to that for the first two years of the 1950s drought, 1952 and 1953 (fig. 30). The climatic conditions for 2012 were drier than for 1953 in both northwest and west-central Kansas, but were not as dry in 2013 as for 1954 for all three western climatic divisions.

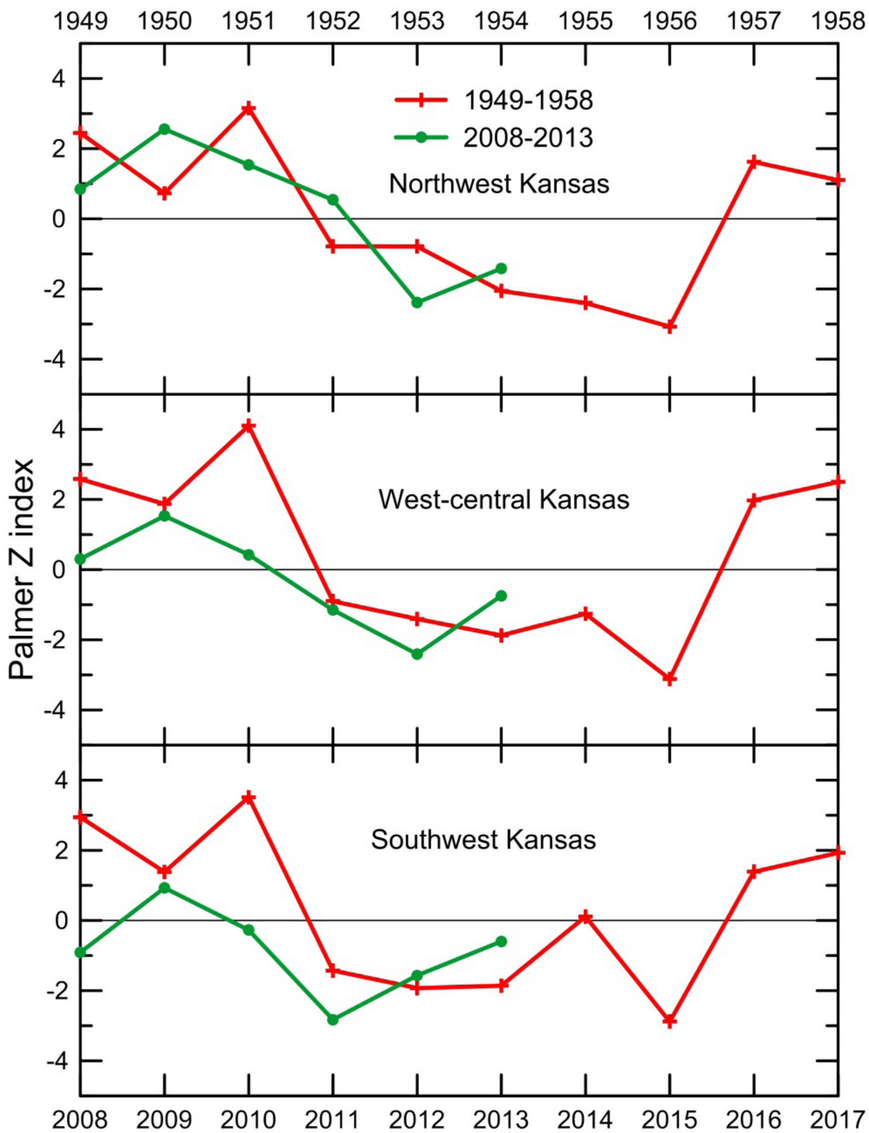

Figure 29—Comparison of the average of the monthly Palmer Z index for the 6-month growing season of April through September for the three western climatic divisions of Kansas during 1949 to 1958 with 2008 through 2013.

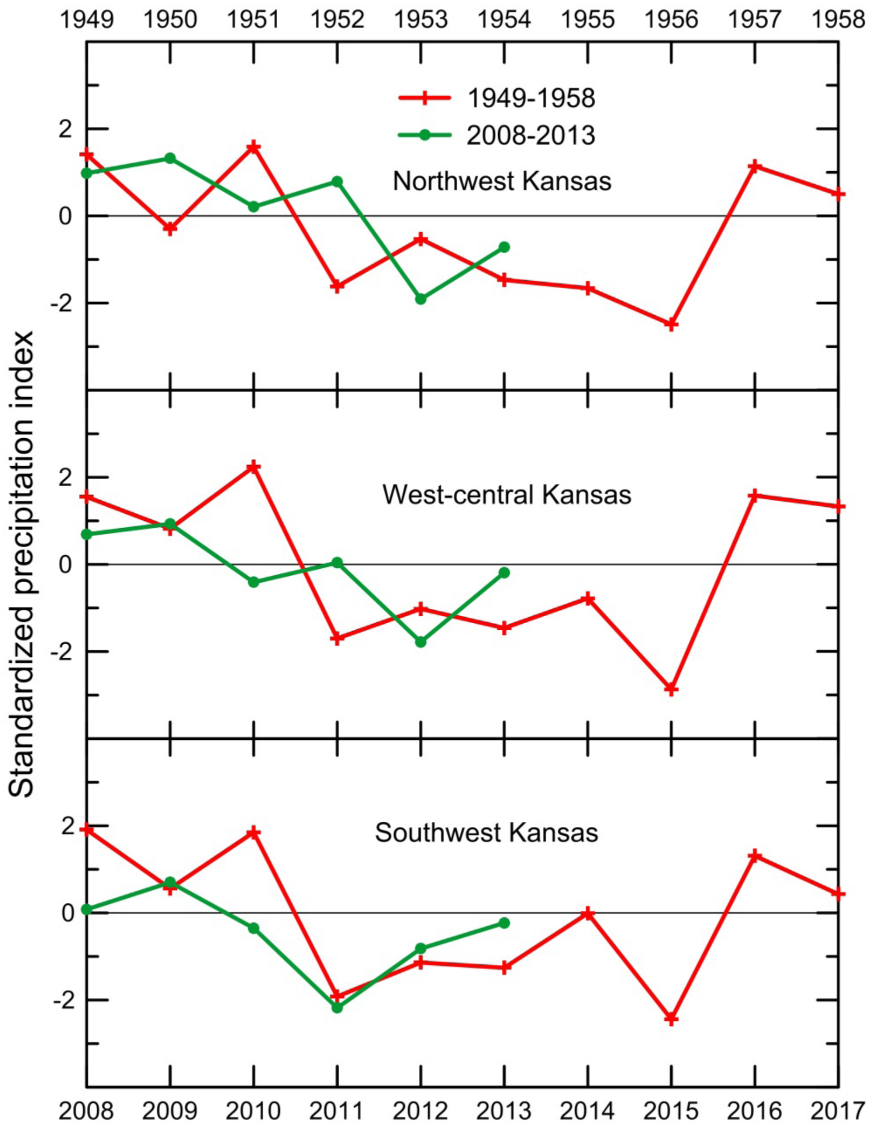

Figure 30—Comparison of the 9-month October SPI values for the three western climatic divisions of Kansas during 1949 to 1958 with 2008 through 2013. The 9-month October SPI correlates well with water-level changes in all three western GMDs.

5.4 Annual Winter Water-Level Measurements

Annual winter groundwater levels have been measured in a network of irrigation and other well types in western Kansas for many decades. Before 1997, the USGS and DWR measured the water levels. Starting in 1997, the KGS took over the cooperative measurements made by the USGS, with DWR continuing their measurements. The KGS then developed additional procedures for measurement acquisition and transfer of the data to a relational database (WIZARD).

Since 1996, 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 1996 to 2012 was less than a couple percent of the current total. For example, the accumulated numbers of points of diversion in Thomas, Scott, and Haskell counties in 2013 were 1,112, 1,340, and 1,597, respectively. The numbers of points of diversion that were added after 1996 were 40, 25, and 0 for these three counties, respectively. Thus, for the period 1996–2012, the main driver for water-level changes in the HPA in western Kansas was the amount of pumping from each well.

5.4.1 Water-Level Change in the Groundwater Management Districts

Figure 31 displays the mean annual year-to-year changes in winter water-levels during 1996–2013 for the three western GMDs based only on wells for which measurements were made during the winters of all years from 1996 to 2014. 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 -4.3 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.

Although average annual water-level declines occurred in all three western GMDs in 2013, the declines were substantially less than for the droughts of 2002 and 2012. However, the declines were the fifth greatest in GMD1, the sixth greatest in GMD4, and the seventh greatest in GMD3 out of the 18 years during the 1996–2014 measurement period.

5.4.2 Water-Level Change in the Index Wells

Winter water levels have been measured by steel tape in the original three index wells since January of 2008 (see tables 3, 5, and 7). Figure 32 shows the annual year-to-year water-level changes for both the tape and transducer values for 2008–2013 (values unadjusted for barometric pressure), along with the mean water-level changes for the GMDs during these same years 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 -0.6 and -1.5 ft; a total absolute range of about 0.9 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 about 4.1 ft), and even greater at the Haskell index well (between -4.0 and -9.1 ft; a total absolute range of about 5.1 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 2008–2013. 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 GMD 4 and 3, respectively. The patterns in the annual water-level changes for the three index wells are generally similar to the patterns for the mean annual changes for the GMDs, especially for the last four years for the Thomas and Scott index wells. This indicates how representative these index wells are of the regional water levels in the GMDs in which the wells are located.

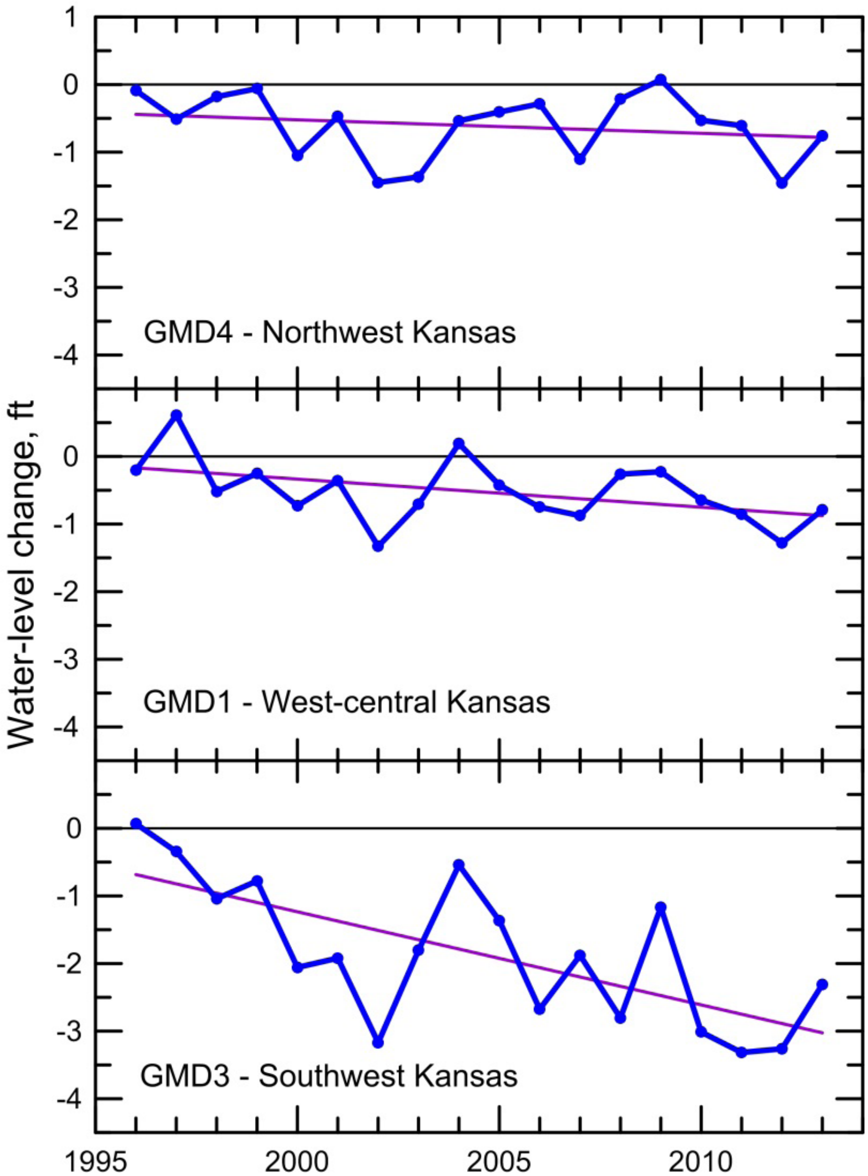

Figure 31—Mean annual water-level change in the HPA in the three GMDs in western Kansas during 1996–2013. The value for a particular year is the water-level difference between that year and the following year. The blue lines and points represent the mean annual water-level change and the purple line is the linear regression for the data.

