Kansas Geological Survey

High Plains Aquifer Index Well Program: 2014 Annual Report

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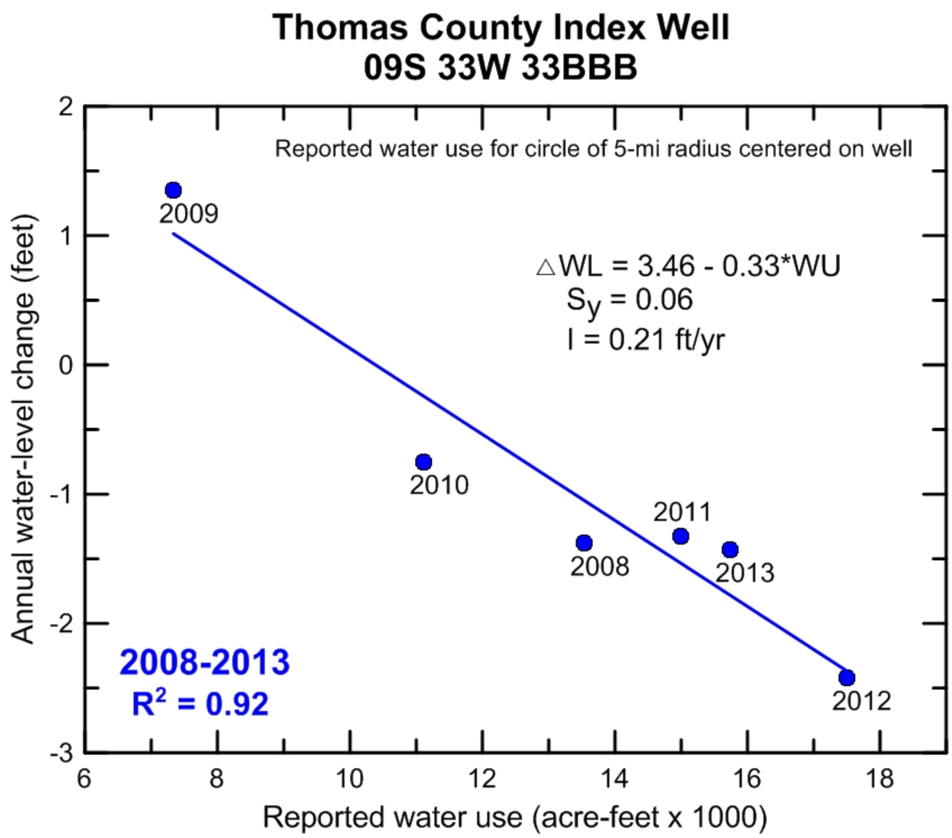

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Acknowledgments

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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 and south-central Kansas. The study is supported by the Kansas Water Office (KWO) with Water Plan funding as a result of KWO's interest in and responsibility for long-term planning of groundwater resources in western and south-central Kansas. The Kansas Department of Agriculture, Division of Water Resources (DWR), provides assistance, as do Groundwater Management Districts (GMDs) 1, 3, 4, and 5, the Kansas State University Northwest Research-Extension Center (KSU-NWREC), and the United States Geological Survey (USGS).

The project began with the installation of three monitoring ("index") wells in late summer 2007. Each well has a transducer for continuous monitoring of water levels that is connected to telemetry equipment to allow real-time monitoring of well conditions on a publicly accessible website. An index well was installed in each of the three western GMDs, with locations deliberately chosen to represent different water use and hydrogeologic conditions and to take advantage of related past or ongoing studies. A major focus of the program has been the development of criteria or methods to evaluate the effectiveness of management strategies at the local scale. Changes in water level—or the rate at which the water level is changing—are considered the most direct and unequivocal measures of the impact of management strategies. At the time of this report, monitoring data (hourly frequency) from seven 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 (expansion wells). In late 2012, wells in four monitoring nests (one well from each nest) along the Kansas-Oklahoma state line in GMD3 were added to the network (border wells); additional wells were added from two of these nests (one well per nest) in August 2013 and, in cooperation with the USGS, telemetry equipment was installed in four of these wells in late 2013. In 2014, equipment for real-time monitoring of water levels was installed in an observation well at the KSU-NWREC facility in Colby and in a well just north of Belpre in GMD5. In addition, the Sheridan-6 Local Enhanced Management Area (SD-6 LEMA) monitoring wells were incorporated into the network.

This report provides (a) an update of the hydrographs for the original three index wells, the new index wells (border wells, the Colby well, the Belpre well, and the five SD-6 LEMA wells), and the expansion wells in the vicinity of the Scott and Thomas index wells (one well near the Scott index well and three wells in the vicinity of the Thomas index well); (b) interpretation of the hydrographs from the original three index wells and the border wells, and an initial discussion of the hydrographs from the newer index wells; (c) a discussion of climatic indices and radar precipitation data and their relationship to annual water-level changes at the original three index wells and to water use in the vicinity of those wells; (d) a discussion of the development of the theoretical support for the linear annual water use versus annual water-level change relationship; and (e) discussion of the results of chemical analyses of groundwater samples obtained from the border wells.

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), in general, may not produce an adequate dataset to evaluate how management decisions affect water-level changes at the local scale in the short term (fewer than four to five years).

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

(3) 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.

(4) 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.

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

(6) 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.

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

(8) 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 2015 will be on the continuation of monitoring at all project wells; continuation of the detailed analyses of hydrographs from all project wells; continued assessment of the subsurface information that can be acquired from an analysis of the water-level response to changes in barometric pressure; drilling of three new index wells in GMD1; further assessment of the relationships among climatic indices, radar precipitation data, annual water-level change, and water use; further development of the theoretical support for the linear water use versus annual water-level change relationship; further interpretation of geochemical results of analyses of water samples from the vicinity of the index wells; 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—henceforth, local or subunit) 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 and south-central Kansas. The Kansas Department of Agriculture, Division of Water Resources (DWR), provides assistance, as do Groundwater Management Districts (GMDs) 1, 3, 4, and 5, the Kansas State University Northwest Research-Extension Center (KSU-NWREC), and the United States Geological Survey (USGS).

A major focus of the program is the development of criteria or methods to evaluate the effectiveness of management strategies at the local scale. Changes in water level—or the rate at which the water level is changing—are considered the most direct and unequivocal measures of the impact of management strategies. Because of the economic, social, and environmental importance of water in western and south-central Kansas, the effects of any modifications in patterns of water use need to be evaluated promptly and accurately. The project has focused on identifying and reducing the uncertainties and inaccuracies in estimates of year-to-year changes in water level, so that the effects of management decisions can be assessed as rapidly as possible. The approach outlined by this study aims to provide more accurate and timely information at the subunit scale than is provided by the annual water-level measurement program. Furthermore, this study provides data that are valuable for the interpretation of the water-level change estimates from the annual measurement program and are the basis for the development of new methods for using the annual program measurements.

At the end of 2014, monitoring data (hourly frequency) from seven full recovery and pumping seasons and one ongoing recovery season have been obtained. With increasing data, the index well program has demonstrated the following:

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

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

(3) 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.

(4) 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.

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

(6) 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.
(7) Continuous monitoring has helped establish the hydrogeologic information conveyed by hydrographs of various forms.
(8) 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 inspired the development of new methods that use the annual measurement program data to predict the effect of management decisions on the subunit and larger scale.

The index well network was enlarged in 2014 to include a well at the KSU-NWREC facility in Colby and a well just north of Belpre in GMD5. Note that the term "index well" is used here to designate a well at which monitoring is anticipated to continue for many years. There are additional wells, designated here as "expansion wells," at which monitoring is not likely to continue over the long term because of constraints imposed by well depth (i.e., water level is anticipated to drop below the bottom of the well screen) or logistical issues; these expansion wells are mostly in the vicinity of the original three index wells. Both types of wells are considered in this report.

This report provides (a) an update of the hydrographs for the original three index wells, the new index wells, wells along the Kansas-Oklahoma border in GMD3 (border wells), the Colby well, the Belpre well, and the five Sheridan-6 Local Enhanced Management Area (SD-6 LEMA) wells, and the expansion wells (one well in GMD1 and three wells in the vicinity of the original Thomas index well); (b) interpretation of the hydrographs from the original three index wells and the border wells, and an initial discussion of the hydrographs from the newer index wells; (c) a discussion of climatic indices and radar precipitation data and their relationship to annual water-level changes at the original three index wells and to water use in the vicinity of those wells; (d) a discussion of the development of the theoretical support for the linear relationship between water use and annual water-level change; and (e) discussion of the results of chemical analyses of groundwater samples obtained from the border wells.

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 ongoing studies (fig. 1). The original experimental design envisioned use of the index wells to anchor and calibrate the manual measurements of annual program wells in their vicinity, thus providing more consistency and confidence in the calculation of the water-table surface and its changes in those general areas. However, the scope of the project was expanded to also focus on the mechanisms that control changes in water level in the vicinity of each well. To establish the generality of the conclusions obtained from the index wells, the project was expanded to include "wells of opportunity" or "expansion wells" in the vicinity of the original three index wells:

1. Haskell County expansion—with the collaboration of the DWR, the project obtained access to water-level records from additional wells in the vicinity of the Haskell index well that are

instrumented by the DWR; this provides an opportunity for more extensive comparisons over a relatively short distance. However, the fact that the producing wells at the Haskell site may draw on and measure either or both of two separate aquifer units makes it more complicated than the commonly adopted view of the HPA as a single unconfined aquifer (see Butler, Stotler, et al., 2013).

2. Scott County expansion—early in 2012, with the assistance of GMD1, two additional expansion wells in the vicinity of the Scott County index well were equipped with transducers, and monitoring is continuing at one of these wells. The commonly adopted view of the HPA as a single unconfined aquifer appears reasonable in the vicinity of the Scott County site.
3. Thomas County expansion—with the collaboration of the DWR and GMD4, six additional wells (two of which are annual program wells) were equipped with transducers. Continuous monitoring is ongoing at three of these additional wells. The commonly adopted view of the HPA as a single unconfined aquifer appears reasonable in the vicinity of the Thomas County site.

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

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

The Scott and Thomas sites are both located in areas where the saturated thickness is generally 100 ft or less, with areas of less than 50 ft nearby. Although both areas have shown long-term declines in water level, detailed analyses of the index well hydrographs indicate inflow into these areas, at least temporarily, is greater than originally thought. The Scott County site is in GMD1, which is the location of 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.

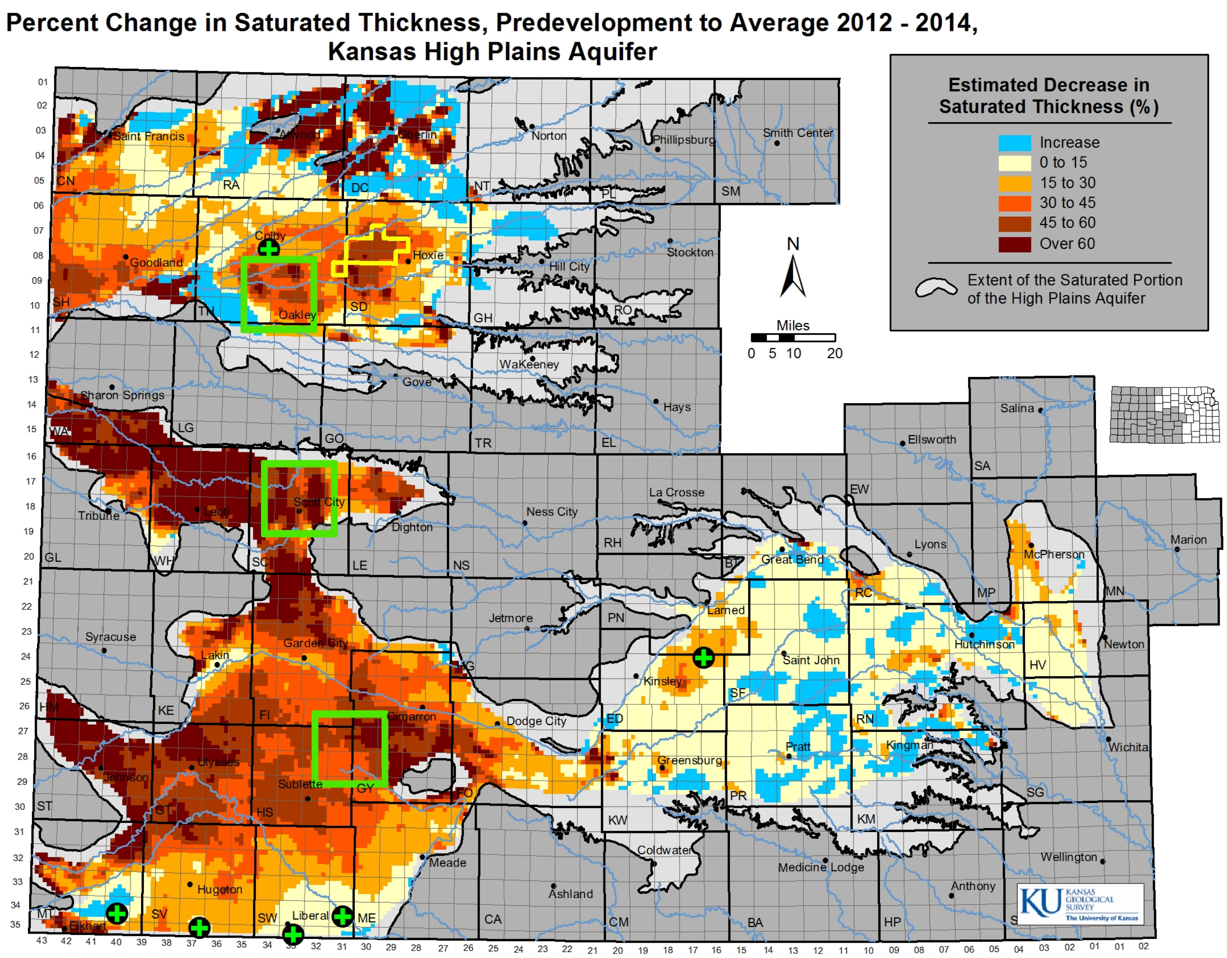


Figure 1—The Kansas portion of the High Plains aquifer, with aquifer and county boundaries shown. Each colored pixel represents one section (1 mi^2), coded for the degree of groundwater depletion from the beginning of large-scale development to the average of conditions in 2012–2014. The green boxes are approximately centered on the original index well sites; the black circles with green plus signs indicate the locations of the border wells, the Colby well, and the Belpre well; the yellow outlined area indicates the location of the SD-6 LEMA where there are five index wells. Additional wells (expansion wells) are monitored within each of the green boxes.