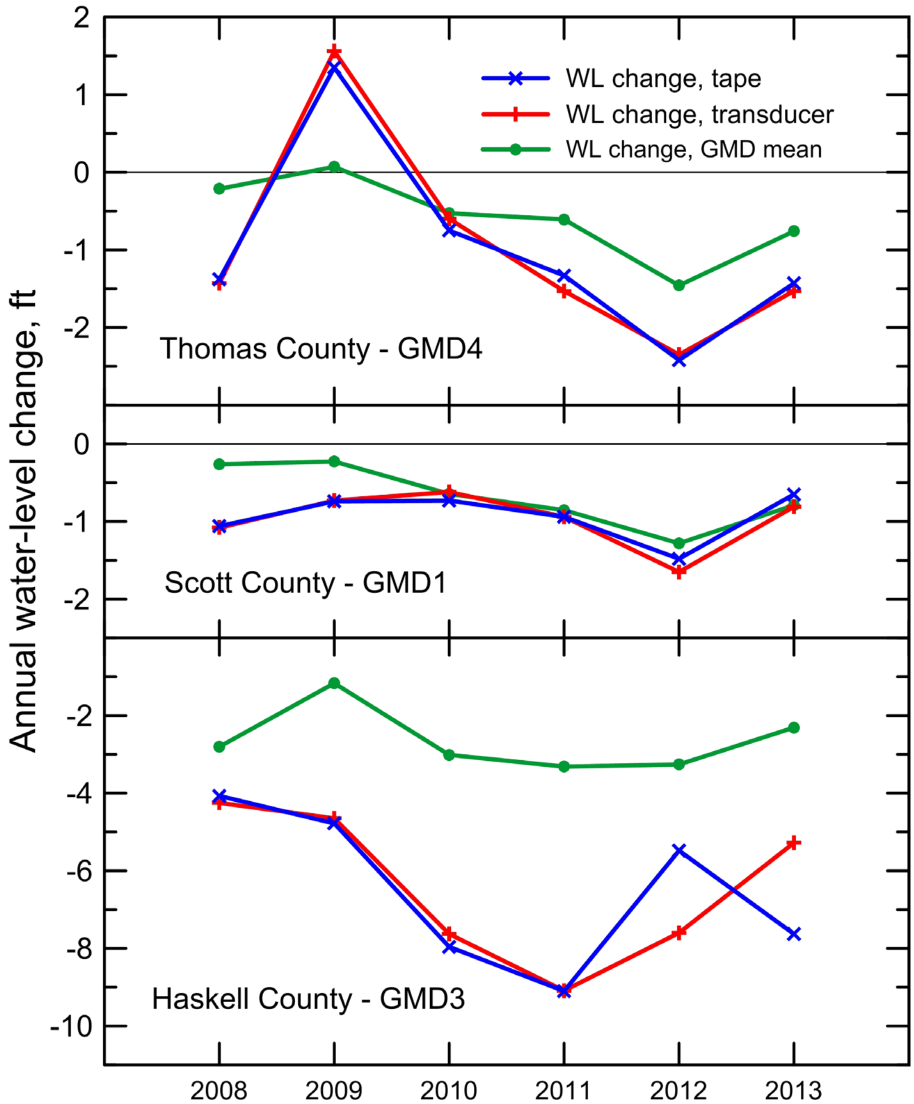

Figure 32—Annual winter water-level changes in the original three index wells and the mean annual changes in the three GMDs in western Kansas in which they are located. The value for a particular year is the water-level difference between that year and the following year. Note the difference in the y-axis scale for Haskell County versus that for Thomas and Scott counties; suspect 2012 tape measurement at the Haskell index well.

5.5 Correlation of Annual Water-Level Change with Climatic Indices

5.5.1 Correlations for the Groundwater Management Districts

Except for a very small strip of southernmost GMD4, GMDs 4, 1 and 3 lie within Kansas climatic divisions 1, 4, and 7, respectively. We have investigated the correlation of water-level changes in the GMDs with common climatic indices and found that the 9-month October SPI correlates well with water-level changes in all three of the western Kansas GMDs (Whittemore et al., 2013; Butler, Whittemore, and Wilson, 2013). Plots of this SPI for climatic divisions 1, 4, and 7 and the mean annual change in winter water levels for the three GMDs during 1996–2013 (fig. 33) show that the variations in water-level change mimic the variations in SPI. The correlations between water level change and SPI are high; Figure 34 indicates that coefficients of determination (R^2) are 0.78, 0.71, and 0.78 for GMDs 4, 1, and 3, respectively. All of these correlations are significant at P = 0.001.

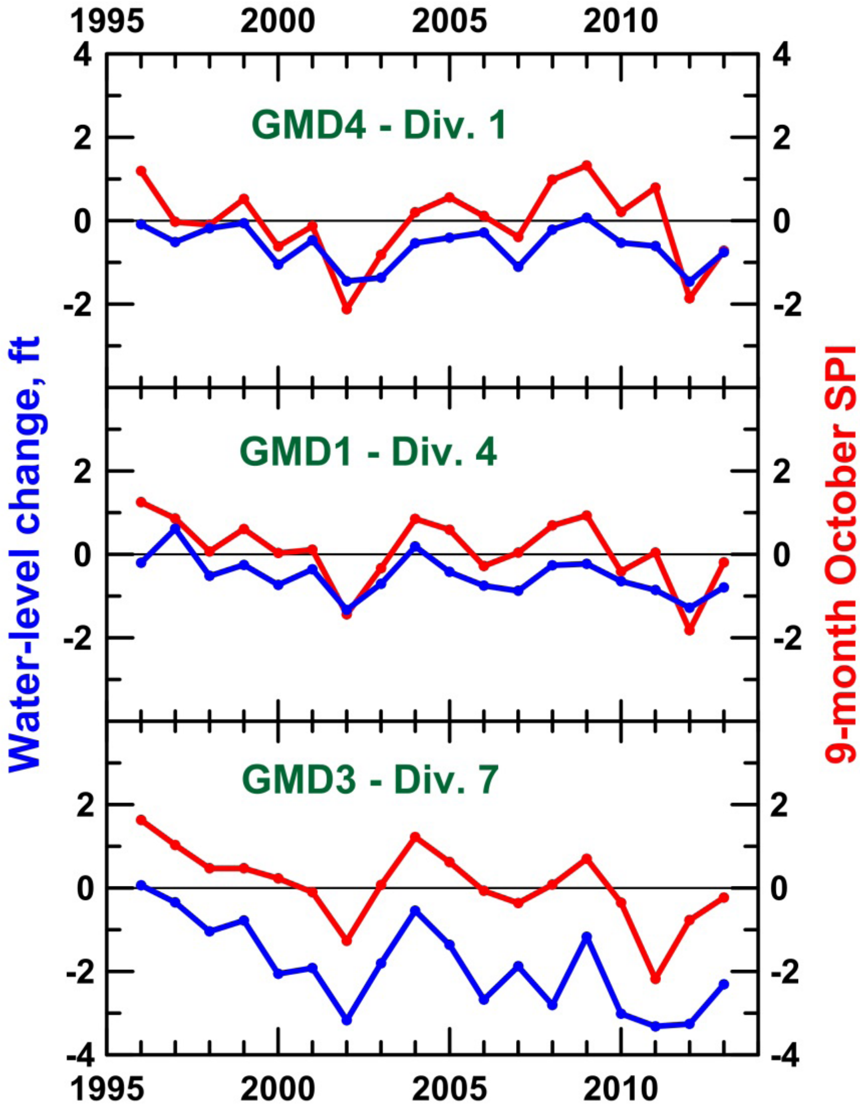

Figure 33—Variations in annual water-level changes for GMDs 4, 1, and 3 and the 9-month October SPI for climatic divisions 1, 4, and 7 during 1996–2013.

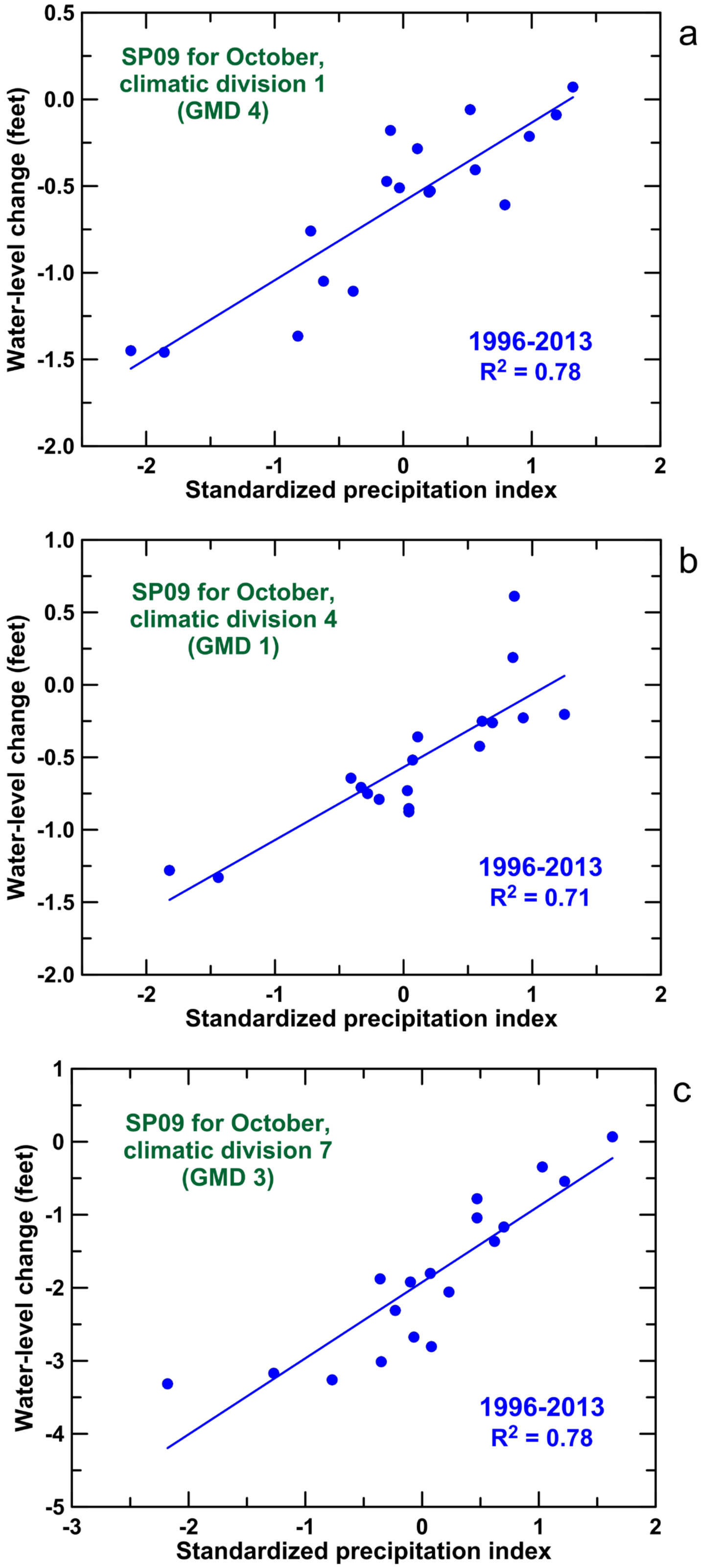

Figure 34—Correlation of mean annual winter water-level change during 1996–2013 for the three western Kansas GMDs with the 9-month October SPI for the appropriate climatic division.

5.5.2 Correlations for the Index Wells

In the previous annual report (Butler, Whittemore, Bohling et al., 2013), we determined the particular periods for the Palmer Z index that give the optimum R^2 in the climatic index and annual water-level change correlations. These forms of the Palmer Z index and the 9-month SPI values for October were used to assess the correlations for data through 2013 for the tape and transducer measurements (uncorrected for atmospheric pressure) at the original three index wells. Note that we have calculated the SPI both for the appropriate climatic division as well as for the immediate area in the vicinity of that index well. Plots of the climatic indices versus water-level changes are given in figs. 35 through 37 and the R^2 values are listed in table 18.

The correlations are significant at the P = 0.01 and 0.05 levels for the relationship between the annual water-level change based on tape and transducer measurements, respectively, at the Thomas County well and the mean Palmer Z index for June to September (table 18). The correlations between both tape and transducer measurements and the SPI for climatic division 1 are not significant. However, the relationships of the tape and transducer measurements with the SPI computed for the index well location are significant at the P = 0.05 level.

The only correlations between annual water-level change and a climatic index that are significant (at the P = 0.05 level) for the Scott County index well are those between the tape and transducer measurements and the SPI computed for the index well location.

All of the correlations between the annual water-level change at the Haskell County well and a climatic index are statistically significant except for that for the tape measurements and the Palmer Z index. The correlations for transducer measurements with the SPI for climatic division 7 and the SPI computed for the index well site are significant at P = 0.01, as is the correlation between the tape measurements and climatic division SPI.

The R^2 values for the correlations between both tape and transducer measurements and the SPI computed for the specific index well location are higher for all index wells. This indicates the value of calculating the SPI for a particular location for water-level change correlations in comparison with using climatic division values.

The correlations for both GMD1 and the Scott County index well are not as strong as for the other two GMDs and index wells. This suggests that explanations other than just climatic variations are important in controlling water-level declines in GMD1. One possible explanation is that the annual water-level changes have a noticeable effect on transmissivity (i.e. transmissivity decreases with the falling water table so a given amount of pumping produces greater annual declines progressively through time). GMD1 has the thinnest saturated thickness of the three western GMDs. A decreasing trend in annual pumping over time in this district might also be affecting the water-level change and climatic index correlations.

Table 18—Coefficients of determination (R^2) for the correlation of mean annual water-level changes at the three index wells with climatic indices for climatic divisions 1, 4, and 7 and for SPI at the index well locations during 2008–2013. The periods for the climatic indices are those that gave optimum R^2 for the correlations with the mean annual water-level changes for GMDs 1, 3, and 4 based on the previous annual report (Butler, Whittemore, Bohling et al., 2013).

Climatic index	Index well, WL Measurement Type, and SPI for Climatic Division or Well Site	R^2
Palmer Z, mean June–September	Thomas County, tape—Division 1	0.77[a]
Palmer Z, mean June–September	Thomas County, transducer—Division 1	0.73[b]
SPI, 9-month, October	Thomas County, tape—Division 1	0.51
SPI, 9-month, October.	Thomas County, transducer—Division 1	0.45
SPI, 9-month, October	Thomas County, tape—Index well site	0.71[b]
SPI, 9-month, October.	Thomas County, transducer—Index well site	0.63[b]
Palmer Z, mean June–November	Scott County, tape—Division 4	0.29
Palmer Z, mean June–November	Scott County, transducer—Division 4	0.33
SPI, 9-month, October	Scott County, tape—Division 4	0.39
SPI, 9-month, October	Scott County, transducer—Division 4	0.44
SPI, 9-month, October	Scott County, tape—Index well site	0.67[b]
SPI, 9-month, October	Scott County, transducer—Index well site	0.68[b]
Palmer Z, mean April–November	Haskell County, tape—Division 7	0.43
Palmer Z, mean April–November	Haskell County, transducer—Division 7	0.75[b]
SPI, 9-month, October	Haskell County, tape—Division 7	0.51
SPI, 9-month, October	Haskell County, transducer—Division 7	0.76[a]
SPI, 9-month, October	Haskell County, tape—Index well site	0.73[b]
SPI, 9-month, October	Haskell County, transducer—Index well site	0.77[a]

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

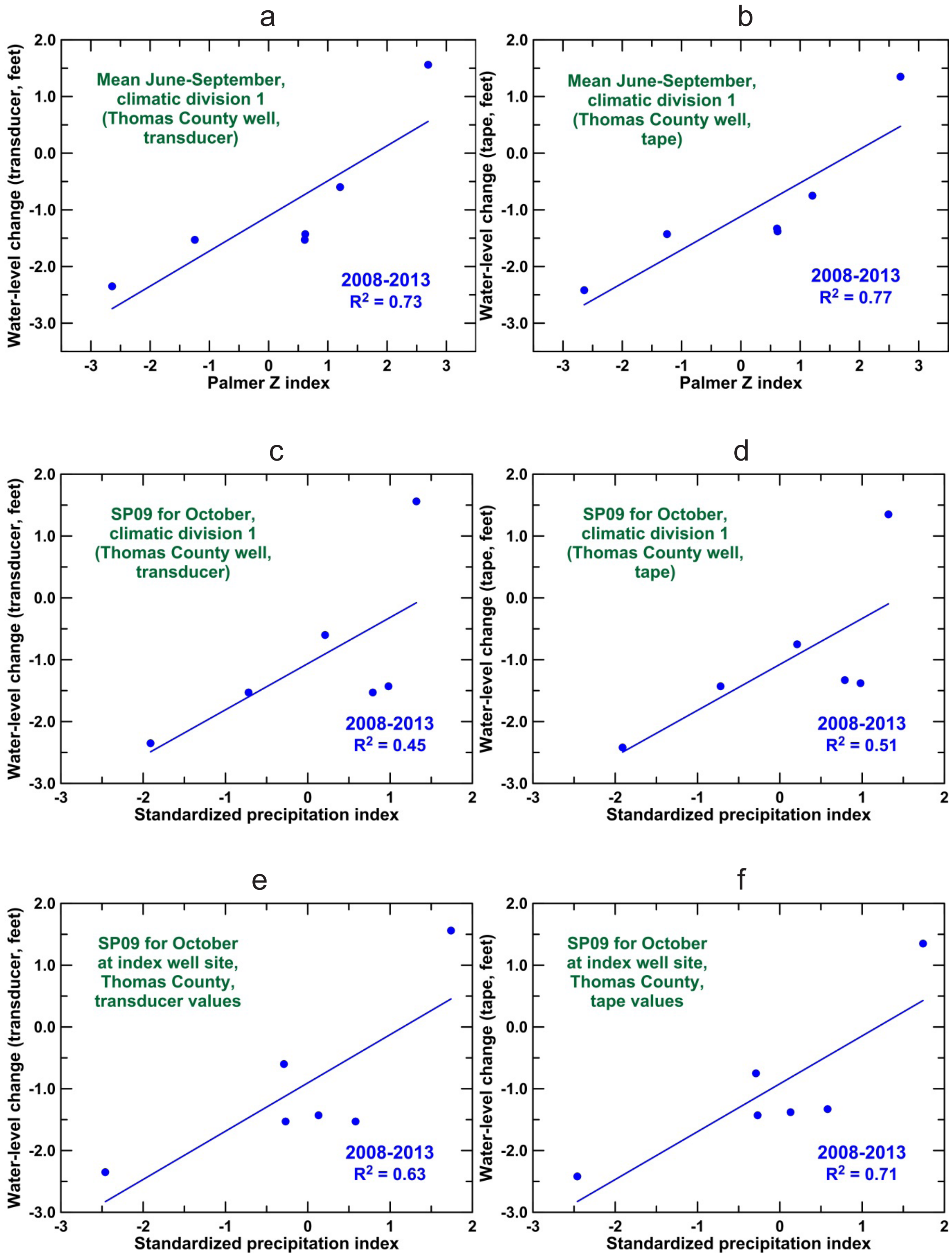

Figure 35—Correlation of annual winter water-level change during 2008–2013 at the Thomas County index well with the mean Palmer Z index for June–September for climatic division 1 (a and b) and the 9-month SPI for October for climatic division 1 (c and d) and the index well site (e and f).

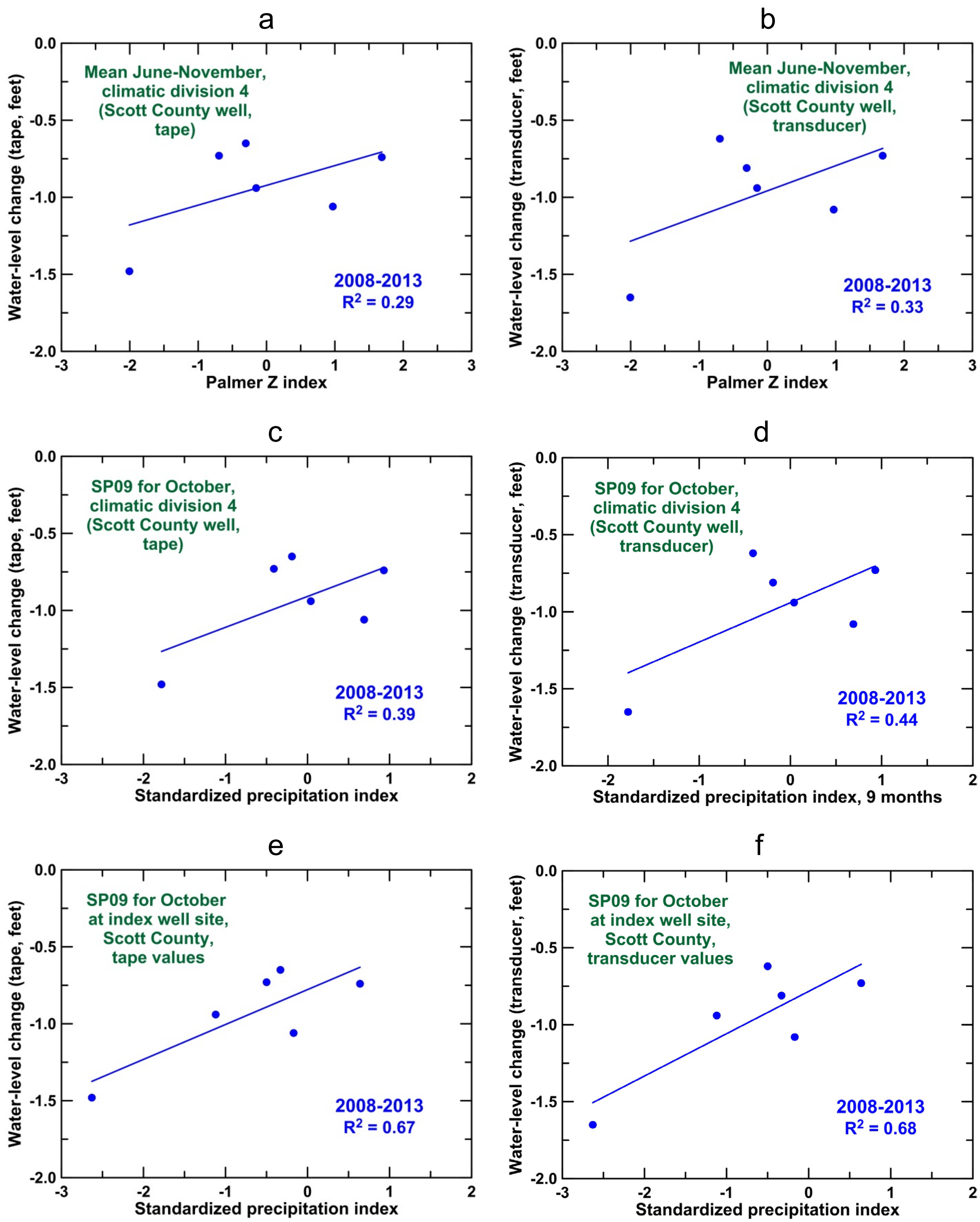

Figure 36—Correlation of annual winter water-level change during 2008–2013 at the Scott County index well with the mean Palmer Z index for June–November for climatic division 4 (a and b) and the 9-month SPI for October for climatic division 4 (c and d) and the index well site (e and f).

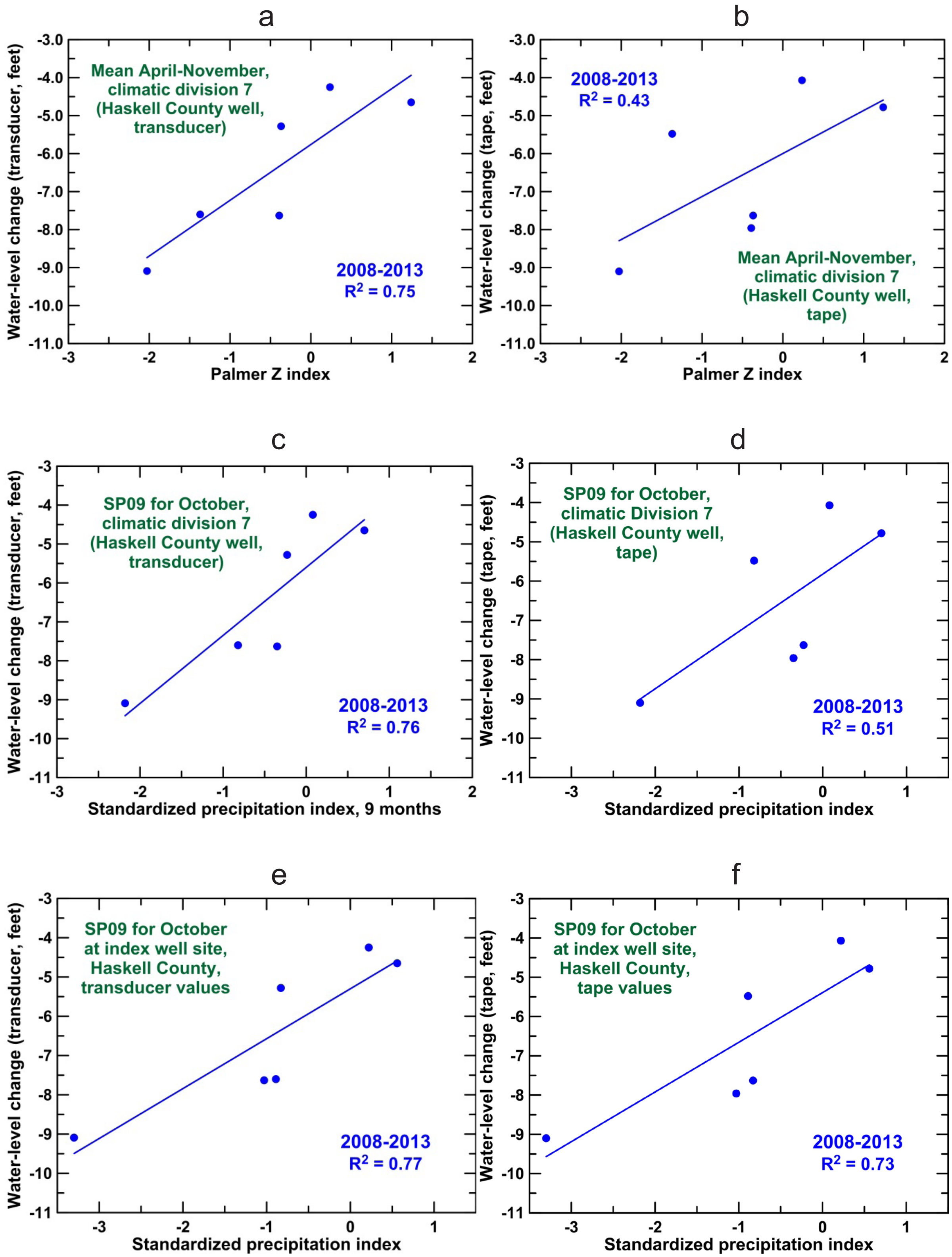

Figure 37—Correlation of annual winter water-level change during 2008–2013 at the Haskell County index well with the mean Palmer Z index for April–November for climatic division 7 (a and b) and the 9-month SPI for October for climatic division 7 (c and d) and the index well site (e and f).