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

Site	2015 WL elev. (ft)[a]	2015 Saturated thickness (ft)	Bedrock depth (estimated ft below land surface)	Screened interval (ft below land surface)	2013 Water Use (ac-ft) 1-mi circle	2-mi circle	5-mi circle
Haskell	2,535.3	130.4	433	420–430	1,376	8,265	46,452
Scott	2,828.3	84.2	223	215–225	1,116	3,228	16,171
Thomas	2,967.9	64.4	284	274–284	1,341	3,432	15,734

[a]2015 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 seven and a half years of hourly measurements, our understanding of water-level responses and trends at all three sites has improved significantly. All three index well hydrographs indicate that, although pumping occurs sporadically throughout the year, the major drawdown in water levels occurs during the pumping season in the summer when the aquifer is stressed significantly for an extended period of time. For this study, the pumping season is defined as the period from the first sustained drawdown during the growing season (often, but not always, following the maximum recovered water level) to the first major increase in water level near the end of the growing season. The recovery season (period) is defined as the time between pumping seasons. Since water levels continue to increase during the recovery period at all three index wells, and full recovery has not been observed at any of the wells, the difference between water levels measured during the recovery period from one year to the next only provides a measure of the year-to-year change in still-recovering water levels. This year-to-year change in recovering water levels must be used cautiously by managers because it can be affected by a variety of factors, such as the duration of recovery at the time of the measurement, that are unrelated to aquifer trends. More importantly, it *does not* involve the final recovered water level, the elevation to which the water level would rise if the recovery were not interrupted by the next pumping season. Efforts to estimate this final recovered water level, which would provide a reliable basis for managers to assess the impact of changes in water use, through various extrapolation procedures, have proven difficult because of the variety of mechanisms that can affect the recovery process (Stotler et al., 2011). Note that all of the original index wells were added to the annual water-level measurement network and, since January 2008, have been measured as part of the annual program.

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

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

3.1.1. Haskell County

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

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

3.1.1.1. Hydrograph and General Observations

Figure 3 shows the complete hydrograph for the Haskell index well, table 2 summarizes its general characteristics , and table 3 compares the manual and transducer measurements from the well. The confined nature of the aquifer zone in which the index well is screened is indicated by the hydrograph form (see Butler et al. [2014]—Section 4.3) and by the 100–120+ ft change in water level during each pumping season, despite the absence of high-capacity pumping wells in the immediate vicinity of the index well (closest pumping well is almost half a mile away). Continuous water-level measurement at the Haskell well unexpectedly terminated on January 12, 2014, as a result of sensor failure. On February 20, the sensor was removed from the well and a replacement sensor was installed on March 26, 2014.

The 2013–2014 recovery started on July 29, 2013, the last date of pumping for the 2013 irrigation season that had a major impact on the index well, and ended sometime in late February or early March of 2014 (exact date not known because of the sensor failure). Other than a 13-day pumping period that lasted from August 21 to September 3, 2013, only a minor amount of pumping took place during the 2013–2014 recovery. Similar to previous years, the 2014 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-planting irrigation of other crops, whereas the break in pumping could be caused by decreased water use during planting of summer crops. The 2014–2015 recovery season began on August 28, 2014, and was continuing at the time of this report (March 6, 2015). Other than an 18-day pumping period that lasted from November 28 to December 15, 2014, only a minor amount of pumping has occurred during the 2014–2015 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. Although the minimum 2014 water-level elevation was 1.2 ft lower than in 2013, it was still 2.0 ft higher than in 2012. The most likely explanation is the cessation of pumping early in the 2013 and 2014 irrigation seasons at two nearby irrigation wells as a result of court decisions (May 21, 2013, Garetson Brothers versus Kelly and Diana Unruh, District Court of Haskell County Kansas, Case No. 12-CV-09; May 5, 2014, Garetson Brothers and Foreland Real Estate, LLC versus American Warrior Inc., and Rick Koehn, District Court of Haskell County Kansas, Case No. 12-CV-09). Water use for 2014 will be available later in 2015 and, as a result of the court decision, is expected to be among the lowest during the monitoring period. In 2013, water use within the 2-mi radius surrounding the index well was 8,265 ac-ft, the lowest use year during the monitoring period, and 1,009 ac-ft below the average for the period (9,274 ac-ft). The 2013 water use was applied on more irrigated acres than all but one year during the monitoring period, resulting in the lowest water use per acre irrigated during the monitoring period (table 2). In 2014, the index well recorded a year-to-year decline in the maximum recovered water level of 7.7 ft (estimated value because of sensor failure), the third largest decline during the monitoring period. Given that the well was still recovering at the time of this report, the expectation is that the decline in the maximum recovered water level in 2015 will be, by far, the smallest observed during the monitoring period.

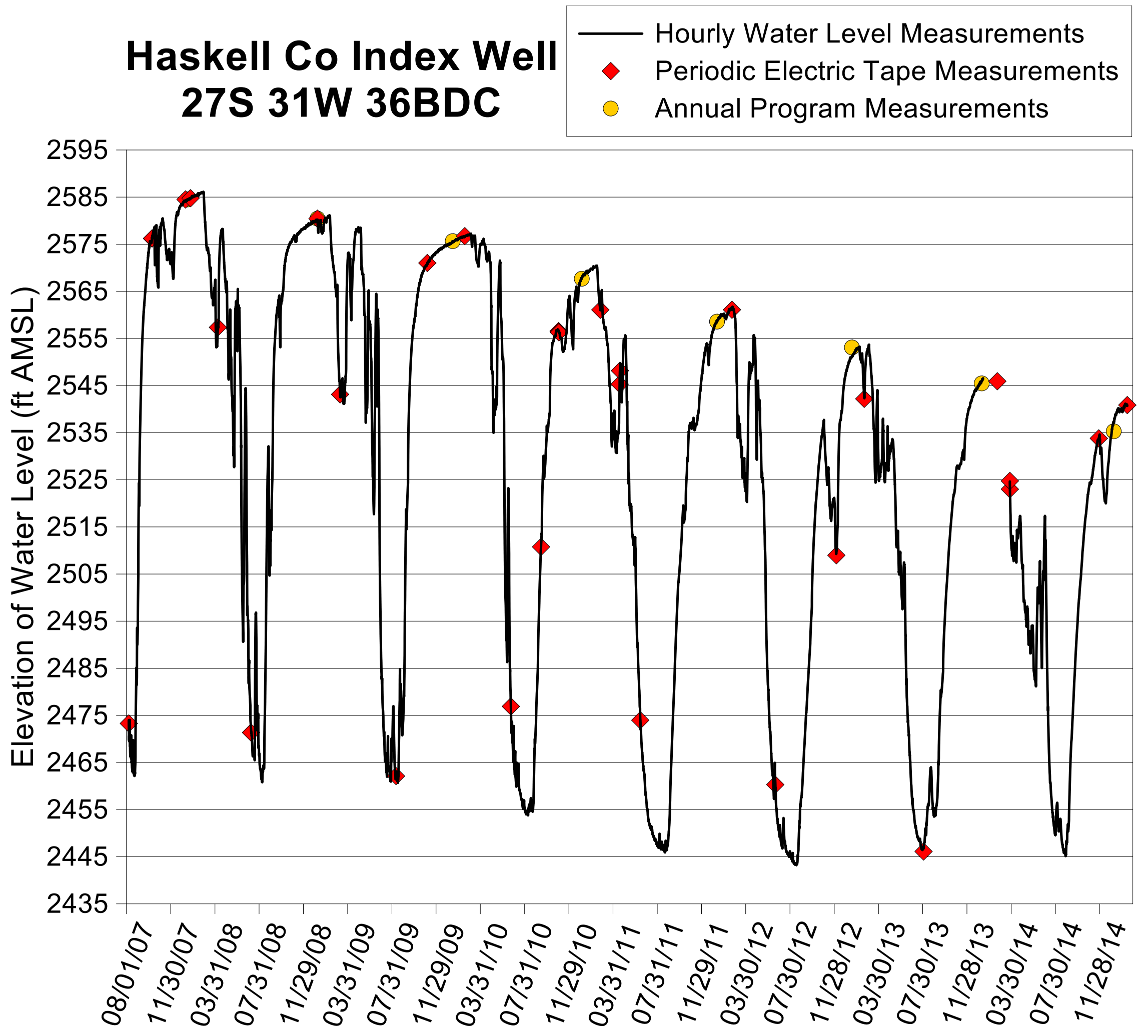


Figure 3—Haskell County index well hydrograph—total data run (continuous measurements) to 2/12/15. A water-level elevation of 2,445 ft corresponds to a depth to water of 392.85 ft below land surface (lsf); the top of the screen is 420 ft below lsf (elevation of 2,417.85 ft) and the bottom of the aquifer is 433 ft below lsf (elevation of 2,404.85 ft). The screen terminates 3 ft above the bottom of the aquifer. Break in monitoring from January to March 2014 was result of sensor failure (see text).

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

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

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

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

3.1.1.2. Measurement Comparisons

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

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/15/2008	2,584.48	NA	Steel tape
	2,584.44[c]	NA	Transducer
1/7/2009	2,580.41	-4.07 (-5.0)	Steel tape
	2,580.19[c]	-4.25	Transducer
	2,580.10[d]	NA	Transducer
1/14/2010	2,575.63	-4.78 (-3.9)	Steel tape
	2,575.54[c]	-4.65	Transducer
	2,574.51[d]	-5.59	Transducer
1/4/2011	2,567.67	-7.96 (-6.8)	Steel tape
	2,567.91[c]	-7.63	Transducer
	2,567.94[d]	-6.57	Transducer
1/11/2012	2,558.57	-9.1 (-8.7)	Steel tape
	2,558.82[c]	-9.09	Transducer
	2,558.75[d]	-9.19	Transducer
1/16/2013	2,553.09[e]	-5.48[e] (-8.1)	Steel tape
	2,551.22[c]	-7.60	Transducer
	2,550.99[d]	-7.76	Transducer
1/8/2014	2,545.46	-7.63[e] (-7.7)	Steel tape
	2,545.94[cf]	-5.28	Transducer
	NA	NA	
1/6/2015	2,535.29[g]	-10.17[g] (NA)	Steel tape
	2,537.27[c,g]	-8.67[g]	Transducer
	2,537.34[d,g]	NA	Transducer

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=373925100395301).
[b] Value in ( ) is the decline in the maximum recovered water level measured by the index well transducer.
[c] Average of values over time interval 0800–1600, not corrected for barometric pressure.
[d] Average of values over time interval 0800–1600, corrected for barometric pressure using the KGS barometric pressure correction program (Bohling et al., 2011).
[e] Suspect 2013 annual measurement value.
[f] Data taken from 2-hour telemetry data, sensor not downloadable after 8/1/13 because of sensor failure.
[g] Measurement affected by 18-day pumping period ending on 12/15/14.

3.1.2. Scott County

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

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

3.1.2.1. Hydrograph and General Observations

Figure 5 shows the complete hydrograph for the Scott index well, table 4 summarizes its general characteristics, and table 5 compares the manual and transducer measurements from the well. The unconfined nature of the aquifer zone in which the index well is screened is indicated by the hydrograph form (see Butler et al. [2014]—Section 4.3) and by the relatively small change (average of 3.8 ft over the monitoring period) and rate of change in water level during each pumping and recovery season, despite at least two high-capacity pumping wells within approximately a half mile of the index well.

The 2013–2014 recovery started on September 13, 2013. There was little pumping during the recovery period; pumping for the 2014 irrigation season started on March 13, 2014. Pumping was off and on in the area until March 25, 2014. Pumping was then near continuous until May 23, after which there was limited pumping until July 2. After a sudden drop of more than 0.7 ft within 24 hours on July 2–3, pumping appeared to continue at all wells in the vicinity until September 4. Other than some pumping in more distant wells in mid-November to mid-December, there was little pumping during the recovery period. The 2014–2015 recovery was continuing at the time of this report (March 6, 2015). Transducer measurements during the recovery period are noisier than previous years; the source of that higher noise level appears to be a plugged vent tube as discussed in section 4.2. The situation will be addressed in the spring of 2015. Note that as a result of the sensor failure at the Haskell County index well on January 12, 2014, the sensor was replaced at the Scott County index well on March 27, 2014.

Each year, the minimum recorded water-level elevation has declined from the previous year at the Scott County index well. The lowest water level observed was in 2014; the minimum 2014 water-level elevation was 2.0 ft lower than in 2013 (the largest single year decline during the monitoring period) and 6.6 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 2014 and was 0.8 ft below that of 2013 and 5.8 ft below that of 2008. Given that the minimum water-level elevation in 2014 was 2.0 ft lower than in 2013, the expectation is that the decline in the maximum recovered water level in 2015 will be considerably more than the 2014 decline. Water-use data for 2014 will be available later in 2015. Water use within the 2-mi radius surrounding the index well in 2013 (3,228 ac-ft) was 174 ac-ft below the average for the monitoring period (3,402 ac-ft).