5.5.3 Comparison of Linear Regressions for GMDs and Index Wells

The linear regressions for the water-level changes versus climatic index values are useful for assessing how representative the annual water-level changes at the index wells are of average annual changes in the GMDs in which they are located. Comparisons of these regressions are shown in fig. 38. The 9-month October SPI values for the index wells are calculated for the immediate vicinity of each index well, not the climatic division. The water-level changes are the annual tape measurements for the index wells and, for the GMDs, the average annual changes for that GMD.

The range of water-level changes at the Thomas County index well is greater than that for the average water-level changes in GMD4 during 1996–2013, although the GMD4 range is within the index well range (fig. 38a). The slope of the linear regression for the Thomas County index well is also greater than those for the GMD4 area regressions. This suggests that the index well location is more sensitive to climatic variations than the average well in GMD4.

The range of water-level changes at the Scott County index well is smaller than that for average water-level changes in GMD1 during 1996–2013; the index well range is within the GMD1 range for 1996–2013 (fig. 38b). The slope of the linear regression for the Scott County index well is less than those for the GMD1 area regressions. The smaller range in water-level change and flatter slope might be related to the location of the Scott County index well in the north-south trough that extends through central Scott County and that contains a greater saturated thickness than in most of GMD1. Groundwater might flow from the sides of and along the trough during and after the pumping season to moderate the water-level declines in comparison to the average condition in GMD1. The greater recovery of water levels (to near -0.2 ft) for 2008–2013 for the average GMD1 well than for the Scott County index well suggests that combined drainage from the unsaturated zone and infiltration of precipitation and irrigation return flow is not as great at the index well as elsewhere in GMD1.

The range of water-level changes at the Haskell County index well is greater than that for average water-level changes in GMD3 during 1996–2013 (fig. 38c). The slope of the linear regression for the Haskell County index well is slightly greater than that for the GMD3 area regression for 1996–2013 and moderately greater than that for the GMD3 2008–2013 regression. The main difference in the index well and GMD3-wide regressions is the much greater water-level declines across the range of SPI values for the index well. The cause of the difference is most likely the confined character of the HPA at the Haskell County index well in comparison to a mixture of unconfined and confined responses in wells elsewhere in GMD3.

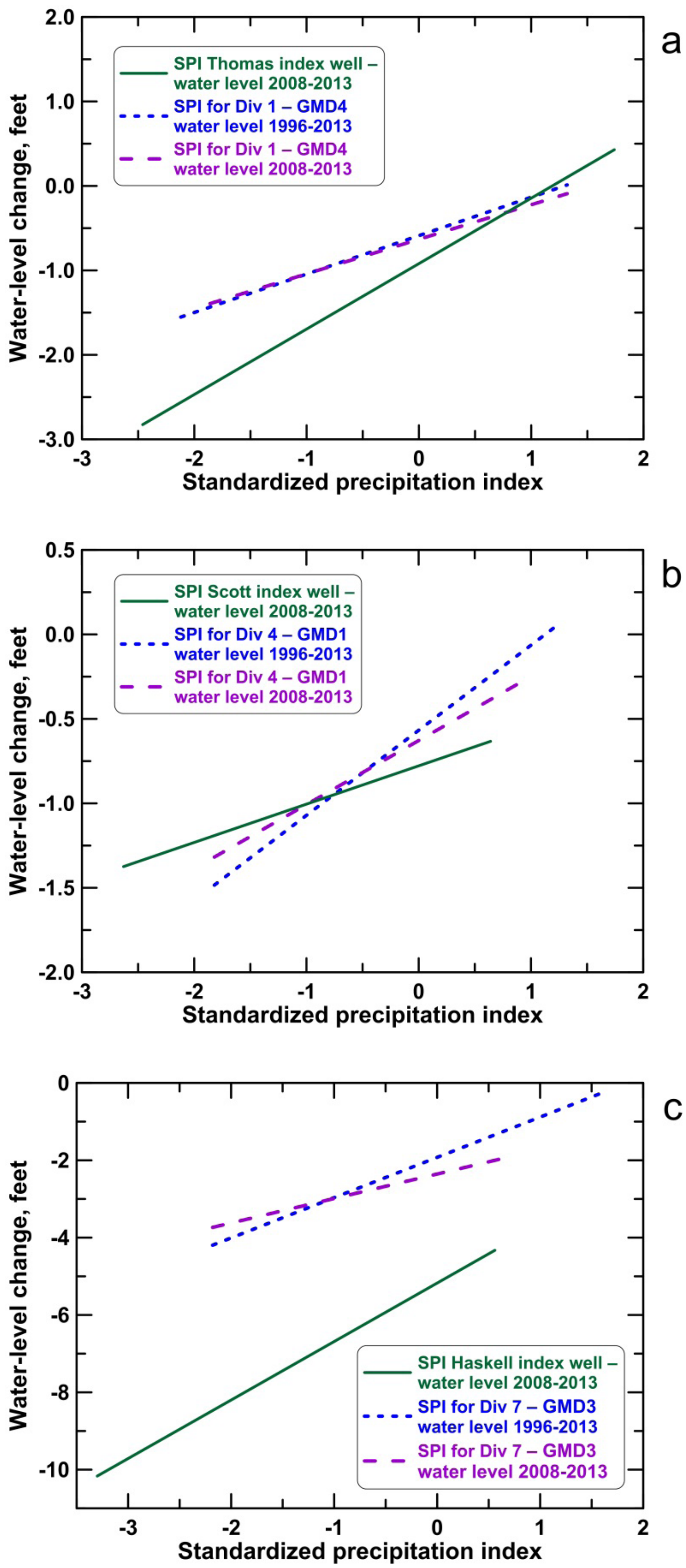

Figure 38—Linear regressions for average annual water-level changes for GMDs versus 9-month October SPI for climatic divisions during 1996–2013 and 2008–2013 and linear regressions for annual water-level change for index well tape measurements versus 9-month October SPI at the index well location during 2008–2013.

5.6 Prediction of Annual Water-Level Changes for Drought

As described earlier, the values of the Palmer Z index for the growing season and the 9-month SPI for October indicated particularly dry conditions in 2011 and 2012 in GMDs 1 and 3, and in 2012 in GMD4 (figs. 29 and 30). Drier than normal conditions occurred during 2013 across all three GMDs, although not as dry as the previous year. It is yet to be seen whether drought conditions will continue during 2014 and 2015 to replicate the last two years of the 1950s drought (1955 and 1956).

The 1955 and 1956 drought index values can be used to predict mean annual water-level declines that would be produced by a repeat of those conditions for each of the three index well locations based on the linear regressions for the climatic index and water-level plots in figs. 35 through 37. These predictions were made using the 9-month SPI for October for climatic divisions 1, 4, and 7 for 1955 and 1956 (fig. 30) and the linear regressions between the SPI values for the index well location and water-level changes, which generally had higher R^2 values than regressions using the Palmer Z index or the climatic division SPI (table 18). A repeat of the 1955 and 1956 portion of the 1950s drought gives total water-level declines of 5.1 ft, 2.4 ft, and 13.9 ft for 2014–2015 for the index wells in Thomas, Scott, and Haskell counties, respectively, based on the regression for the annual tape measurements. For the regression based on the transducer measurements, the total water-level declines would be 5.1 ft, 2.6 ft, and 13.7 ft for the index wells in Thomas, Scott, and Haskell counties, respectively. The assumption of 1956 conditions for 2015 alone would give annual water-level declines of 2.8 ft, 1.4 ft, and 8.5 ft based on the tape measurements, and declines of 2.9 ft, 1.6 ft, and 8.4 ft based on the transducer values for the index wells in Thomas, Scott, and Haskell counties, respectively. Note that the inferred declines for 2015 would exceed the greatest annual decline measured at the Thomas index well (2.4 ft during 2012 for both tape and transducer values) and be about the same as observed for the Scott County index well (1.65 ft during 2012 for transducer values). However, the inferred declines for 2015 would not exceed the greatest decline at the Haskell County index wells (9.1 ft during 2011 for tape and transducer values), in part because the 2011 SPI computed for the well location (-3.30) is lower than both the 1956 (-2.44) and 2011 (-2.18) SPI values in climatic division 7.

Although the water-level declines inferred for 1955–1956 conditions would represent substantial decreases in the saturated thickness at the Thomas and Scott index wells, the aquifer thickness would still be great enough to allow irrigation pumping. However, the total estimated decline at the Haskell index well would be so great that expected pumping rates would be substantially smaller than sustained in the recent past.

5.7 Correlation of Annual Water Use with Water-Level Change and SPI

The statistically significant correlations between the SPI computed for the index well locations and annual water-level changes in the index wells described in Section 5.5.2 suggest that correlations might also be significant between water use near the index well and water-level changes and SPI. Indeed, the correlations between annual water-level change and annual water use within a 1-mi, 2-mi, or 5-mi circle around the Thomas County index well are statistically significant (particularly the correlation for the 5-mi circle, which has a P of 0.01), showing the control of pumping on water levels at the index well (table 19). A similar correlation with water use within a 5-mile radius of the Scott County index well is statistically significant, although not as significant as for the Thomas County well (table 19). The correlation between water-level change and water use at the Haskell County index well is only significant for water use within a 1-mi radius (table 19); this may be another indication of compartmentalized aquifer behavior (e.g., Butler, Stotler, Whittemore, and Reboulet, 2013) within the Haskell area and will be examined further in 2014. The larger radius (5-mi) of water use giving the highest correlations for the Thomas and Scott counties index wells does not necessarily indicate that this is the area that affects water levels most at these sites but could represent more uniform water use for each year than a smaller area (lessening the effect of reporting errors, for example).

Table 19—Correlation (R^2 values) of annual use around the index wells with annual water-level changes (tape measurements) in the index wells and with the 9-month October SPI computed for the index well locations.

	Correlation with water-level change			**Correlation with 9-month October SPI**		
Index well	Water use, 1-mi radius	Water use, 2-mi radius	Water use, 5-mi radius	Water use, 1-mi radius	Water use, 2-mi radius	Water use, 5-mi radius
Thomas Co.	0.78[a]	0.80[a]	0.94[b]	0.65	0.53	0.64
Scott Co.	0.58	0.52	0.66[a]	0.82[a]	0.21	0.77[a]
Haskell Co.	0.81[a]	0.28	0.39	0.58	0.49	0.60

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

Plots of the annual water-level change versus water use for the radius for which the highest R^2 is observed illustrate the expected smaller water-level decline for the years of smaller water use and vice-versa (fig. 39). The years with the smallest water use during 2008–2012 within a particular radius of an index well are not the same for each well. The substantially smaller water use in 2009 around the Thomas index well was accompanied by a water-level rise (fig. 39a) and is consistent with the wet climatic conditions during 2009 at this well (fig. 40a); the 9-month SPI value for October at the Thomas well for 2009 was the most positive SPI value at the three index well sites during the monitoring period. The smallest water use of 2008–2012 around the Scott index well occurred during the years of 2009 and 2010 and resulted in the least water-level decline at this well (fig. 39b). The least water was used in 2010 during 2008–2012 at the Scott well, even though 2010 was slightly dry and 2009 was slightly wet around the well (fig. 40b). The least water used during 2008–2012 around the Haskell index well occurred during 2012 even though that year was dry (figs. 39c and 40c). However, the water-level decline was also smaller during 2012 than during 2010, which had an SPI about the same as for 2012. The slightly wet conditions of 2008 and 2009 at the Haskell well were accompanied by smaller water use than the average during 2008–2012 and the two smallest water-level declines of the period.

The drought year of 2012 was associated with the greatest water use and water-level decline at both the Thomas and Scott index wells (figs. 39a and 39b); 2012 was by far the driest of 2008–2012 at these locations (figs. 40a and 40b). In comparison, 2011 was the driest at the Haskell index well and was characterized by the greatest water use and water-level decline at the Haskell well (figs. 39c and 40c); the 9-month SPI value for October was also the most negative of the 2008–2012 period for the three index well locations and indicated a severe drought. The extremes in the water-use, water-level change, and climatic index (SPI) for 2011 at the Haskell well contrast strikingly with the opposite extremes for 2009 at the Thomas County well. These extremes at different index well locations for different years point to the value of the index wells in representing different conditions that can exist across the HPA in western Kansas.

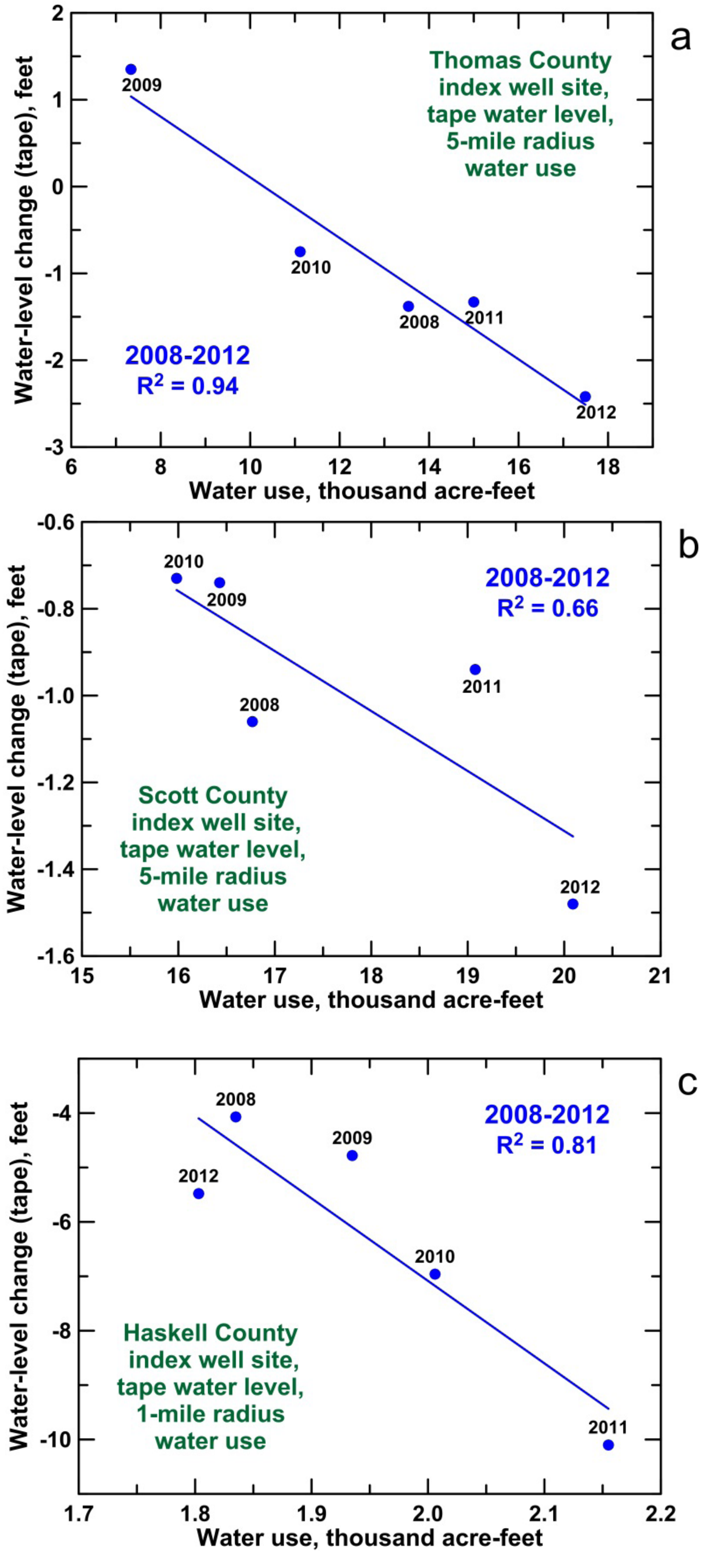

Figure 39—Correlation of annual water-level changes based on tape measurements in the index wells versus annual water use within a particular radius surrounding the index wells during 2008–2012.

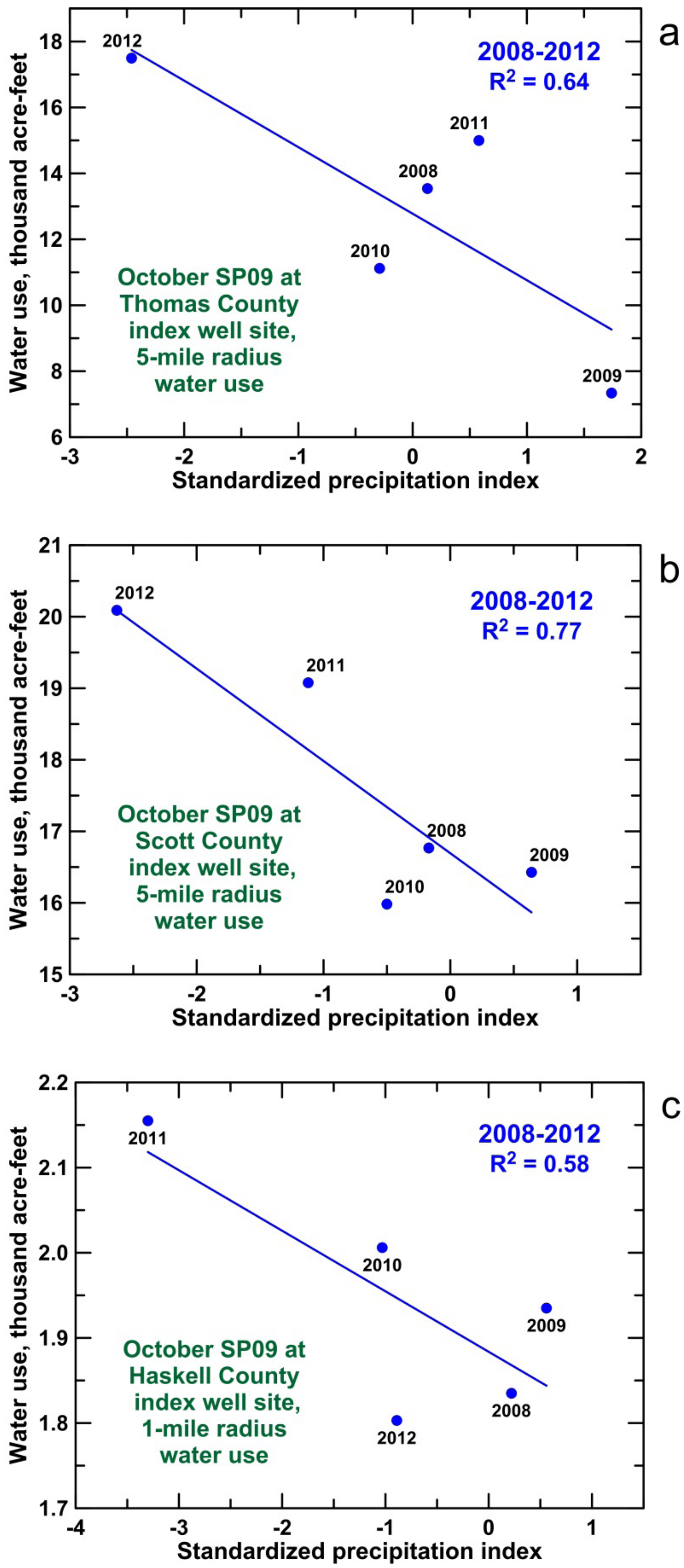

Figure 40—Correlation of annual water use within a particular radius surrounding the index wells with the 9-month SPI for October computed for the index well location during 2008–2012. The water use radius for each well is the same as in fig. 39.

6. The Dakota Aquifer in the Vicinity of the Haskell County Index Well

The Dakota aquifer consists of sandstone lenses distributed within the shale that forms most of the Lower Cretaceous deposits where they exist in southwest Kansas. The location of the Haskell County well lies along the border of where the Dakota aquifer is confined by shale of younger Cretaceous strata (fig. 41). The bedrock underlying the HPA at the Haskell County index well is thus part of the Dakota aquifer or shale of the Upper Cretaceous depending on the specific location of the confined Dakota border underlying the site.

The Haskell index well is located in the approximate center of a four-township block (T. 27–28 S. and R. 30–31 W.) that extends across northeast Haskell and west-central Gray counties. Many irrigation wells in this block of townships are completed within both the HPA and Dakota aquifer (fig. 41); an estimated 49 irrigation wells are screened in both aquifers and have at least 10 percent of their yield from the Dakota aquifer (based on an investigation of well construction and water rights information available up to the end of 2011 [Whittemore et al., in press]). The estimated percent of the total yield of the 49 irrigation wells screened in both aquifers ranges from about 10 percent to 30 percent (fig. 42), with an average of approximately 24 percent. The bottom of a few additional wells in the area are screened or gravel packed into the top of the Dakota aquifer but probably obtain only a few percent or less of their total yield from that aquifer. Within the 25-section area centered on the Haskell index well (about a 2.5 to 3 mi radius around the well location), eight irrigation wells are completed in both the Dakota aquifer and the HPA. The approximate Dakota yield from these eight wells ranges from 10 to 30 percent and averages about 20 percent.

Only three irrigation wells completed in both the Dakota aquifer and the HPA are located in the nine-section area centered on the Haskell index well; their locations are T. 27 S., R. 30 W., sec. 30 (in Gray County about 0.9 mi to the northeast of the index well); T. 27 S., R. 31 W., sec. 26 (in Haskell County more than a mile to the northwest of the index well); and T. 28 S., R. 30 W., section 6 (in Gray County more than a mile to the southeast of the index well); none of these wells are in the section in which the index well is located (T. 27 S., R. 31 W., sec. 36). One domestic well that is completed in the Dakota aquifer is also located in this nine-section area (the southwest corner of T. 28 S., R. 31 W., sec. 2), about 2 mi southwest of the index well. This well is screened in the lowermost part of the HPA and in the underlying Dakota aquifer but is gravel packed from 21 ft below land surface to its completed depth of 575 ft.

The water level of a well completed in both the HPA and Dakota aquifer will be a transmissivity-weighted average of the water levels in both aquifers (Sokol, 1963). Depending on the head difference between the two aquifers, water may flow from one unit to the other. The gravel pack that exists in most irrigation wells typically extends across the zones separating the screened intervals in wells completed in the two aquifers. The flow through the gravel pack could provide the main amount of multi-year flow from one aquifer to another where the Dakota sandstones are separated from the HPA by shale. The amount of this flow is unknown, although a rough estimate could be made for a selected area based on assumptions about the borehole and casing diameter, the permeability of the gravel pack, the difference in hydraulic head between the aquifers, the time during which the wells are not pumping, and the number of irrigation wells in the area.

In addition to the flow in the borehole and gravel pack, leakage could occur from one aquifer to another if there is a head difference between the HPA and the Dakota aquifer. This leakage would depend on the hydraulic connection between the two aquifers. Typically, some shale exists between the bottom of the HPA and the top of the uppermost Dakota sandstone. If shale were present between the aquifers, the leakage rate would be expected to be very low, meaning that the water transfer between aquifers would be minimal relative to the exhaustion rate of the HPA in the area. However, in some locations, a Dakota sandstone could directly underlie sands and gravels of the HPA. In that case, the inter-aquifer communication could be substantial enough to affect water levels within an irrigation season.

Groundwater withdrawal from both the HPA and Dakota aquifer will produce water-level declines in each aquifer. The relative rate of decline in the Dakota aquifer is unknown in northeast Haskell County because no existing wells are known to be completed only in the Dakota aquifer to provide a comparison of water level with the index well.

As water levels in the HPA continue to decline in the vicinity of the Haskell index well, the percentage of pumping from the Dakota aquifer is expected to increase. Additional wells completed in both the HPA and Dakota aquifer may be constructed as replacement wells for wells completed only in the HPA. This would further increase the relative amount of pumping from the Dakota aquifer. The sustainability of water from the northeast Haskell County area thus will not only depend on the rate of decline in the HPA but also the response of the Dakota aquifer to the potentially increasing stress placed on it. A monitoring well completed in the first sandstone underlying the HPA in the vicinity of the Haskell index well would be very valuable for answering questions of relative water levels, leakage, and stresses on the two aquifers in that area.