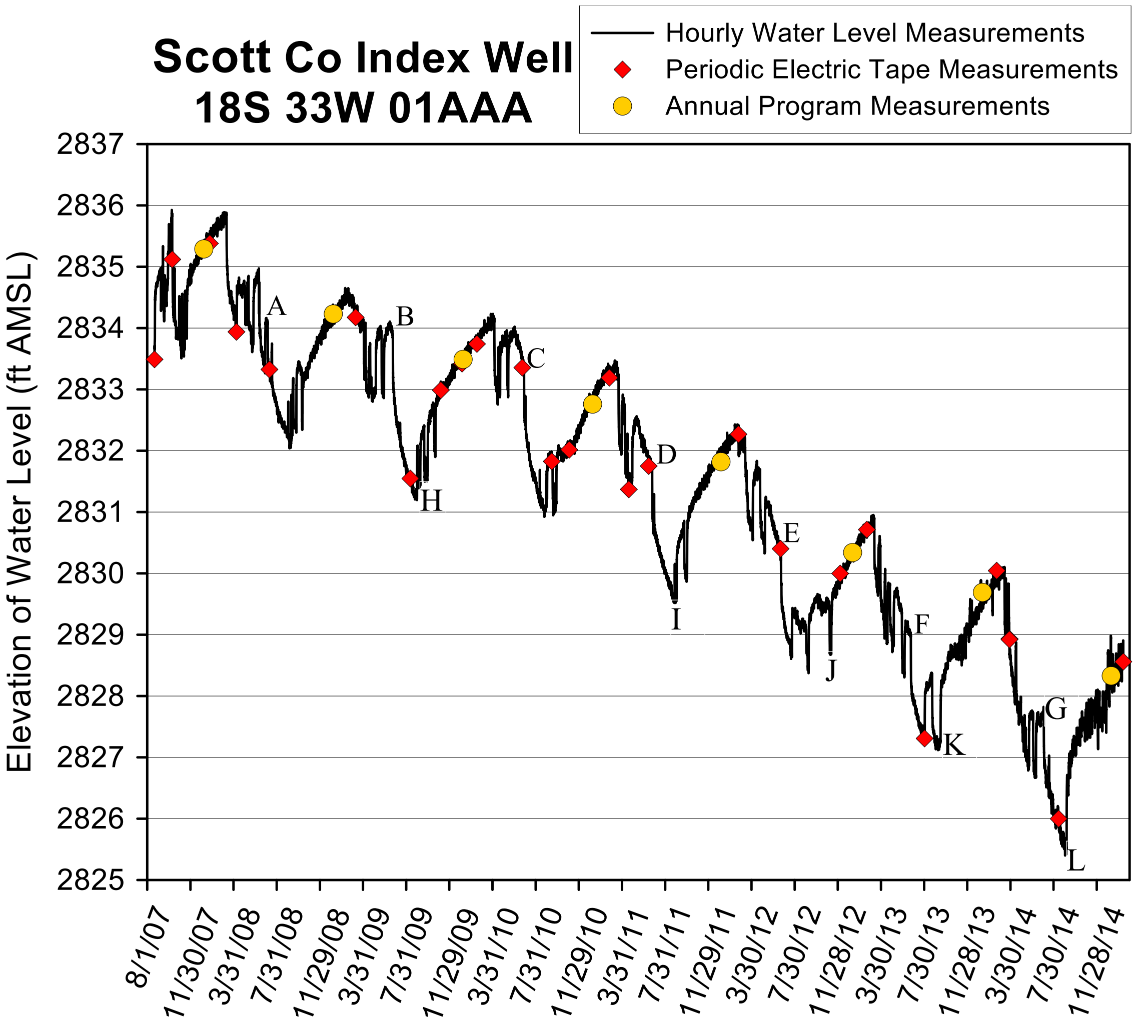


Figure 5—Scott County index well hydrograph—total data run to 2/11/15. A water-level elevation of 2,829 ft corresponds to a depth to water of 138.15 ft below land surface (lsf); the top of the screen is 215 ft below lsf (elevation of 2,752.15 ft) and the bottom of the aquifer is 223 ft below lsf (elevation of 2,744.15 ft). The screen terminates 2 ft below the bottom of the aquifer. A–L 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	2014
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	2.825.40
	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	8/31/14
Maximum Observed Recovery Elevation	Feet	NA	2.835.9	2.834.6	2.834.2	2.833.5	2.832.6	2.830.9	2.830.1
	Date	NA	3/4/08	2/17/09	3/26/10 and 4/1/10	3/11/11	2/28/12	3/9/13	3/13/14
Apparent Recovery	Feet	NA	> 2.5	2.6	3.0	2.6	3.1	2.2	2.7
Annual Change in Maximum Observed Recovery	Feet	NA	NA	-1.3	-0.4	-0.7	-0.9	-1.7	-0.8
Recovery Season	Start	NA	< 8/21/077	9/13/08	8/30/09	8/29/10	9/1/11	9/7/12	9/13/13
	End	NA	3/11/08	4/2/09	4/5/10	3/17/11	3/12/12	3/11/13	3/13/14
	Length (Days)	NA	> 203	201.3	217.8	200.2	192.8	185.25	180.33
Pumping During Recovery Season	Length (Days)	NA	> 48.2	13.7	21.0	12.8	8.7	5	8.6
Length of Pumping Season	Days	NA	182.3	150.0	145.7	168.1	186.42	186.8	175.0
2-mi Radius Water Use	Irrigated Acres	4132	3,950	3,923	3,665	4,078	3,734	3,857	NA
	Total Use (ac-ft)	3,175.1	4,059.0	2,955.5	3,035.9	3,595.6	3,760.8	3,228.2	NA
	Irrigation Use Only (ac-ft)	3,095.8	4,014.3	2,955.5	3,017.9	3,580.6	3,747.7	3,212.0	NA
	Use per Irrigated Acre (ft)	0.75	1.02	0.75	0.82	0.88	1.00	0.83	NA

3.1.2.2. Measurement Comparisons

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

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/7/2008	2,835.29	NA	Steel tape
	2,835.29[c]	NA	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 (-0.85)	Steel tape
	2,829.46[c]	-0.81	Transducer
	2,829.50[e]	-0.75	Transducer
1/8/2015	2,828.33	-1.36 (NA)	Steel tape
	2,828.22[c]	-1.24	Transducer
	2,828.28[e]	-1.22	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, an additional annual program well, and nearby points of diversion.

Figure 6 is an aerial overview of the Thomas County site at a scale that shows the index well, an additional annual program well, and the nearby wells with active water rights. The Thomas County site expansion wells are discussed in Section 3.2.5.

3.1.3.1. Hydrograph and General Observations

Figure 7 shows the complete hydrograph for the Thomas County index well, table 6 summarizes its general characteristics, and table 7 compares the manual and transducer measurements from the well. The unconfined nature of the aquifer zone in which the index well is screened is indicated by the form of the hydrograph and by the relatively small change and rate of change in water level during each pumping and recovery season, despite eight high-capacity pumping wells within a mile of the index well.

The 2013–2014 recovery was the second shortest observed during the monitoring period at the Thomas well, beginning on September 13, 2013, and ending on March 24, 2014, only 0.5 days longer than the shortest observed recovery (2010-2011). The 2014 pumping season began with an initial pumping period of about two weeks. This was then followed by intermittent pumping from April 8 to June 18, after which sustained pumping essentially continued until the end of the pumping season on August 28, 2014. There has been little pumping during the 2014–2015 recovery period, which was still continuing at the time of this report (March 6, 2015). Note that as a result of the sensor failure at the Haskell County index well on January 12, 2014, the sensor was replaced at the Thomas County index well on March 27, 2014.

Unlike the Haskell index well (until the court-ordered shutdowns of two nearby irrigation wells in 2013 and 2014) and the Scott index well, the minimum recorded water-level elevation at the Thomas index well has not declined every year. The minimum observed water-level elevation in 2014, which was the lowest recorded over the monitoring period, was 0.8 ft below that of 2013 and 6.9 ft below that of 2010 (the highest recorded minimum water-level elevation during the monitoring period). Water-use data for 2014 will be available later in 2015. In 2013, water use within the 2-mi radius surrounding the index well (3,432 ac-ft) was the second highest during the monitoring period and 535 ac-ft above the average for the period (2,897 ac-ft). The 2013 water use was applied on only slightly more (< 1%) irrigated acres than the average irrigated acres over the monitoring period (3,028 ac), so the water use per acre irrigated was the second highest for the period (table 6). The maximum observed water level in 2014 was 1.6 ft below that of 2013 and 6.1 ft below that of 2010 (the highest maximum observed water level during the monitoring period). Given that the 2014 minimum water level (recorded on August 26) was the lowest minimum recorded water-level elevation during the monitoring period, the expectation is that, in the absence of the recovery period extending into late April or beyond, the maximum observed water level at the end of the 2014–2015 recovery will be the lowest value recorded to date at the Thomas County index well.

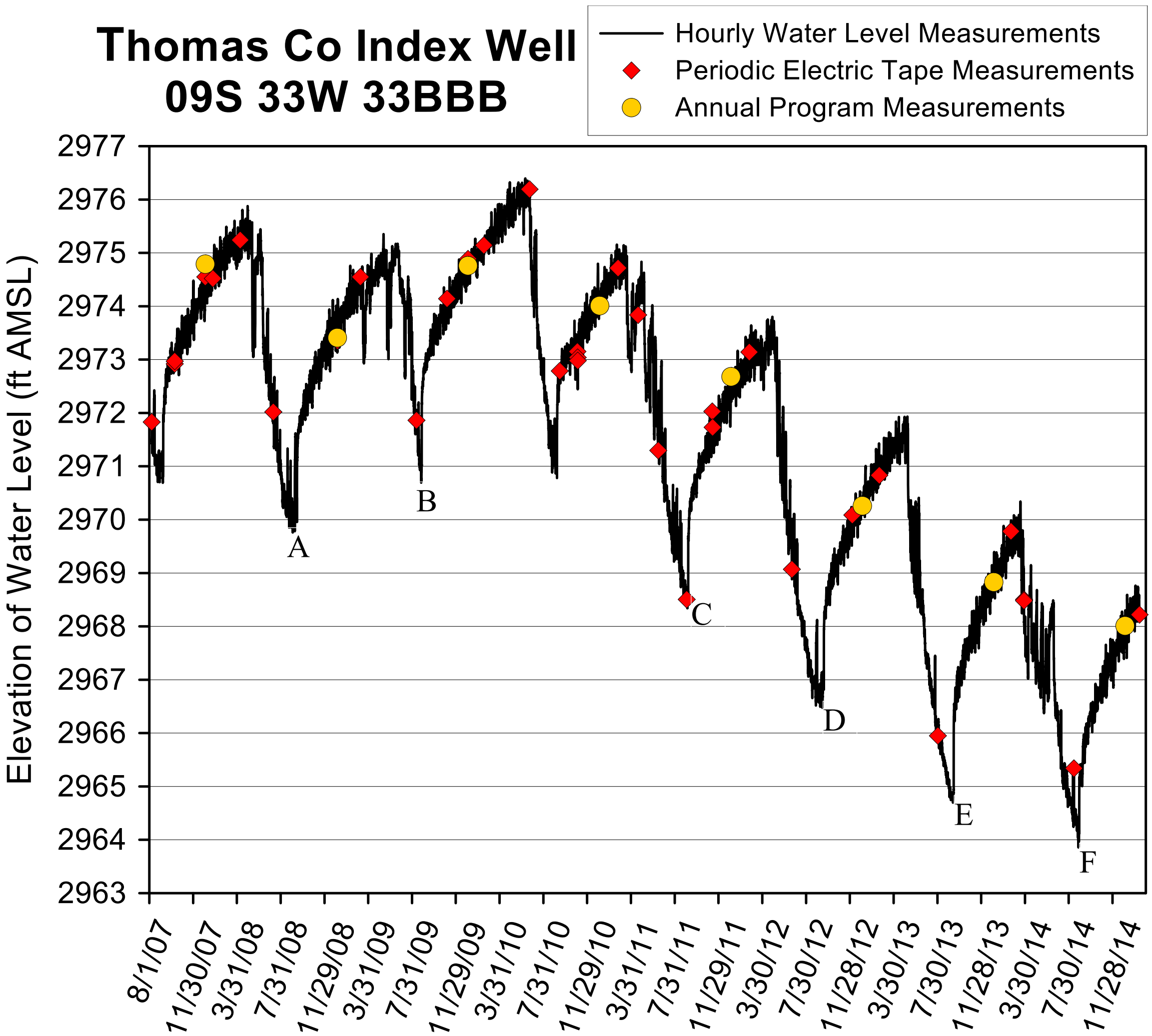


Figure 7—Thomas County index well hydrograph—total data run to 2/11/15. A water-level elevation of 2,968 ft corresponds to a depth to water of 219.56 ft below land surface (lsf); the top of the screen is 274 ft below lsf (elevation of 2,913.56 ft), and the bottom of the aquifer is 284 ft below lsf (elevation of 2,903.56 ft). The screen terminates at the bottom of the aquifer. A–F defined in text (Section 4.2).

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

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

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

3.1.3.2. Measurement Comparisons

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

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/3/2008	2,974.67	NA	Steel tape
	2,974.61[c]	NA	Transducer
1/4/2009	2,973.29	-1.38 (-0.53)	Steel tape
	2,973.18[c]	-1.43	Transducer
	2,973.59[d]	NA	Transducer
1/2/2010	2,974.64	+1.35 (+1.05)	Steel tape
	2,974.74[c]	+1.56	Transducer
	2,974.65[d]	+1.06	Transducer
1/3/2011	2,973.89	-0.75 (-1.24)	Steel tape
	2,974.14[c]	-0.60	Transducer
	2,974.15[d]	-0.50	Transducer
1/3/2012	2,972.56	-1.33 (-1.40)	Steel tape
	2,972.61[c]	-1.53	Transducer
	2,972.36[d]	-1.79	Transducer
1/2/2013	2,970.14	-2.42 (-1.87)	Steel tape
	2,970.26[c]	-2.35	Transducer
	2,970.31[d]	-2.05	Transducer
1/2/2014	2,968.71	-1.43 (-1.64)	Steel tape
	2,968.73[c]	-1.53	Transducer
	2,968.37[d]	-1.94	Transducer
1/2/2015	2,967.89	-0.82 (NA)	Steel tape
	2,968.08[c]	-0.65	Transducer
	2,967.95[d]	-0.42	Transducer

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=383132100543101).
[b] Value in ( ) is the change in the maximum recovered water level measured by the index well transducer.
[c] Average of values over time interval 0800–1600, not corrected for barometric pressure.
[d] Average of values over time interval 0800–1600, corrected for barometric pressure using KGS barometric correction program.

3.2. New Index Wells and the Expansion Well Network

3.2.1. Border Index Wells

In the spring of 2012, we identified wells in four well nests that were originally installed by the USGS (NAWQA program) in 1999 just north of the Oklahoma border. The USGS, which had not used these wells for more than a decade, agreed that the KGS could use the wells for both annual water-level measurements and continuous monitoring. The well nests are located in Morton, Stevens, and Seward counties (filled black circles with green plus signs along the Kansas-Oklahoma border in fig. 1—from right to left (east to west), Cimarron, Liberal, Hugoton, and Rolla sites). These monitoring locations are important additions to the index well network because they provide valuable information about aquifer responses in the areas of thick saturated intervals in southernmost GMD3.

In the first week of December 2012, we installed transducers in one well at each site and a barometer at the site near Hugoton. The two criteria used to select the well at each site for monitoring were 1) the nature of pumping-induced water-level responses determined from an examination of manual water-level data collected by the USGS in 1999 and 2000 (McMahon, 2001—fig. 8), and 2) the position of the well within the HPA (the objective was to have a well that would provide information about conditions in the main body of the HPA). All four of these wells have been added to the annual water-level measurement network and, since January 2013, have been measured as part of the annual program.

On August 1–2, 2013, we placed transducers in one additional well each at the Hugoton and Liberal sites. In the third week of December 2013, working cooperatively with the USGS, we installed telemetry equipment at the Liberal and Hugoton sites and began to obtain real-time water-level data from the four monitored wells at those sites. Those data can be viewed on the KGS (www.kgs.ku.edu/HighPlains/OHP/index_program/index.shtml) and USGS (waterdata.usgs.gov/ks/nwis/current/?type=gw) websites. Data from the Cimarron and Rolla sites can be viewed up to the latest download on the KGS website. On February 20, 2014, a barometer was added at the Rolla site. A barometer will be added to the Cimarron site in the spring of 2015.

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

Table 8—Characteristics of the border index wells.

<table>
<tr><th rowspan="2">Site</th><th rowspan="2">2015 WL elev. (ft)[a]</th><th rowspan="2">2015 Saturated thickness (ft)</th><th rowspan="2">Bedrock depth (estimated ft below land surface)[b]</th><th rowspan="2">Screened interval (ft below land surface)[b]</th><th colspan="3">2013 Water Use (ac-ft)</th></tr>
<tr><th>1-mi circle</th><th>2-mi circle</th><th>5-mi circle</th></tr>
<tr><td>Cimarron 210</td><td>2,474.18</td><td>290.18</td><td>345</td><td>200–210</td><td>116</td><td>116</td><td>9,860</td></tr>
<tr><td>Liberal 160[c]</td><td>2,691.90[d]</td><td>446.90</td><td>576</td><td>140–160</td><td rowspan="2">0.77</td><td rowspan="2">1287[e]</td><td rowspan="2">32,254[e f]</td></tr>
<tr><td>Liberal 436</td><td>2,661.83</td><td>416.83</td><td>576</td><td>426–436</td></tr>
<tr><td>Hugoton 313[c]</td><td>2,922.57[d]</td><td>457.57</td><td>635</td><td>303–313</td><td rowspan="2">1,263</td><td rowspan="2">3,685</td><td rowspan="2">42,308[e]</td></tr>
<tr><td>Hugoton 495</td><td>2,919.05</td><td>454.05</td><td>635</td><td>485–495</td></tr>
<tr><td>Rolla 366</td><td>3,189.50</td><td>213.50</td><td>399</td><td>356–366</td><td>276</td><td>1,554</td><td>10,603</td></tr>
</table>

[a] 2015 annual tape water-level measurements from WIZARD database.
[b] Measurements from table 2 in McMahon (2001).
[c] Not an annually measured index well but an additional sensor and telemetry equipped well.
[d] 2015 water-level measurements from hand measurements taken 2/12/2015.
[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 6,797 ac-ft of non-irrigation water for city of Liberal.

3.2.1.1. Cimarron Site

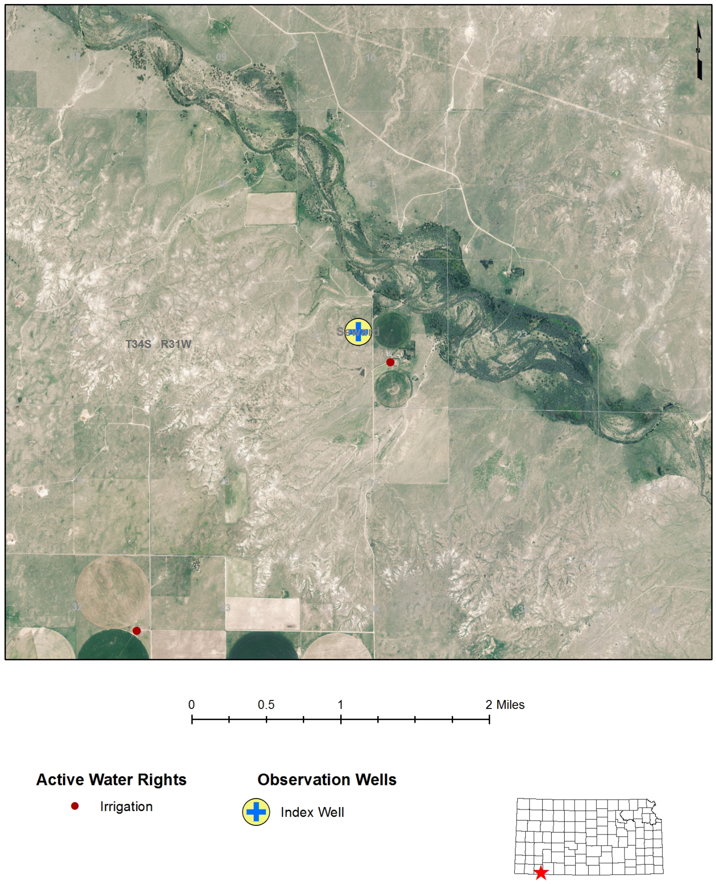


Figure 8—Aerial view of Cimarron index well site and nearby points of diversion.

Figure 8 is an aerial view of the Cimarron site (T. 34 S., R. 31 W., 22 BDD) at a scale that shows the index well and the nearby wells with active water rights; there was no additional annual network well in the area. The site includes three wells in the HPA and one in the Permian bedrock; the middle well in the HPA, screened 200–210 ft below land surface, has been instrumented (henceforth, Cimarron 210 or Cimarron index well).

3.2.1.1.1. Hydrograph and General Observations

Figure 9 shows the complete hydrograph for the Cimarron index well, table 9 summarizes its general characteristics, and table 10 compares the manual and transducer measurements from the well. The unconfined nature of the aquifer zone in which the index well is screened is indicated by the hydrograph form and by the small change in water level during the pumping season, despite the nearby (within 0.3 mi) irrigation well. The fluctuations superimposed on the water levels, particularly evident during the recovery periods, are produced by variations in barometric pressure. The small magnitude of these fluctuations (< 0.2 ft) is due to the relatively shallow depth to water (55 ft) at the site.

The 2013–2014 recovery began on October 5, 2013, and ended on April 2, 2014. Other than a few days of pumping in mid-December, there was very little pumping during the recovery period. During the 2014 pumping season (April 2–August 21), the water level was affected by sporadic pumping at the nearby irrigation well (e.g., the abrupt decline at A on fig. 9) and by more regional pumping effects (e.g., the gradual decline during period B on fig. 9). The 2014–2015 recovery season was continuing at the time of this report (March 6, 2015). Other than small magnitude regional pumping effects in September 2014, there appears to have been little pumping in nearby wells during the recovery period.

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 2015, the water level appears to be recovering to near 2,474.4 ft, a loss of about 1.6 ft in 15 years.

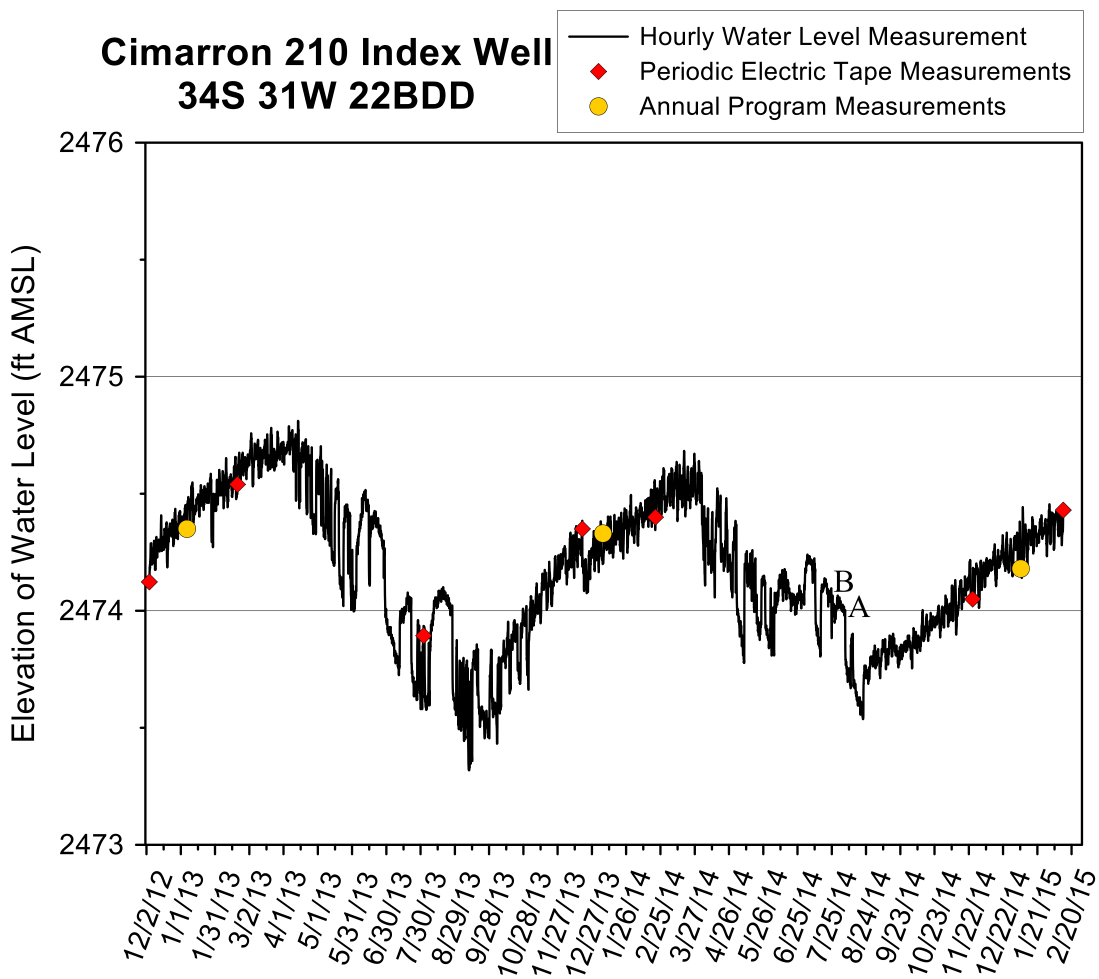


Figure 9—Cimarron 210 index well hydrograph—total data run to 2/12/15. A water-level elevation of 2,474 ft corresponds to a depth to water of 55.0 ft below land surface (lsf); the top of the 10-ft screen is 200 ft below lsf (elevation of 2,329 ft), and the bottom of the aquifer is 345 ft below lsf (elevation of 2,184 ft). A and B defined in text.

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

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

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

3.2.1.1.2. Measurement Comparisons

Table 10—Annual water-level measurement[a] comparison with transducer measurements, Cimarron 210 index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/6/2013	2,474.35	NA	Steel tape
	2,474.41[c]	NA	Transducer
	2,474.40[d]	NA	Transducer
1/5/2014	2,474.33	-0.02 (-0.13)	Steel tape
	2,474.21[c]	-0.20	Transducer
	2,474.28[d]	-0.12	Transducer
1/6/2015	2,474.18	-0.15 (NA)	Steel tape
	2,474.24[c]	+0.03	Transducer
	2,474.27[d]	-0.01	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. <u>Liberal Site</u>

Figure 10—Aerial view of Liberal index well site, an additional annual program well, and points of diversion in the area. The solid horizontal black line less than a mile south of the Liberal site marks the Kansas-Oklahoma border.

Figure 10 is an aerial view of the Liberal site (T. 35 S., R. 33 W., 15 ABC) at a scale that shows the index well site, an additional annual program well, and the nearby wells with active water rights in Kansas (Oklahoma wells not shown). The site includes four wells in the HPA; the second deepest well, screened at 426–436 ft below lsf, was initially instrumented (henceforth, Liberal 436 or Liberal 436 index well). In the first week of August 2013, the shallow well, screened at 140–160 ft below lsf, was also instrumented (henceforth, Liberal 160 or Liberal 160 index well). The fields in the immediate vicinity of the site appear to be dryland farmed.

3.2.1.2.1. <u>Hydrograph and General Observations</u>

Figure 11 shows the hydrographs for the two Liberal index wells, table 11 summarizes the general characteristics of the Liberal 436 hydrograph, and table 12 compares the manual and transducer measurements from Liberal 436. The confined nature of the aquifer zone in which Liberal 436 is screened is indicated by the hydrograph form and the relatively small (< 0.35 ft) amplitude fluctuations, which are produced by variations in barometric pressure, superimposed on water levels (particularly evident during the recovery period). This interpretation was confirmed through an analysis using the BRF software developed earlier in this program (Bohling et al., 2011). The interval in which Liberal 160 is screened is likely unconfined as the amplitude of the fluctuations produced by variations in barometric pressure is, in general, considerably larger than that observed in Liberal 436, which would be expected for an unconfined aquifer with a relatively large (> 150 ft) depth to water. The hydraulic conditions in the screened interval at the Liberal 160 well will be clarified in 2015.

The 2014 pumping season began on April 7 and continued through September 7. The muted response to the pumping season in Liberal 160 demonstrates that that interval has a weak hydraulic connection with the more heavily stressed deeper portion of the HPA at the site. The elevation difference between water levels in the two wells indicates that the pumping induces downward flow from the shallower interval. The 2014–2015 recovery was continuing at the time of this report (March 6, 2015). Note that the sensor in the Liberal 160 index well was misprogrammed so hourly water-level data were not acquired from August 20, 2014, to November 25, 2014. However, 15-minute data were collected with the sensor via another means and are used to fill in that interval.

The vast majority of the recovery in Liberal 436 in both 2013 and 2014 occurred relatively quickly after cessation of pumping, with only limited (2014–2015) or virtually no (2013–2014) recovery after that initial rapid rise in water level. This is likely an indication that the aquifer in the vicinity of Liberal 436 is at least partially compartmentalized, similar to conditions seen in wells in the upper sand interval in the vicinity of the Haskell index well (Butler, Stotler, et al., 2013).

On November 25, 2014, water samples were taken from both the Liberal 160 and Liberal 436 wells. During the sampling, Liberal 160 was inadvertently pumped dry. After the sampling, the water level recovered in Liberal 160 to an elevation approximately 1 foot below the elevation prior to sampling (step change at A in fig. 11). Manual measurements confirmed the 1-ft change in water level. The cause of the step change in water level accompanying the sampling event will be explored further in 2015. There was no change in the pre- and post-sampling water level at Liberal 436.

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 2015 at Liberal 436 is recovering to near 2,662 ft, a loss of about 21 ft in 15 years (1.4 ft/yr), which is consistent with the 22-ft decline over this same period measured at a nearby well of the annual measurement program (T. 35 S., R. 33 W., 16 BCA 01). For Liberal 160, the water level recovered to an elevation of approximately 2,706 ft after the 1999 pumping season; the recent data indicate that the water level in early 2015 at Liberal 160 is recovering to an elevation of approximately 2,692 ft, a loss of about 14 ft in 15 years (< 1 ft/yr).