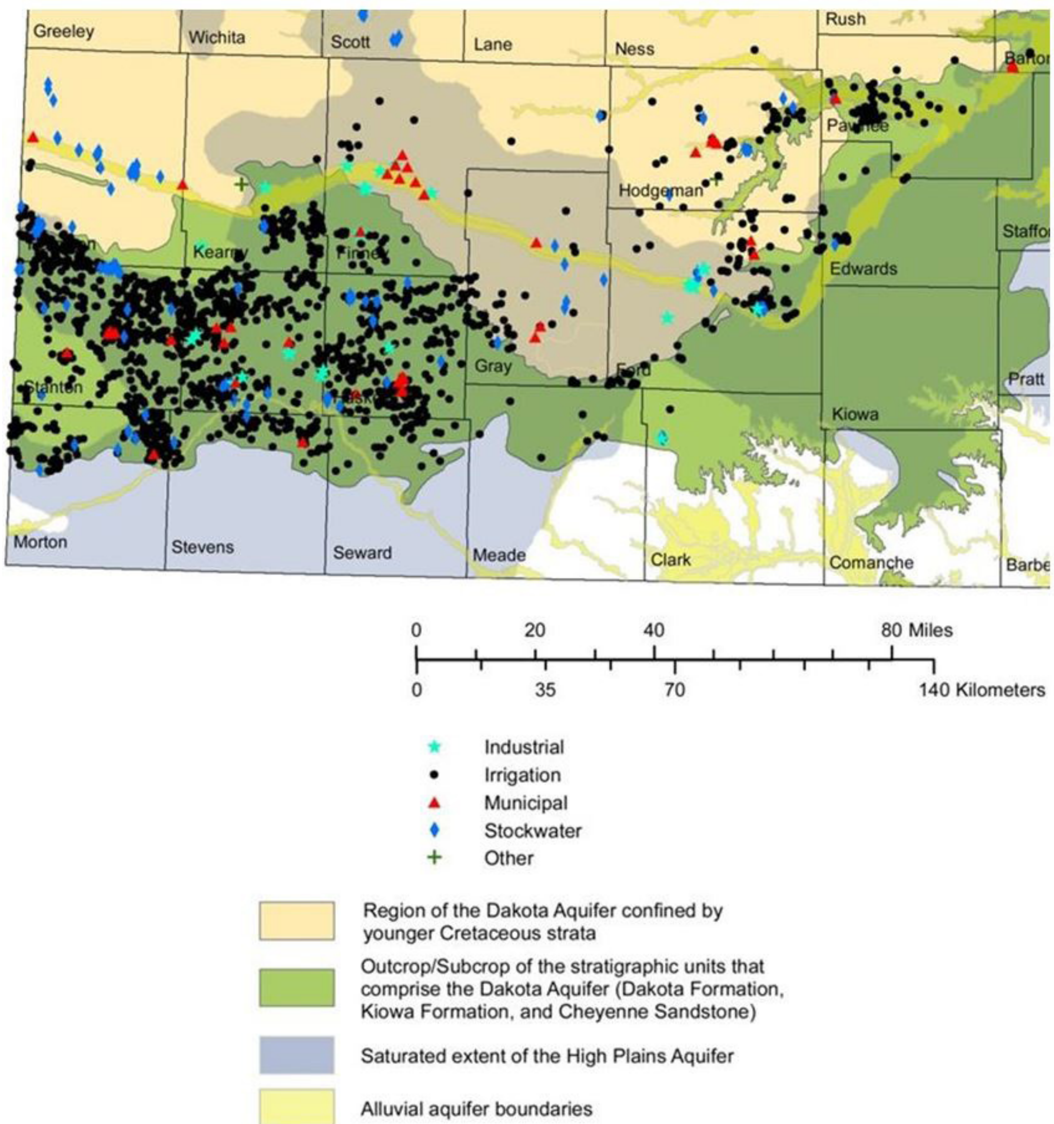

Figure 41—Distribution of water-right permitted wells that draw part or all of their yield from the Dakota aquifer in southwest Kansas according to use type (figure cropped from portions of a figure in the soon-to-published KGS bulletin on the Dakota aquifer [Whittemore et al., in press]).

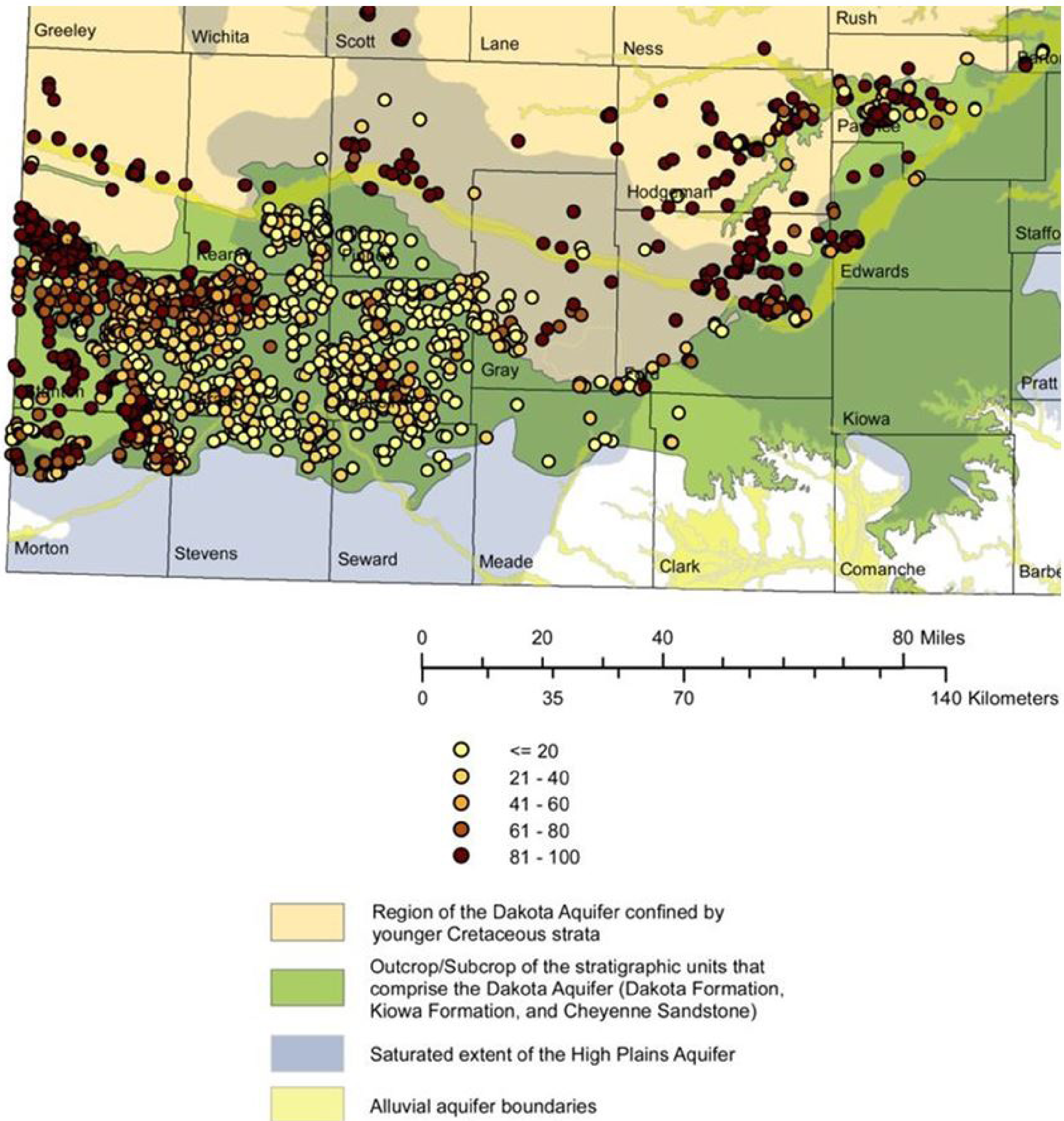

Figure 42—Distribution of wells producing partially or entirely from the Dakota aquifer in southwest Kansas according to percent of total yield from the Dakota system. The distribution is based on wells with active water rights and water use as of the end of 2011 (figure cropped from portions of a figure in the soon-to-published KGS bulletin on the Dakota aquifer [Whittemore et al., in press]).

7. Discussion of HPA Geochemistry near the Index Wells

Geochemical sampling was added to the Index Well Program to better determine the sources of water in the aquifer. Samples were first collected from the original three index wells and irrigation wells near the Thomas County index well in 2011; additional sampling of irrigation wells in Thomas and Haskell Counties was conducted in 2013. Samples were collected for cation, anion, stable isotope ($\delta^2H/\delta^{18}O$), ^3H, and ^{14}C determinations. Geochemical data, collected from core fluids, are also available from drilling projects near the Thomas and Haskell index well sites.

It has been postulated that the underlying Dakota (Lower Cretaceous bedrock) aquifer could supply water to the HPA at the index well in Haskell County, where the HPA directly overlies the Dakota aquifer (see previous section). Groundwater is expected to be fresh in the Dakota aquifer below the Haskell index well based on water quality in the general region, although no specific chemical data are available for the Dakota aquifer in northeast Haskell County (Whittemore et al., in press). However, sulfate concentration in the Dakota aquifer is commonly greater than that of chloride in the freshwater portions of the aquifer due to oxidation of pyrite often present in the fine-grained Dakota deposits. Chemical data for the HPA in Haskell County also indicates that the sulfate concentration is greater than the chloride concentration, although not usually as high as expected to occur in freshwater portions of the Dakota aquifer in the region of the Haskell index well. In general, the total dissolved solids (TDS) concentration in the Dakota aquifer at the Haskell well location would be expected to be somewhat greater than in the HPA.

The HPA is underlain by the Pierre Shale (Upper Cretaceous bedrock) at the Thomas index well location as indicated by well logs in the general area (Frye, 1945). The top of the Pierre Shale below the HPA is usually yellowish before grading to dark gray with depth. The yellow color suggests that pyrite common in the shale has oxidized to produce precipitated ferric oxyhydroxides and release dissolved sulfate. In addition, pore water in the Pierre could have some chloride-rich marine water that would have a much higher dissolved solids content than in the HPA. The sulfate/chloride ratio of water in the uppermost Pierre is not known, but the combined effect of the sulfate released by weathering and possible marine pore water would be to produce a higher TDS concentration than in the HPA.

The generally higher TDS and sulfate/chloride ratio expected in groundwater in the Dakota aquifer and weathered Pierre Shale are useful as tracers to identify mixing between aquifers. The TDS concentration of irrigation and index well waters at all three index well sites are low, ranging from 202 to 336 mg/L. This argues against any large-scale contribution of water from the Dakota aquifer or the Pierre Shale. A comparison of sulfate and chloride provides a more sensitive indicator of water contributions from the Cretaceous bedrock (fig. 43). The sulfate/chloride ratios for groundwater in the HPA near the Haskell index well are higher than those near the Thomas index well. A mixing trend may be indicated in the four samples collected in Haskell County and the two lowermost core fluid samples (which sample the upper unconfined aquifer at the Haskell site). As will be discussed with the stable isotope data, it is believed that all three sampled irrigation wells collect a majority of their water from the same lower confined aquifer interval that is monitored by the Haskell index well. Water-level response to pumping indicated the aquitard and/or upper aquifer provide some leakage to the lower aquifer (Butler et al., 2012; Butler, Stotler, Whittemore, and Reboulet, 2013). The similarity of the SO_4/Cl ratio between the lowermost core fluids and at least one irrigation well provides geochemical support for that hypothesis.

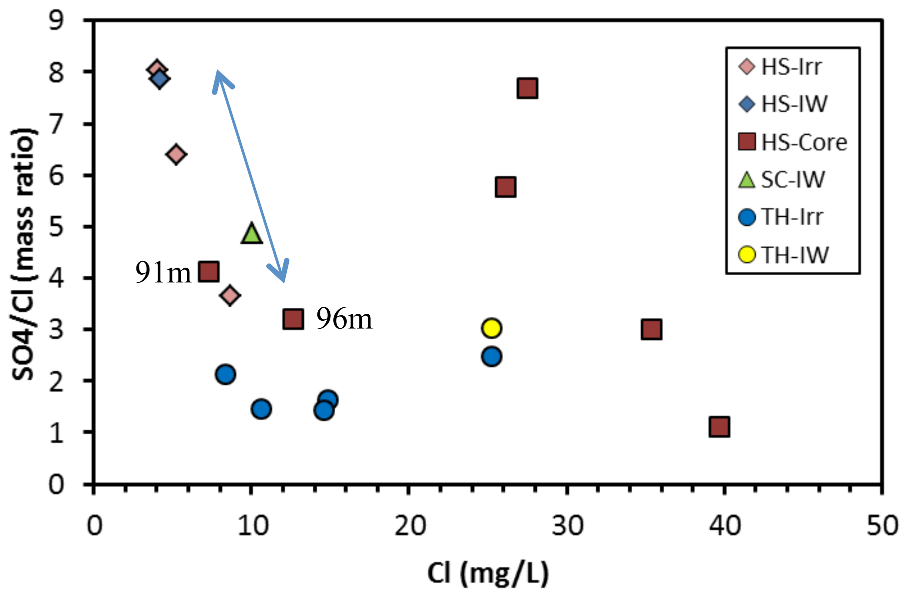

Figure 43—Comparison of sulfate/chloride mass ratio versus chloride concentration in water from the index wells, nearby irrigation wells, and core samples. In the legend, IW = index well, Irr = irrigation well, and Core = core fluids. Depths below ground surface are shown for the two lowermost core fluid samples.

A comparison of bromide/chloride ratios provides another important indicator of processes and fluid sources (fig. 44). The most interesting data are from the Haskell area, where the shallowest core samples (closest to the water table) have the highest chloride values. The decrease in chloride concentration with depth in the core samples is not accompanied by a significant change in the bromide/chloride ratio. This indicates that both bromide and chloride concentrations accompanying recharge water are more concentrated at the water table than in the underlying aquifer water. The relatively constant bromide/chloride ratio with depth suggests that earlier recharge to the HPA had a similar ratio as later recharge but that dissolved solids in the later recharge were more concentrated by evapotranspiration at and near the land surface before infiltrating to the water table. Nitrate concentrations in the Haskell core fluids also behave in this manner (fig. 45). Increased concentrations of chloride and nitrate near the water table are common in semi-arid regions (e.g., Scanlon et al., 2006). A general trend of increasing nitrate with increasing chloride concentrations is observed at all three sites, although the relationship is strongest in the irrigation wells near the Thomas County index well (fig. 46). It should also be noted that the Haskell irrigation well sample with the highest bromide/chloride mass ratio also has the highest sulfate/chloride ratio.