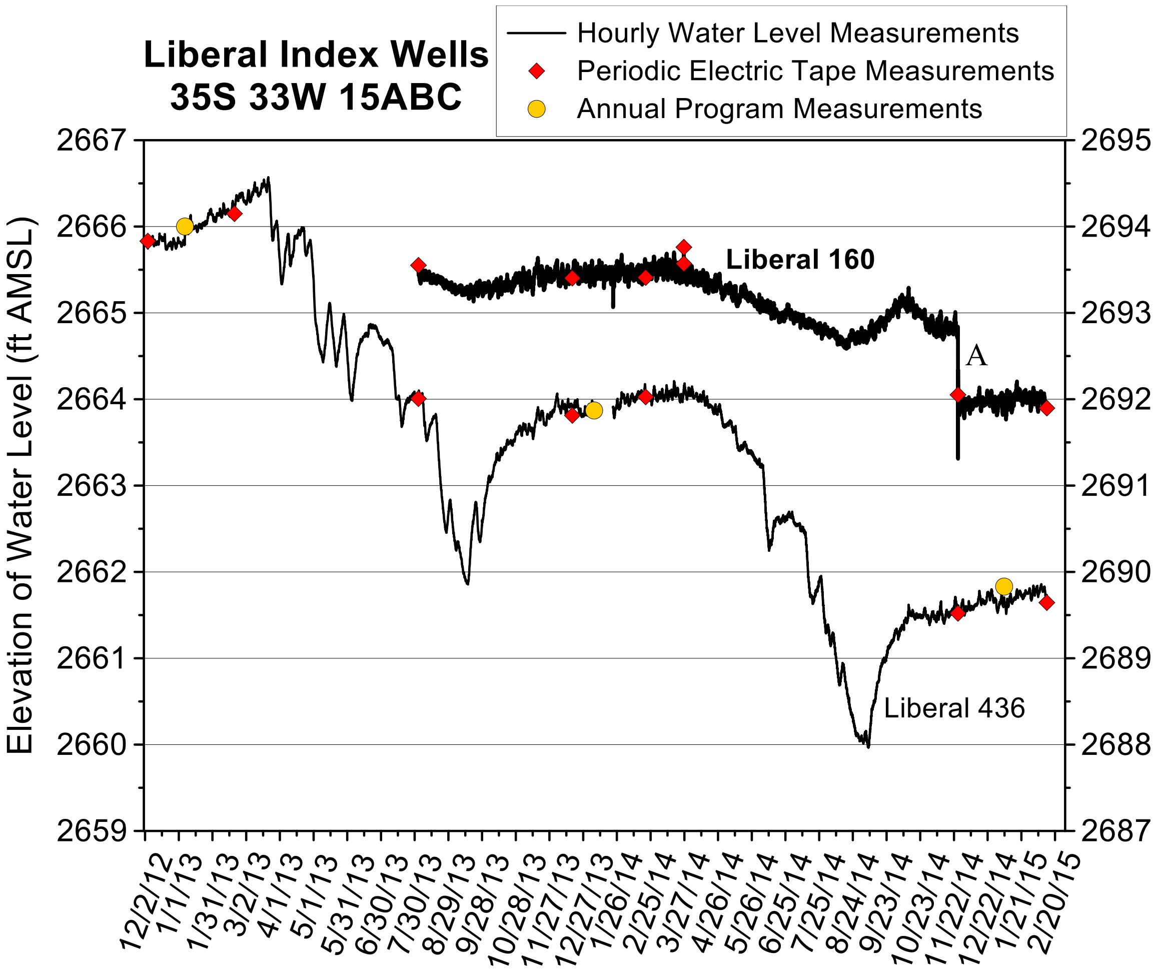


Figure 11—Hydrographs of Liberal index wells—total data run to 2/12/15. The Liberal 436 plot corresponds to the left y-axis; a water-level elevation of 2,664.0 ft corresponds to a depth to water of 157.0 ft below land surface (lsf); the top of the 10-ft screen is 426 ft below lsf (elevation of 2,395 ft). The Liberal 160 plot corresponds to the right y-axis; a water-level elevation of 2,694.0 ft corresponds to a depth to water of 127.0 ft below lsf; the top of the 20-ft screen is 140 ft below lsf (elevation of 2,681 ft). Bottom of the aquifer is 576 ft below lsf (elevation of 2,245 ft). Interruption of continuous monitoring at the Liberal 436 index well shortly after the 2014 annual program measurement discussed in the previous annual report (Butler et al., 2014); step change in water level in Liberal 160 on 11/25/14 (marked by A) is discussed in text.

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

		2013	2014
Minimum Water-Level Elevation	Feet	2,661.8	2,660.0
	Date	9/15/13	9/6/14
Maximum Observed Recovery Elevation	Feet	2,666.6	2,664.2
	Date	3/21/13	3/17/14
Apparent Recovery	Feet	NA	2.4
Annual Change in Maximum Observed Recovery	Feet	NA	-2.4
Recovery Season	Start	NA	10/15/13
	End	3/22/13	4/7/14
	Length (Days)	NA	174.3
Pumping During Recovery Season	Length (Days)	NA	6.3
Length of Pumping Season	Days	188.1	152.3
2-mi Radius Water Use[a]	Irrigated Acres	122	NA
	Total (ac-ft)	1,286.81	NA
	Irrigation Use Only (ac-ft)	821.0	NA
	Use per Irrigated Acre (ft)	1.71	NA

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

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 (-2.4)	Steel tape
	2,663.87[c]	-2.01	Transducer
	2,663.90[d]	-2.07	Transducer
1/5/2015	2,661.83	-2.04 (NA)	Steel tape
	2,661.67[c]	-2.2	Transducer
	2,661.68[d]	-2.22	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

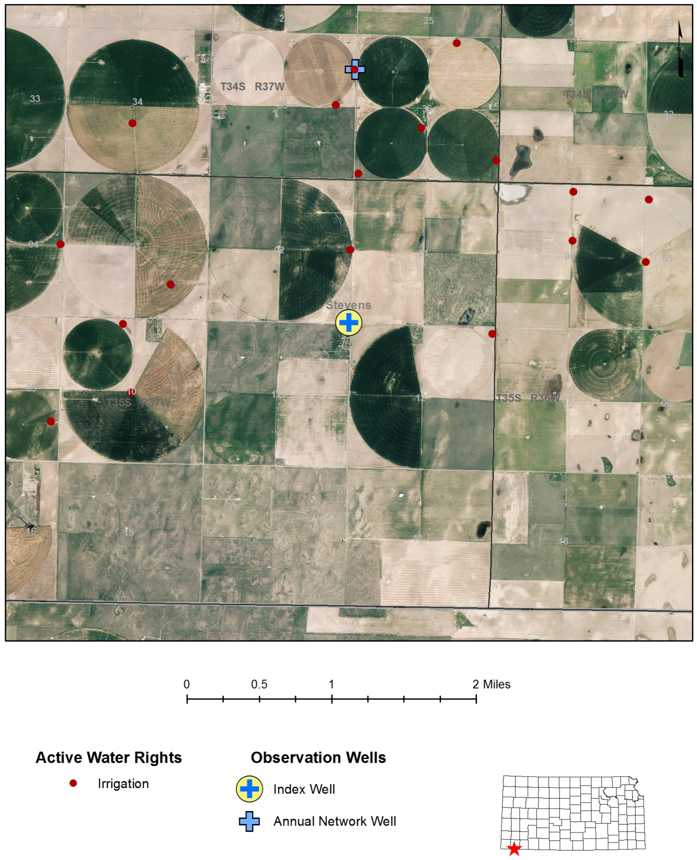


Figure 12—Aerial view of Hugoton index well site, an additional annual program well, and nearby points of diversion.

Figure 12 is an aerial view of the Hugoton site (T. 35 S., R. 37 W., 2 DDD) at a scale that shows the index well site, an additional annual program well, and nearby wells with active water rights. The site includes four wells, one near the water table and three at increasingly greater depths in the HPA; the second deepest well, screened at 485–495 ft, 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 2013 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 2013 water use).

3.2.1.3.1. Hydrograph and General Observations

Figure 13 shows the hydrographs for the two Hugoton index wells, table 13 summarizes the general characteristics of the Hugoton 495 hydrograph, and table 14 compares the manual and transducer measurements from Hugoton 495. The large rapid drops and rises following commencement and cessation, respectively, of pumping are similar to the behavior observed at the Haskell index well and indicate that the intervals in which both wells are screened act as a confined aquifer. This interpretation was confirmed through an analysis of water-level fluctuations induced by variations in barometric pressure using the BRF software developed earlier in this program (Bohling et al., 2011).

The 2014 pumping season began on March 11 with a 15-day pumping period, most likely for winter wheat and pre-planting irrigation; widespread pumping in the area began on April 21. Widespread pumping continued through September 6, although sporadic pumping occurred in the area until October 28. 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 (81 ft of drawdown at peak of 2014 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 2014–2015 recovery was continuing at the time of this report (March 6, 2015). Note that both sensors at the Hugoton site were misprogrammed, so hourly water-level data were not acquired from February 20, 2014, to November 24, 2014. However, 15-minute data were collected with these sensors via another means and are used to fill in that interval.

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 and 2014 (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 2015 at both wells are recovering to near 2,922 ft, a loss of about 48 ft in 15 years (> 3 ft/yr); the water level in the closest annual measurement program well (T. 34 S., R. 37 W., 35 AAD 01) declined 46.8 ft over this same time period.

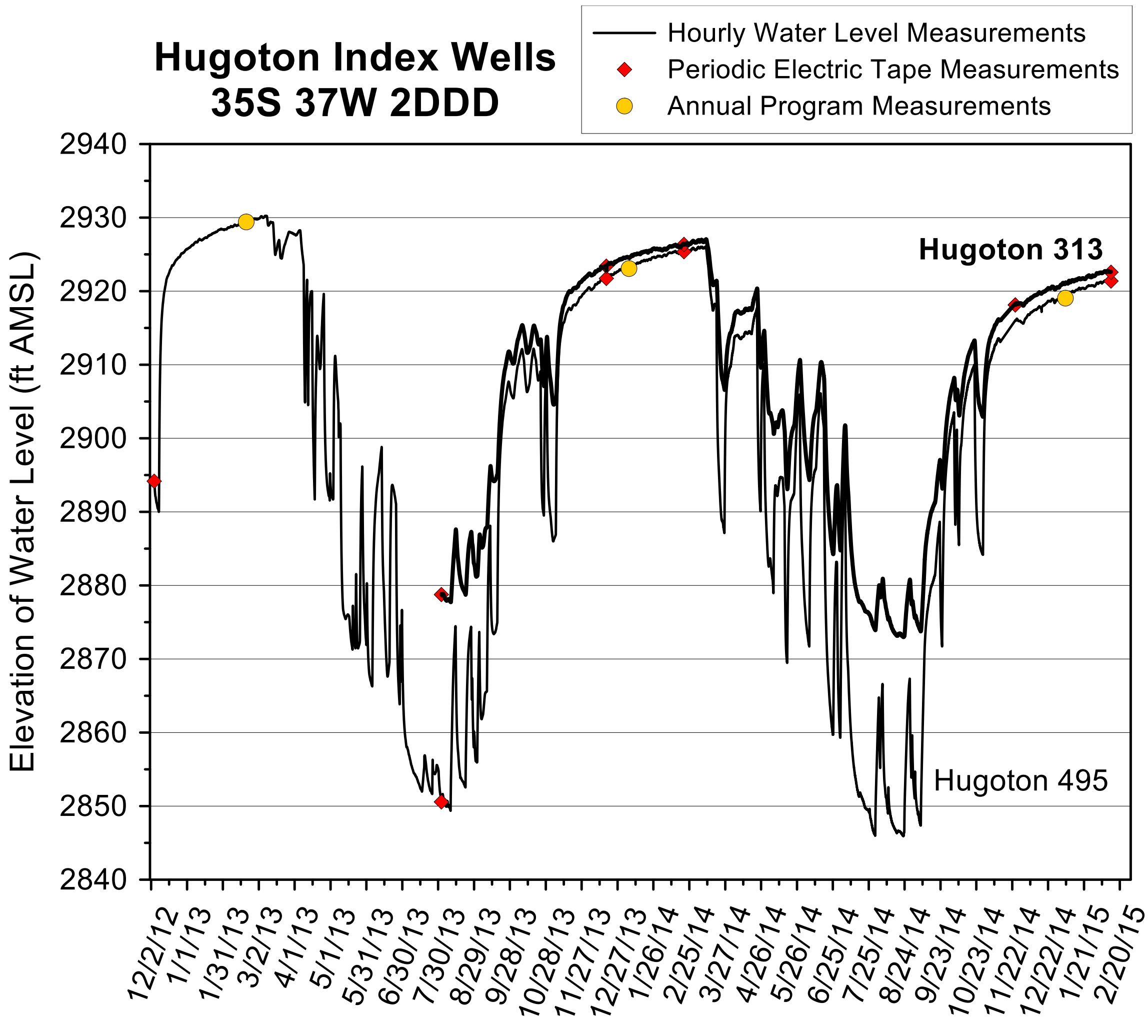


Figure 13—Hydrographs of Hugoton index wells—total data run to 2/12/15. A water-level elevation of 2,930.0 ft corresponds to a depth to water of 170.0 ft below land surface (lsf). For the Hugoton 495 well, the top of the 10-ft screen is 485 ft below lsf (elevation of 2,615 ft). For the Hugoton 313 well, the top of the 10-ft screen is 303 ft below lsf (elevation of 2,797 ft). Bottom of the aquifer is 635 ft below lsf (elevation of 2,465 ft).

Table 13—General characteristics of the Hugoton 495 index well hydrograph and local water-use data.

		2013	**2014**
Minimum Water-Level Elevation	Feet	2,849.4	2,845.9[b]
	Date	8/9/13	8/22/14
Maximum Observed Recovery Elevation	Feet	2,930.2	2,926.1[b]
	Date	3/7/13	3/10/14
Apparent Recovery	Feet	NA	76.7
Annual Change in Maximum Observed Recovery	Feet	NA	-4.2
Recovery Season	Start	NA	9/4/13
	End	3/8/13	3/11/14
	Length (Days)	NA	188.1
Pumping During Recovery Season	Length (Days)	NA	39.3
Length of Pumping Season	Days	153.6	179.0
2-mi Radius Water Use[a]	Irrigated Acres	2,531	NA
	Total (ac-ft)	3,685	NA
	Use per Irrigated Acre (ft)	1.45	NA

[a]2012 Irrigated Acres—2,700, Total—3,828.39 ac-ft, Use per Irrigated Acre—1.42 ft
[b]Based on 15-minute telemetry data, hourly sensor data not available as a result of a programming error.

3.2.1.3.2. Measurement Comparisons

Table 14—Annual water-level measurement[a] comparison with transducer measurements, Hugoton 495 index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/6/2013	2,926.37[c,d]	NA	Transducer
2/19/2013	2,929.85	NA	Steel tape
	2,929.22[c]	NA	Transducer
	2,929.34[e]	NA	Transducer
1/5/2014	2,923.07	NA (-4.20)	Steel tape
	2,923.18[c]	-3.19	Transducer
	2,923.27[e]	-3.10	Transducer
1/5/2015	2,919.05	-4.02 (NA)	Steel tape
	2,919.55[c]	-3.63	Transducer
	2,919.47[e]	-3.80	Transducer

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

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

[c] Average of values over time interval 0800–1600, not corrected for barometric pressure.

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

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

3.2.1.4. Rolla Site

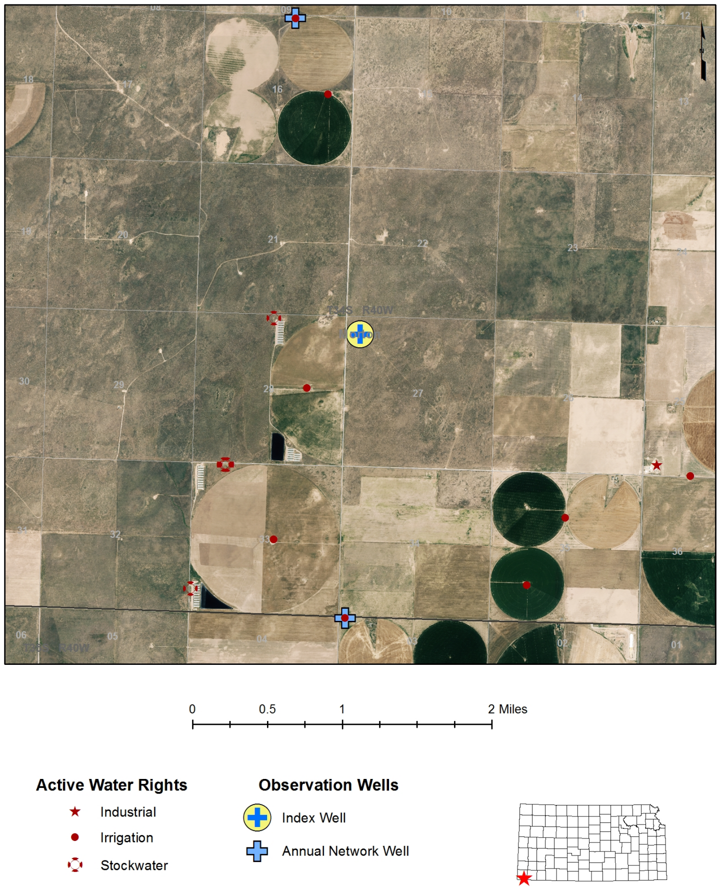


Figure 14—Aerial view of Rolla index well site, two additional annual program wells, and nearby points of diversion.

Figure 14 is an aerial view of the Rolla site (T. 34 S., R. 40 W., 27 BBB) at a scale that shows the index well site, two additional annual program wells, and the nearby wells with active water rights. The site includes two wells in the HPA, one near the water table and one near the base. The deeper well, for which the screened interval is 356–366 ft, has been instrumented (henceforth, Rolla 366 or Rolla 366 index well).

3.2.1.4.1. Hydrograph and General Observations

Figure 15 shows the hydrograph for the Rolla index well, table 15 summarizes its general characteristics, and table 16 compares the manual and transducer measurements from the well. The relatively large (up to 0.7 ft) amplitude fluctuations superimposed on the water levels (particularly evident during recovery periods) are similar to those observed at the Thomas County index well and the hydrograph form are indications that the interval in which the well is screened is behaving as an unconfined aquifer. This interpretation was confirmed through an analysis using the BRF software developed earlier in this program (Bohling et al., 2011). Although the periodic electric tape measurements are consistent with the hourly transducer measurements, the last two annual program measurements appear to be questionable and will be assessed further in 2015.

The 2014 pumping season began on March 17 and ended on September 20. 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 7 and continued, save for a few brief shutdowns and a week break beginning June 10, until September 20. Pumping at more distant wells ceased on September 7. The 2014–2015 recovery season was continuing at the time of the February 12, 2015, download used for this report.

Although the maximum observed water level at the end of the 2013–2014 recovery was above that of the previous year, the maximum observed water level for the 2014–2015 recovery should be nearly a foot below that level. Water use data for 2014 will be available later in 2015. The 2014 use will likely be considerably larger than the 2013 water use (1,554 ac-ft for a 2-mile radius centered on the index well). That larger water use is undoubtedly responsible for the expected lower maximum observed recovery for 2015.

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 2015 is recovering to near 3,188.3 ft, a loss of about 8.7 ft in 15 years (0.6 ft/yr); the water level in the closest annual measurement program well (about 2 mi south—T. 35 S., R. 40 W., 03 BBB 03 and 02 [well redrilled in 2003]) declined 8.3 ft over this same time period.

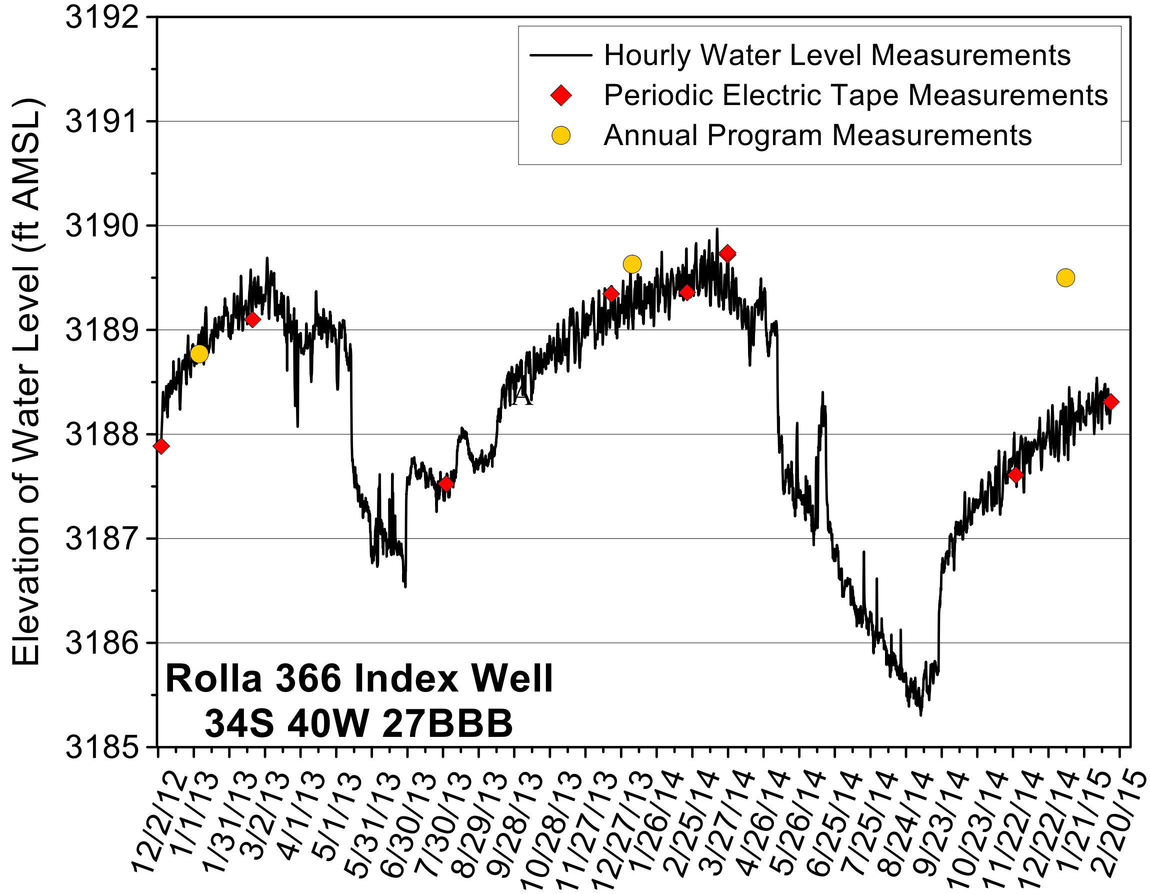


Figure 15—Rolla 366 index well hydrograph—total data run to 2/12/15. A water-level elevation of 3,188 ft corresponds to a depth to water of 187 ft below land surface (lsf). The top of the 10-ft screen is 356 ft below lsf (elevation of 3,019 ft) and the bottom of the aquifer is 399 ft below lsf (elevation of 2,976 ft); note the suspect 2014 and 2015 annual program measurement.

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

		2013	2014
Minimum Water-Level Elevation	Feet	3,186.5	3,185.3
	Date	6/28/13	9/5/14
Maximum Observed Recovery Elevation	Feet	3,189.7	3,189.97
	Date	3/3/13	3/17/14
Apparent Recovery	Feet	NA	3.5
Annual Change in Maximum Observed Recovery	Feet	NA	+0.27
Recovery Season	Start	NA	9/12/13
	End	3/9/13	3/17/14
	Length (Days)	NA	185.6
Pumping During Recovery Season	Length (Days)	NA	5.3
Length of Pumping Season	Days	186	187
2-mi Radius Water Use[a]	Irrigated Acres	1,331	NA
	Total (ac-ft)	1,553.6	NA
	Irrigation Use Only (ac-ft)	1,448.0	NA
	Use per Irrigated Acre (ft)	1.09	NA

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

3.2.1.4.2. Measurement Comparisons

Table 16—Annual water-level measurement[a] comparison with transducer measurements, Rolla 366 index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/5/2013	3,188.77	NA	Steel tape
	3,188.87[c]	NA	Transducer
	3,188.82[d]	NA	Transducer
1/5/2014	3,189.63[e]	+0.86[e] (+0.27)	Steel tape
	3,189.08[c]	+0.21	Transducer
	3,189.28[d]	+0.46	Transducer
1/5/2015	3,189.50[f]	-0.13[e,f] (NA)	Steel tape
	3,188.15[c]	-0.93	Transducer
	3,188.09[d]	-1.19	Transducer

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id= 370402101394401).
[b] Value in ( ) is the change in the maximum recovered water level measured by the index well transducer.
[c] Average of values over time interval 0800–1600, not corrected for barometric pressure.
[d] Average of values over time interval 0800–1600, corrected for barometric pressure using KGS barometric correction program.
[e] Suspect 2014 annual measurement value.
[f] Suspect 2015 annual measurement value.

3.2.2. Colby Index Well

In February 2014, the KGS and staff at the KSU-NWREC facility in Colby began to discuss adding the long-time monitoring well at that facility to the index well network. An integrated pressure transducer/datalogger unit was installed in the well in August 2014 shortly before the centennial celebration of the facility.

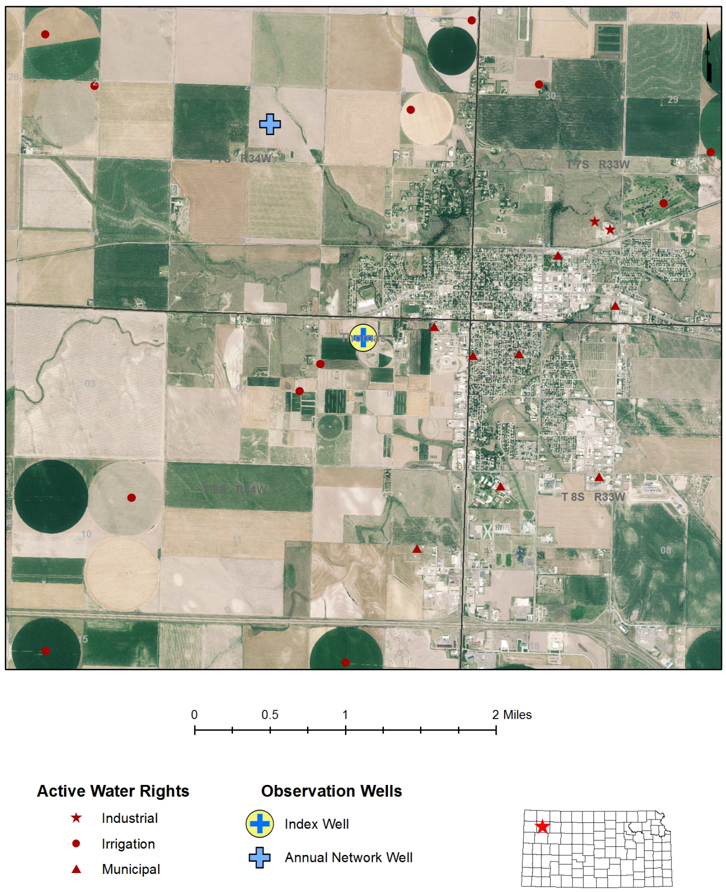


Figure 16—Aerial view of Colby index well, an additional annual program well, and nearby points of diversion.

Figure 16 is an aerial view of the Colby index well site (T. 08 S., R. 34 W., 01 BAC) at a scale that shows the site of the index well, an additional annual program well, and the nearby wells with active water rights. The index well terminates 175 ft below land surface; information about the screened interval is not currently available. We are attempting to use the facility's wi-fi system instead of a stand-alone telemetry system. In early February 2015, the facility completed running a power cable to the well and installing a wi-fi transmitter. The wi-fi system was successfully tested concurrent with the February 11, 2015, download, and we anticipate that real-time data from this well will be available on the KGS website later this spring. The well has been part of the annual measurement program since at least 1997. Based on well logs to the bottom of the aquifer in the general vicinity, the base of the aquifer at the Colby index well should be between 250 and 300 ft below land surface.

3.2.2.1. Hydrograph and General Observations

Figure 17 shows the hydrograph for the Colby index well, table 18 summarizes its general characteristics, and table 19 compares the manual and transducer measurements from the well. The relatively large (up to 1.0 ft) amplitude fluctuations superimposed on the water levels are similar to those observed at the Thomas County index well and are an indication that the interval in which the well is screened is behaving as an unconfined aquifer. The 2014–2015 recovery was continuing at the time of the download used for this report (February 11, 2015). Further assessment of the Colby index well hydrograph will be provided in the 2015 annual report.