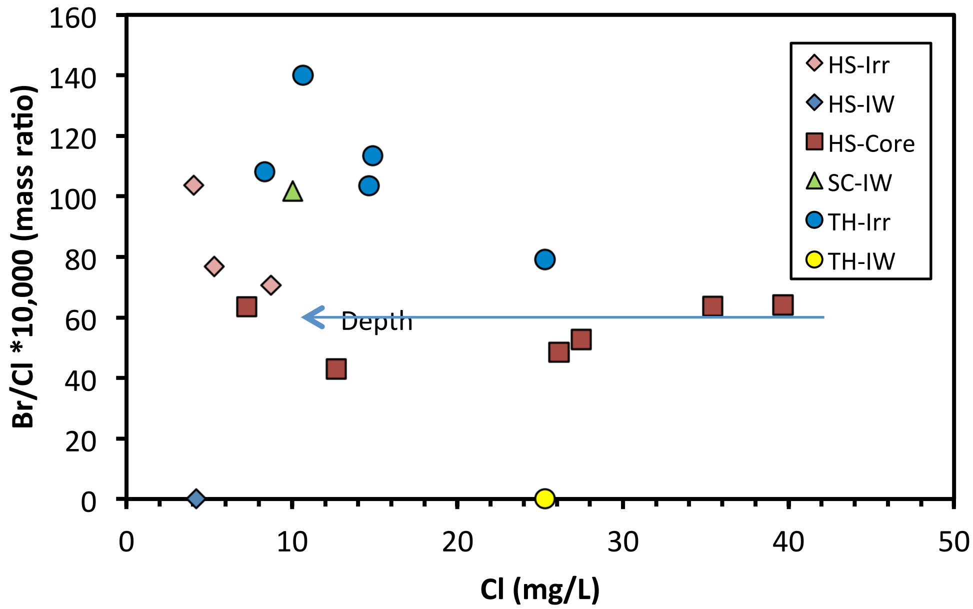

Figure 44—Comparison of the bromide/chloride mass ratio versus chloride concentration in water from the index wells, nearby irrigation wells, and core samples. Bromide concentration was below the detection limit (<0.1 mg/L) in samples from the Thomas and Haskell counties index wells. In the legend, IW = index well, Irr = irrigation well, and Core = core fluids. The depth line refers to the HS-core samples.

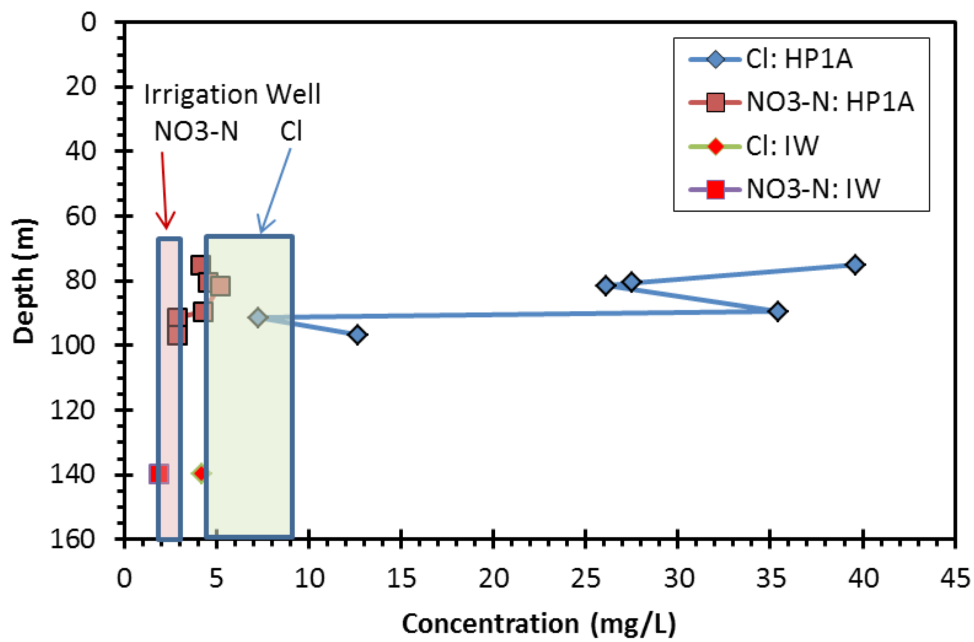

Figure 45—Nitrate and chloride concentrations in well and core waters in the area near the Haskell County index well. Values at 140 m depth are for the index well; values between 75 and 95 m depth below ground surface are for the HP1A core. The range of values found for nearby irrigation wells are represented by the shaded boxes.

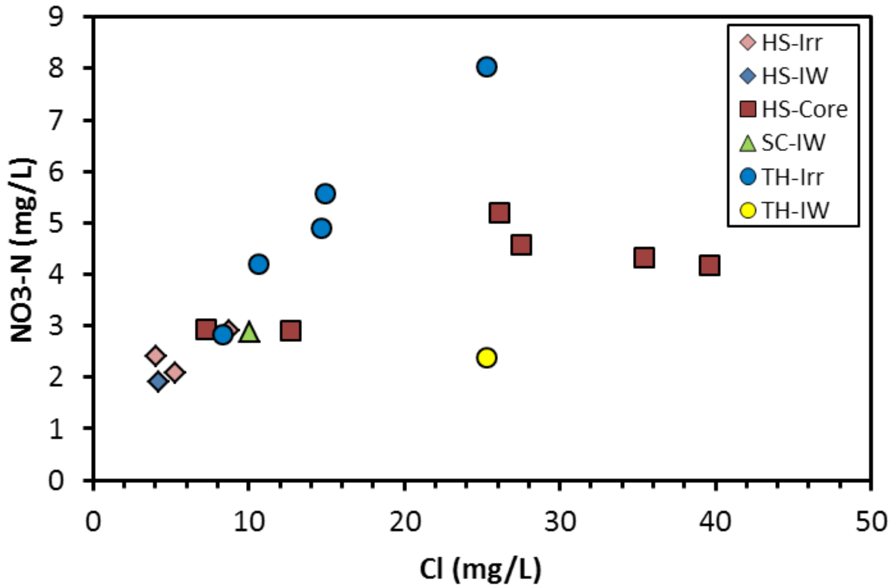

Figure 46—Nitrate vs. chloride concentration for all well and core samples. In the legend, IW = index well, Irr = irrigation well, and Core = core fluids.

Some interesting trends are apparent in the stable isotope data. First, nearly all the samples plot near the Global Meteoric Waterline (GMWL), indicating a meteoric source for the water in the aquifer (fig. 47). Waters with isotopic signatures that fall near the GMWL have not been significantly affected by evaporation. This suggests very little, if any, water within the HPA is irrigation return water, which would have an evaporative isotopic signature. However, a couple of the core samples plot to the right-hand side of the GMWL, suggesting that they may have been somewhat affected by evaporation. These samples are from the deepest section of the core that has been obtained to date (about 300 ft). Second, the isotopic signatures become lighter (i.e. more negative values) from south to north across the state (fig. 47). Finally, at the Haskell site, water sampled from wells also exhibits a distinctly lighter isotopic signature compared with core pore water (fig. 48). These statewide and local trends are significant and indicative of distinctly different sources of water within the HPA in Kansas.

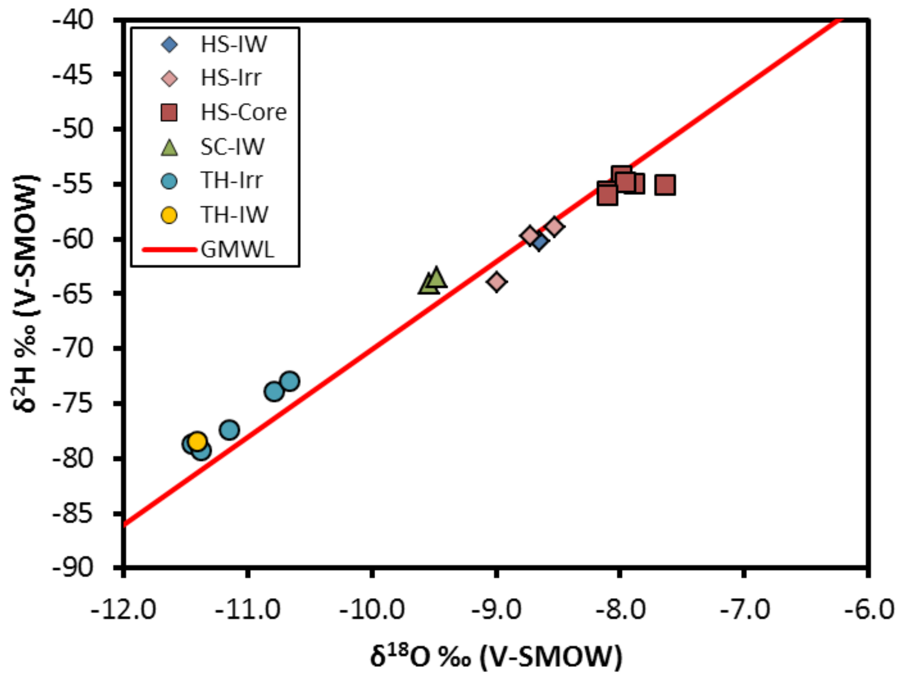

Figure 47—HPA δ^2H vs. $\delta^{18}O$ for waters sampled at the three original index well sites, nearby irrigation wells, and pore water, relative to the Global Meteoric Waterline (GMWL). In the legend, IW = index well, Irr = irrigation well, and Core = core fluids.

A south-to-north trend of progressively lighter stable isotopic composition is commonly observed in modern precipitation across eastern North America. This is due to a variety of factors, including temperature and rain-out effects. Typically, precipitation falling at colder temperatures has a lighter isotopic composition than that falling at warmer temperatures. Likewise, the further moisture moves from its source, the lighter the isotopic composition of the resulting precipitation. In Kansas, the Gulf of Mexico is generally the most significant source of atmospheric moisture. Thus, this south-to-north trend in the aquifer would appear to make sense at first glance. Unfortunately, the interpretation is not quite that simple; a check of expected annual mean isotopic values for modern precipitation indicates $\delta^{18}O$ should vary from -6.4 ±1.3 ‰ to -6.8 ±1.3‰ VSMOW (Vienna Standard Mean Ocean Water) from Haskell to Thomas counties (Bowen, 2014; Bowen and Revenaugh, 2003). Thus, the range for modern precipitation is significantly smaller (0.4‰ vs. 3.0 ‰ VSMOW) and heavier (-6.4 ‰ to -6.8 ‰ vs. -8.5 ‰ to -11.5 ‰) than observed in aquifer water. The difference is greatest in waters sampled in Thomas County. This indicates that waters sampled from the aquifer either recharged under different climatic conditions than presently affect the region or recharged at significantly higher elevations and the water has been transported over a large distance to its present location. The larger variation in values in the aquifer compared to modern precipitation might also indicate the HPA in Kansas was not recharged synchronously (i.e. water in northwest Kansas recharged at a different time compared with that found in southwest Kansas).

The local trend observed at the Haskell site is also very informative. Currently, coring has only been completed through the upper unconfined aquifer interval. The isotopic signature of pore water in this part of the aquifer is significantly heavier than the water in the deeper confined aquifer interval (sampled by the Haskell index well). This suggests the water in the unconfined aquifer interval recharged under different climate conditions than the water in the deeper aquifer (warmer temperatures or less intense precipitation events). This also provides an excellent tracer for determining which aquifer is providing water to irrigation wells, many of which are screened across both aquifers. Of the three irrigation wells sampled near the Haskell index well, two have nearly the same isotopic signature as the Haskell well, and one has an even lighter isotopic signature, indicating virtually no contribution from the upper aquifer. Further sampling of irrigation wells in the area will identify the relative importance of each aquifer interval for water supply. Likewise, continued collection of pore water through the aquitard will help provide information about contributions from aquitard leakage. Pore-water collection near the Haskell index well is part of an on-going NSF project awarded to the KGS to map HPA stratigraphy. Finally, given the possible hydraulic connection with the Dakota aquifer, a comparison of these data with results from samples collected nearby and known to be drawn from the Dakota aquifer would also help identify local water sources.

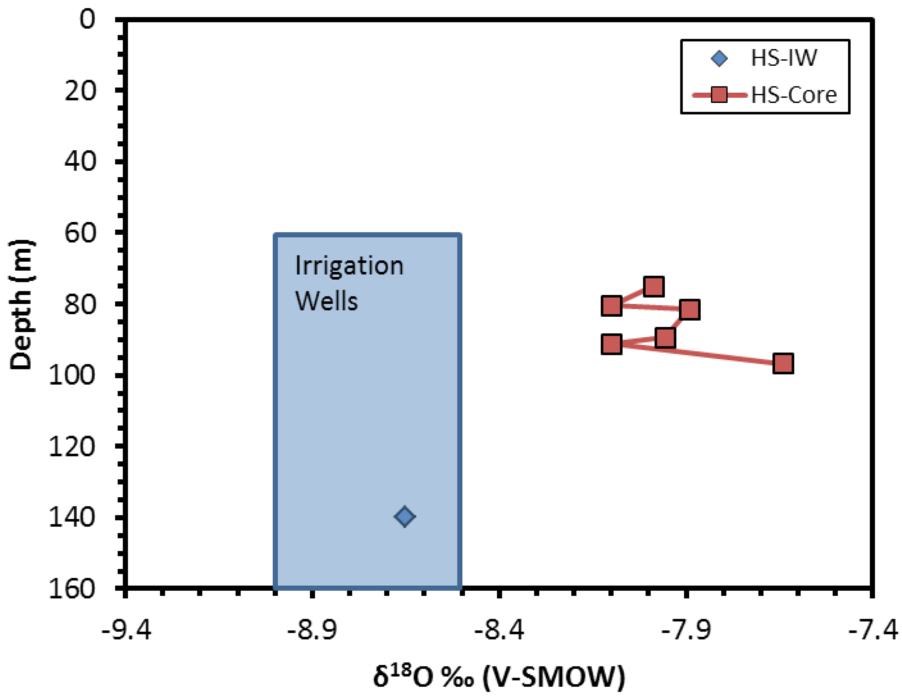

Figure 48—Depth vs. $\delta^{18}O$ for the Haskell index well and pore water from the HP1A core hole. The range of isotopic values for irrigation wells is also displayed (blue box).