The Colby index well has been measured manually by facility staff and GMD4 personnel on a weekly to quarterly basis since May 1947. The water level was 114 ft below land surface in early May of 1947. In early January 2015, the water level was more than 147 ft below land surface. The water level changed little from 1947 to the mid-1960s, after which it decreased in a relatively constant manner until the mid-1980s (depth to water in late January 1986 was 125 ft below lsf). In the late 1980s, the declines accelerated; the declines further increased in the early 2000s (depth to water was 134 ft below lsf in late January 2001).

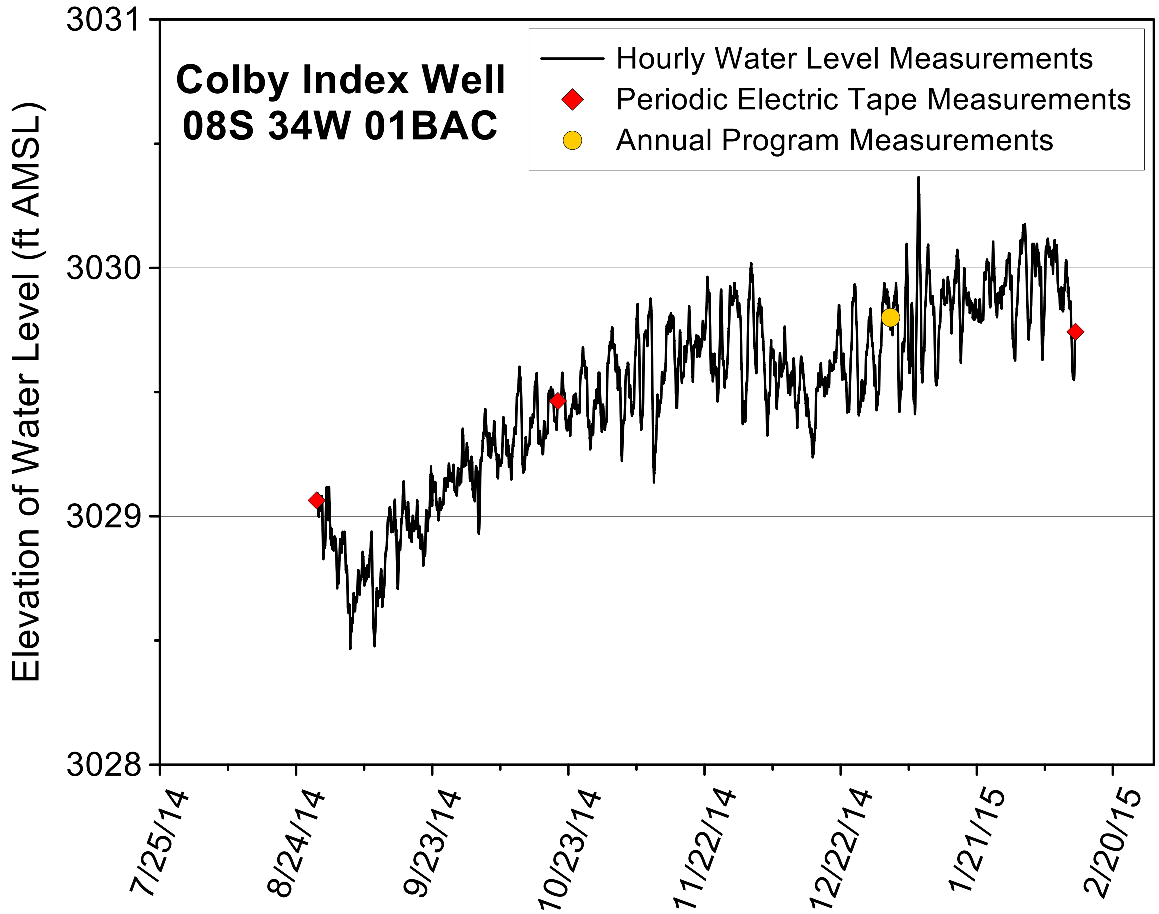


Figure 17—Colby index well hydrograph—total data run to 2/11/15. A water-level elevation of 3,029 ft corresponds to a depth to water of 148 ft below land surface (lsf). Total depth of the well is 175 ft below lsf (elevation of 3,002 ft). Information about the screened interval is not currently available. The base of the aquifer is estimated to be 250–300 ft below lsf (see text).

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

		2014
Minimum Water-Level Elevation	Feet	3,028.5
	Date	9/4/14
Maximum Observed Recovery Elevation	Feet	NA
	Date	NA
Apparent Recovery	Feet	NA
Annual Change in Maximum Observed Recovery	Feet	NA
Recovery Season	Start	NA
	End	NA
	Length (Days)	NA
Pumping During Recovery Season	Length (Days)	NA
Length of Pumping Season	Days	NA
2-mi Radius Water Use[a]	Irrigated Acres	NA
	Total (ac-ft)	NA
	Irrigation Use Only (ac-ft)	NA
	Use per Irrigated Acre (ft)	NA

[a]2013 Irrigated Acres—712, Total—2661.97 ac-ft, Irrigation use only—967.42 ac-ft, Use per Irrigated Acre—1.36 ft

Table 18—Annual water-level measurement[a] comparison with transducer measurements, Colby index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/2/2014	3,030.59	NA	Steel tape
	NA	NA	Transducer
	NA	NA	Transducer
1/2/2015	3,029.80	-0.79 (NA)	Steel tape
	3,029.79[c]	NA	Transducer
	NA	NA	Transducer

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=392329101040201).
[b] Value in ( ) is the change in the maximum recovered water level measured by the index well transducer.
[c] Average of values over time interval 0800–1600, not corrected for barometric pressure.

3.2.3. Belpre Index Well

In the spring of 2014, GMD5 expressed interest in expanding the index well program into its area. KGS and GMD5 staff worked together to identify a monitoring well that was drilled 20 years earlier by the KGS north of Belpre and just south of the Edwards-Pawnee county line. The well is in an area of groundwater level declines that is of concern to the district.

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

Figure 18 is an aerial view of the Belpre index well site (T. 24 S., R. 16 W., 05 CBB 01) at a scale that shows the site of the index well and the nearby wells with active water rights; there are no annual program wells within 2 mi of the Belpre well. The site includes two wells in the HPA, one screened near the water table and one screened deeper in the aquifer. The deeper well, for which the screened interval is 89–109 ft below land surface, has been instrumented (henceforth, Belpre 109 or Belpre index well). As of the time of this report, the Belpre data were not available on the KGS website because of limitations of the telemetry system vendor's website. We will switch telemetry providers if we cannot resolve this situation by June 2015. Based on well logs to the bottom of the aquifer in the general vicinity, the base of the aquifer at the Belpre index well should be between 175 and 200 ft below land surface.

3.2.3.1. Hydrograph and General Observations

Figure 19 shows the hydrograph for the Belpre 109 index well, table 19 summarizes its general characteristics, and table 20 compares the manual and transducer measurements from the well. The very small amplitude fluctuations superimposed on the water levels are an indication of unconfined conditions with a relatively shallow depth to water. The impact of nearby pumping wells appears small, which is consistent with a shallow unconfined aquifer. The 2014–2015 recovery was continuing at the time of the download used for this report (February 25, 2015). Further assessment of the Belpre 109 hydrograph will be provided in the 2015 annual report.

The Belpre 109 well has been measured manually by GMD5 staff on a quarterly basis since its installation in 1987. Although water levels in the well have risen and fallen over the last 27+ years, the general trend has been downward with a total decline of 10.5 ft.

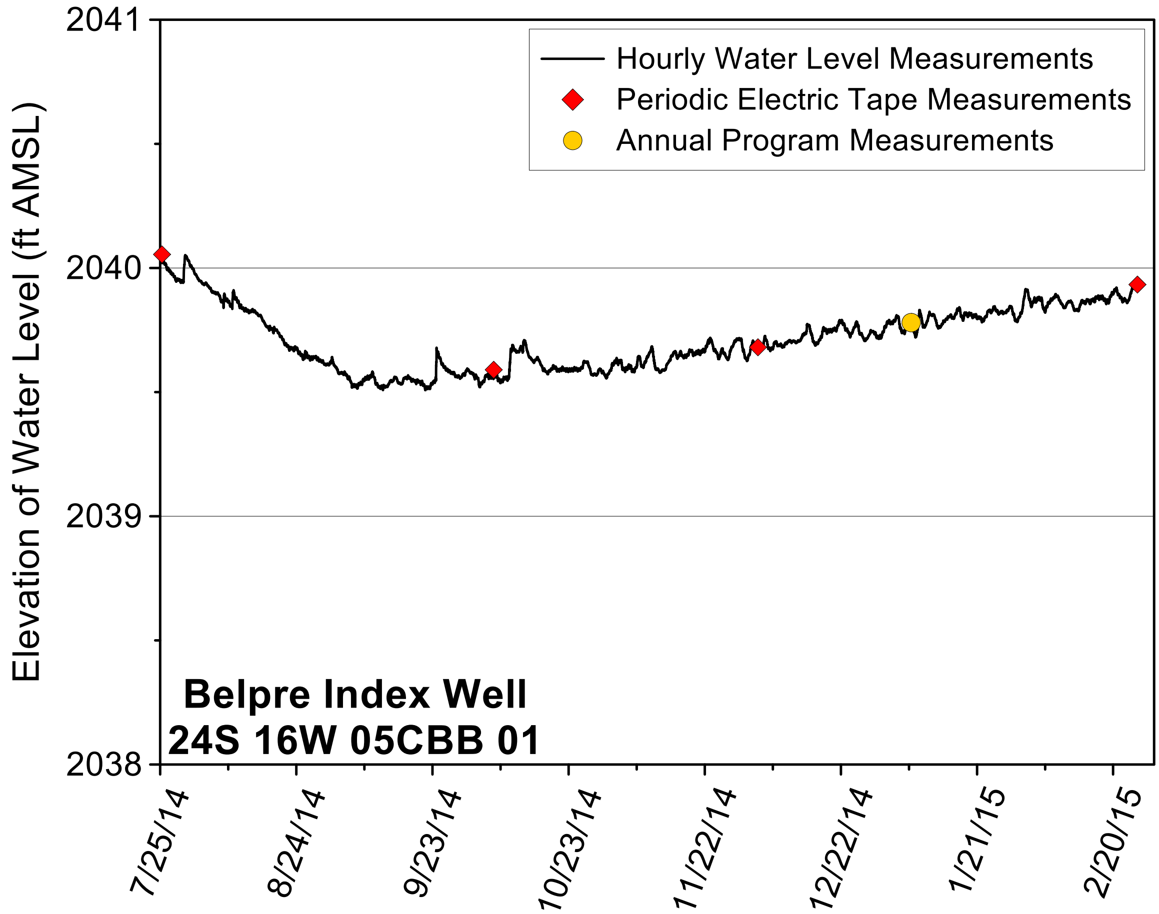


Figure 19—Belpre index well hydrograph—total data run to 2/25/15. A water-level elevation of 2,040 ft corresponds to a depth to water of 40 ft below land surface (lsf). The top of the 20-ft screen is 89 ft below lsf (elevation of 1,951 ft) and the bottom of the screen is 109 ft below lsf (elevation of 1,931 ft). The base of the aquifer is estimated to be 175–200 ft below lsf (see text).

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

		2014
Minimum Water-Level Elevation	Feet	2,039.5
	Date	9/12/14 and 9/21/14
Maximum Observed Recovery Elevation	Feet	NA
	Date	NA
Apparent Recovery	Feet	NA
Annual Change in Maximum Observed Recovery	Feet	NA
Recovery Season	Start	NA
	End	NA
	Length (Days)	NA
Pumping During Recovery Season	Length (Days)	NA
Length of Pumping Season	Days	NA
2-mi Radius Water Use[a]	Irrigated Acres	NA
	Irrigation Use Only	NA
	Use per Irrigated Acre (ft)	NA

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

Table 20—Annual water-level measurement[a] comparison with transducer measurements, Belpre index well.

Date	WL Elevation (ft)	Indicated Annual WL Change (ft)[b]	Method
1/15/2014	2,040.45	NA	Steel tape
	NA	NA	Transducer
	NA	NA	Transducer
1/6/2015	2,039.78	-0.67 (NA)	Steel tape
	2,039.76[c]	NA	Transducer
	NA	NA	Transducer

[a] Steel tape measurements are from annual water-level measurement program (http://hercules.kgs.ku.edu/geohydro/wizard/wizardwelldetail.cfm?usgs_id=375926099064001).
[b] Value in ( ) is the change in the maximum recovered water level measured by the index well transducer.
[c] Average of values over time interval 0800–1600, not corrected for barometric pressure.

3.2.4. GMD1 Expansion Wells

Late in 2011, arrangements were made with landowners and GMD1 to install KGS pressure transducers in two old USGS recorder wells in the area of the Scott index well; the sensors were installed on February 22, 2012. One of the new locations 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 ft and 10 ft, respectively, at the onset of monitoring. The water table dropped below the bottom of the screen at WH-1 during 2013 and was still below the bottom of the screen on February 19, 2014. As a result, the transducer was removed from that well on February 19, 2014.

3.2.4.1. SC-8 Site

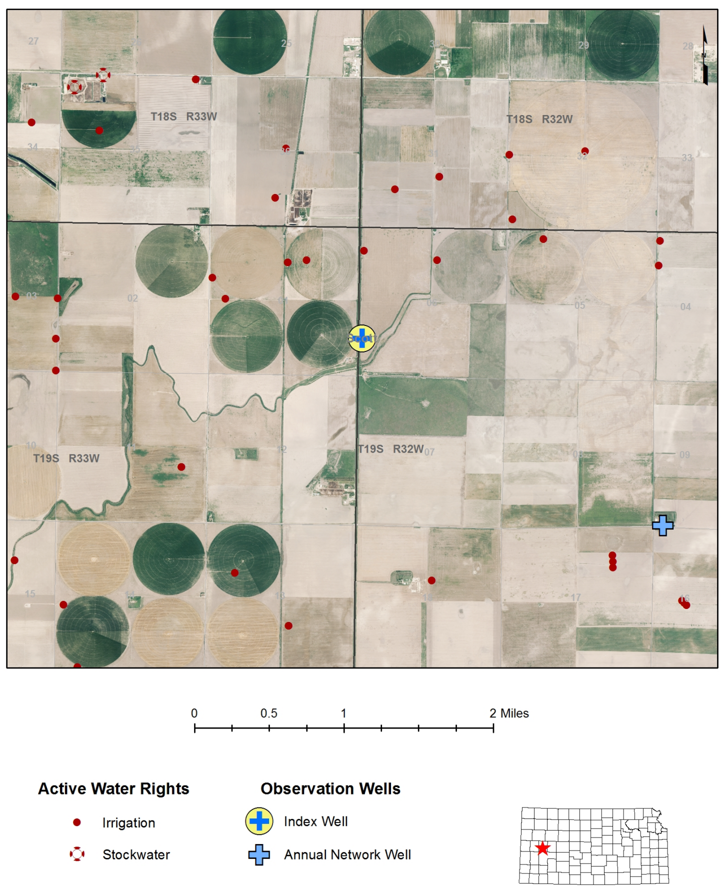


Figure 20—Aerial view of SC-8 site, an additional annual program well, and nearby points of diversion.