Water samples from additional irrigation wells in the vicinity of the Haskell (two wells) and Thomas (one well) index wells were analyzed for radiocarbon to continue to refine estimates of groundwater recharge age at both sites. The radiocarbon values have not yet been corrected for carbonate dissolution and other processes that can affect dissolved carbon concentrations; however, the value obtained in Thomas County agrees quite well with uncorrected data for previously collected samples. The values obtained in Haskell County roughly bracket the uncorrected value for the previously obtained sample from the Haskell index well (table 20).

This method of dating groundwater actually dates the age of the dissolved inorganic carbon. Dissolved carbon can be affected by a number of sources and processes, including dissolving (or precipitating) carbonates in the subsurface as well as the original dissolved atmospheric carbon as the water recharged. Several models have been developed to account for these processes and provide a means for correcting ^{14}C activity in groundwater samples (e.g., Fontes and Garnier, 1979). Some additional information about water-rock interactions and the $\delta^{13}C$ of soil CO_2 and carbonate precipitates in the aquifer is needed to determine the most appropriate correction for the HPA (or even each individual site). The values reported here are uncorrected but will be evaluated and corrected in 2014.

Table 20—Uncorrected radiocarbon and δ[13]C data from the index well study areas.

Well Type	County	Location	Date	δ13C ‰ (PDB)	F (modern carbon)	14C age BP
Index Well	SC	18S-33W-01AAA	6/14/11	-7.3	0.2397	11,470
Index Well	TH	09S-33W-33BBB	6/15/11	-6.4	0.5911	4,220
Irrigation well	TH	09S-33W-32BBA	9/1/11	-4.1		3,830
Irrigation well	TH	09S-33W-32A	9/1/11	-8.1		3,960
Irrigation well	TH	09S-33W-32DBC	9/1/11	-4.7		4,600
Irrigation well	TH	09S-32W-29B	9/1/11	-3.9		4,400
Irrigation Well	TH	10S-33W-04B	3/20/13	-9.9	0.6025	4,070
Irrigation Well	HS	HS-6	8/1/13	-11.5	0.1779	13,870
Irrigation Well	HS	NE 1/4 Sec. 31	8/1/13	-11.2	0.3644	8,110
Index Well	HS	27S-R31W-36BDC	6/14/11	-6.7	0.2368	11,570

The distribution of anion and cation concentrations, and stable and radioactive isotope values, across western Kansas can also be compared with physical data to gain further insight into recharge and flow paths within the HPA. The geochemical data continue to corroborate physical data, showing the youngest water is at the Thomas County site, likely a reflection of relatively more recent recharge to the system. The stable isotope data indicate that the volume contribution of modern precipitation to groundwater at all three sites is minimal or non-existent.

Overall, the current geochemical data suggest the following hypothesis as a mechanism controlling the general recharge and water quality. Much of the water in the HPA in western Kansas appears to have been recharged several thousand to more than ten thousand years ago during a cooler climate than present. Some of the recharge at the index well sites could also have been sourced farther to the west in Kansas or easternmost Colorado at higher elevations and have moved to the east during regional groundwater flow. During a more recent period, probably less than a thousand years, a warmer climate could have decreased recharge and increased the dissolved solids content where the recharge originated at the surface through evapotranspiration water loss. This more recent recharge, with a higher dissolved solids concentration, has affected the chemistry of the water near the water table but has not been great enough in volume to significantly affect the isotopic composition of the water. As the volume of irrigation return flow increases with time in the water near the water table, changes in the isotopic composition as well as in the chemistry of water near the water table may become great enough to be observable.

As additional pore water, monitoring well, and irrigation well samples are collected and analyzed across the HPA, additional insights into recharge areas and flow path evolution will be possible. This information will be particularly useful for evaluating the conclusion that the aquifer is increasingly compartmentalized with depth (Butler, Stotler, Whittemore, and Reboulet, 2013).

8. Spin-offs and Related Research

In 2013, complementary research furthered the work of the project.

8.1 Haskell County NSF Project

In the summer of 2010, the KGS was awarded a $381,000 grant from the National Science Foundation (NSF) to study the subsurface stratigraphic framework, sedimentary facies, and chronostratigraphy of the Ogallala Formation and overlying units. Additional funding was provided to this project by the Kansas Water Office and the Bureau of Reclamation. Haskell County is the focus of this investigation. In April 2011, drilling began at a location adjacent to the Haskell County index well using the new KGS sonic drilling rig. However, a series of problems were encountered. Scheduling issues have prevented a return to the site, so the borehole had not yet been completed. The stratigraphy of the upper portion of the borehole has been described (Harlow, 2013), and analyses of fluid chemistry and isotopic composition have been performed (see Section 7). An additional four holes are set to be drilled in southwestern Kansas.

8.2 Department of Energy Grant

In 2011, the KGS was awarded the second phase ($225,000) of a grant subcontract from the Department of Energy to work together with Stanford University and Vista Clara, a company located near Seattle, Washington, to assess the potential of nuclear magnetic resonance (NMR) technology for estimation of water-filled porosity and permeability in small-diameter (2- to 5-in) wells. In the late fall of 2010, a prototype NMR tool was tested at the Thomas and Haskell index wells. The conclusion of those tests was that the tool was not reaching (sensing) beyond the borehole annulus. The tool was modified in 2011 to allow a greater sensing radius. The modified tool was tested at the Thomas index well in November 2011. Surface NMR soundings were also obtained in the vicinity of the Thomas index well at that time using a system developed by Vista Clara. The analysis of the measurements from both the logging tool and the surface soundings continues and should be completed in 2014.

8.3 Kansas Water Resources Institute Grants

Investigation of recharge to the High Plains aquifer, northwestern Kansas

The KU Geology and Geography departments and the KGS were jointly awarded a two-year $30,000 grant to investigate sources of recharge in the area of the Thomas County index well (total award was reduced by $7,000 due to federal budget sequestration). In March and April of 2013, 70 m of core were collected from within an irrigated circle located approximately one mile south of the Thomas County index well. Fluid has been collected from sediment core samples, and physical and chemical profiles (e.g., grain size, water content, chloride and nitrate concentrations) have been constructed (some of the chemical data were presented earlier in Section 7). Work is currently underway to determine recharge rates through the unsaturated zone and should be completed by summer of 2014.

Getting the information modelers need: Extracting hydrostratigraphic information from drillers' logs

The KGS was awarded a two-year $30,000 grant to investigate approaches to better use the information in drillers' logs (total award was reduced by $7,000 due to federal budget sequestration). The objectives of this project, now dubbed HyDRA (Hydrostratigraphic Drilling Record Assessment), are to 1) develop software and protocols to increase efficiency and accuracy of transcription of drillers' logs into a standardized and accessible database; 2) develop a protocol for three-dimensional (3D) interpolation of lithological data from drillers' logs, properly accounting for the categorical nature of these data, and a related cross-validation procedure for assessing log quality; and 3) apply the procedures developed under objectives 1 and 2 to create 3D depictions of the subsurface for use in simulations of water-level variations in the vicinity of the Thomas County index well. During the second year of the HyDRA project (March 2013–February 2014), a graduate student funded by the project has continued to work on development of the Thomas County model. Continuing work (in a no-cost extension) also includes application of the procedures to develop the aquifer property distributions for a groundwater flow model being developed for GMD1. The procedures described above have been used to develop a 3D grid representing the spatial distribution of the proportions of each of five hydraulic conductivity (K) categories based on drillers' logs from 2,216 wells. This grid will provide the basis for computing the spatial distribution of K based on typical K values for the five categories, providing a simple means to calibrate the model while still allowing for a rich, data-based representation of the spatial distribution of K. Figure 49 shows a representation of the distribution of the proportion-weighted average K category over the model domain.

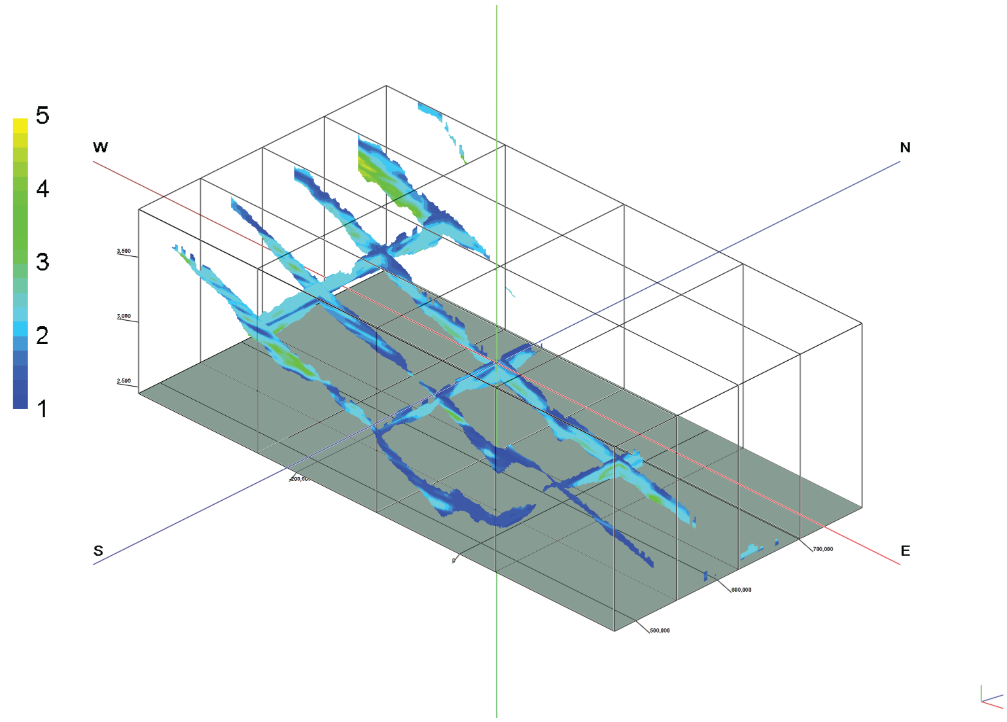

Figure 49—Average hydraulic conductivity category (1 for lowest permeability materials to 5 for highest) in slices of a three-dimensional model of the HPA in GMD1. The view is from the southeast. The model region is 111 miles east-west, 58 miles north-south, and 1,430-ft thick.

9. Summary of 2013 Accomplishments and Plans for 2014

9.1 2013 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 presentation. Data collection and analysis from the Thomas and Scott expansion wells have continued.
- Expanded activities at border well sites. Added two wells to the network (one each at the Liberal and Hugoton sites) and installed telemetry equipment at the Liberal and Hugoton sites; telemetered data now obtained from four wells at these two sites. Provided initial interpretation of the hydrographs from the four border well sites.
- Continued detailed analysis of hydrographs at all three original index well sites.
- Developed method for rapidly assessing hydraulic conditions in the screened interval of a well from inspection of the well hydrograph.
- 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.
- Initiated an analysis of climatic indices and their relationship to annual reported water use in the vicinity of the index wells.
- Continued integration of program data into the digital Kansas High Plains Aquifer Atlas (Fross et al., 2012).
- Presentations about the index well program given to KWO, DWR, GMD personnel, among others.

9.2 Planned Activities, 2014

- Continue monitoring and processing water-level data from the three original index wells and the expansion wells in their vicinity, the new index wells along the Kansas-Oklahoma border (border 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 new border index wells, and any other data sets that we can find.
- Assess recovery and pumping for 2013 and 2014 periods.
- Seek new wells to add to the network with a particular emphasis on GMD1.
- 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.
- Cooperate with GMD4 on interpretation of monitoring data from the Sheridan-6 monitoring wells.
- Assess effect of Dakota aquifer on water levels in the vicinity of the Haskell County index well and the direction of possible leakage between the HPA and Dakota aquifers.
- Continue assessment of relationship between climatic indices, annual water-level changes, and annual water use in the three western GMDs.
- Integrate information from drillers' logs in the vicinity of the Thomas and Scott index wells into interpretation of water-level responses in those areas.

9.3 Outstanding Issues

Major unresolved issues include the following:

- The source and areal extent of the inflow, which is not induced by pumping activity, in the vicinity of the Thomas County index well.
- 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.
- Conditions in the HPA in the area of thick saturated interval along the Kansas-Oklahoma border.

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