Figure 20 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, an additional annual program well, and nearby wells with active water rights. The well is located just north of an old drainage channel (the landowner said that the old USGS recorder used to show a hydraulic connection—i.e. a water-level rise—when water flowed in the channel). In the autumn of

2012, a new irrigation well was installed in the field in which the well is located. However, that field does not appear to have been irrigated during the monitoring period. The fields adjacent to the site to the west have been irrigated during the monitoring period.

3.2.4.1.1. Hydrograph and General Observations

Figure 21 displays the complete hydrograph for the SC-8 well. The approximately three years of monitoring data show a record that is similar to the hydrographs of wells in the upper unconfined interval in the vicinity of the Haskell site (see, for example, wells HS-10, HS-13, and HS-14 in Appendix A of Buddemeier et al. [2010]). These hydrographs are thought to indicate a compartmentalized aquifer interval in which the monitoring well is at some distance from the closest pumping well in that aquifer compartment. If the SC-8 well had been closer to a nearby pumping well, water levels would have risen up more after cessation of seasonal pumping before flattening out (see Butler, Stotler, et al. [2013] fig. 5 and related discussion). There is not a clear indication of commencement of pumping at a nearby well; water level responses are much more gradual, which may also indicate a relatively poor hydraulic connection with nearby pumping wells. The relatively large (up to 1.0 ft) amplitude fluctuations superimposed on the compartmentalized aquifer hydrograph are similar to those observed at the Thomas County index well and are an indication that the interval in which the well is screened is behaving as an unconfined aquifer. This interpretation was confirmed through an analysis using the BRF software developed earlier in this program (Bohling et al., 2011). In earlier reports, the hydrograph displayed a systematic deviation between the transducer and manual measurements. That deviation appears to have been introduced by an incorrect offset parameter for the transducer. Correcting the offset parameter produces a much better agreement between the transducer and manual measurements.

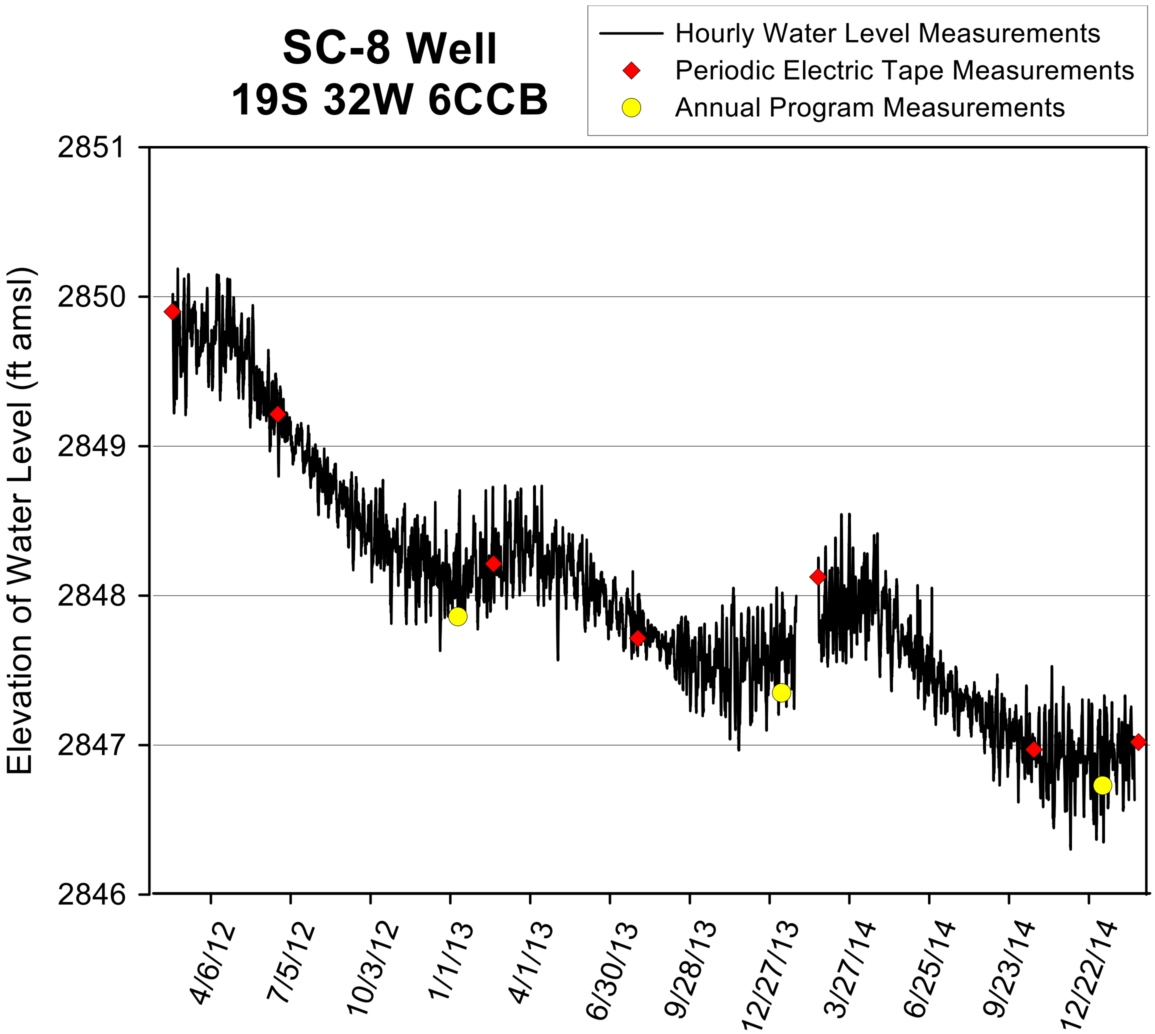


Figure 21—SC-8 well hydrograph—total data run until 2/11/15. A water-level elevation of 2,847 ft corresponds to a depth to water of 89 ft below land surface (lsf). Bottom of well is approximately 102 ft below lsf (elevation of 2,835 ft). Note that transducer measurements have been corrected from earlier reports for an incorrect offset parameter.

3.2.5. 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. 22). 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 21 provides a summary of sensor installation dates and other significant events for the currently operating wells. Only three of the wells are operating in a near-continuous fashion. Figure 23, shows hydrographs from the Thomas index well and these three currently operating expansion wells. Data from the closest expansion wells (TH9 and TH11) are briefly examined here. The interpretation of these hydrographs and those from wells TH7 and TH10 will be explored further in 2015.

Table 21—Installation date and other notes for currently operating Thomas County expansion wells.

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

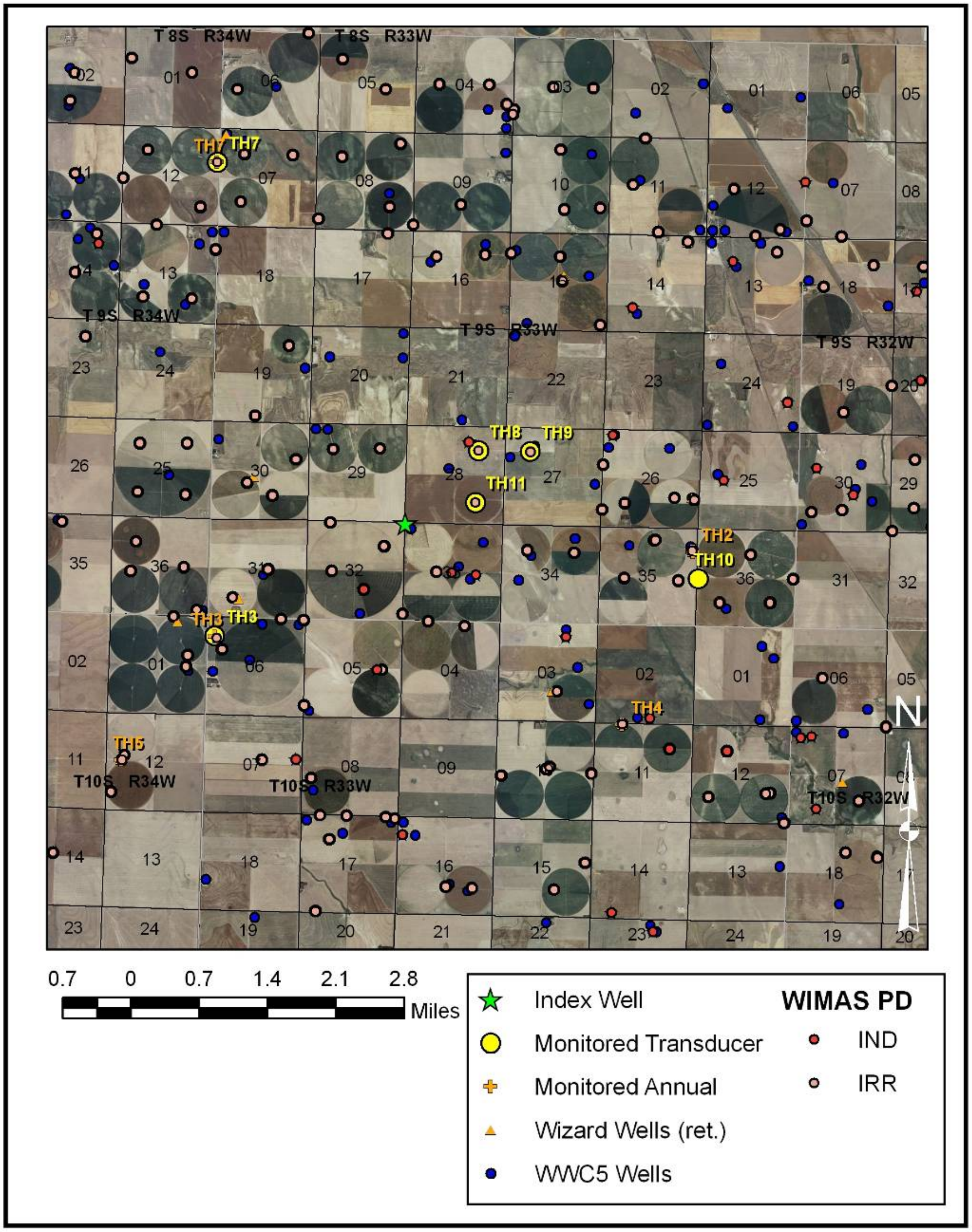


Figure 22—Aerial view of portion of Thomas County in the vicinity of the index well, showing the index well, nearby wells that have or had been equipped with transducers, surrounding annual program wells, and points of diversion in the area.

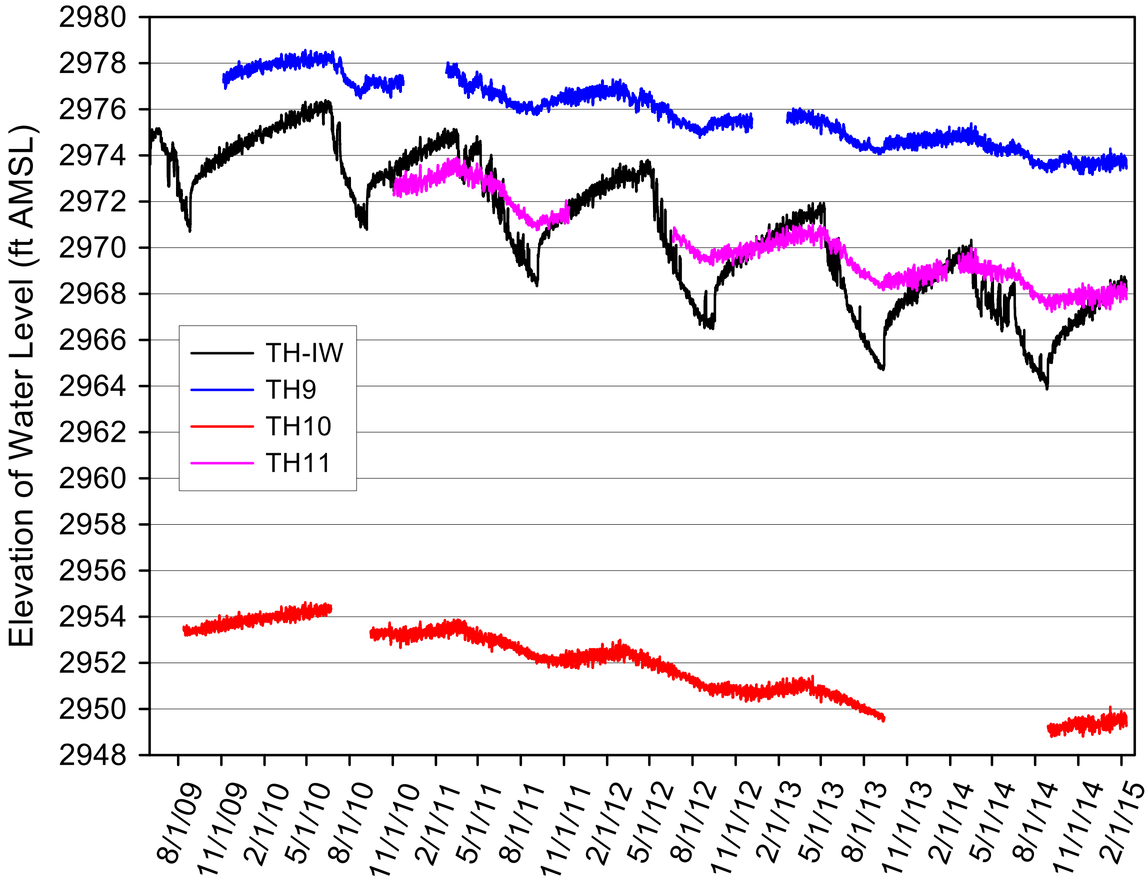


Figure 23—Hydrograph comparison from the Thomas index well and currently continuously operating Thomas expansion wells—total data run to 2/11/15. The general water-level trend indicates west-to-east groundwater flow.

The hydrograph at well TH9 appears to be responding to many of the same pumping events as the Thomas index well (fig. 24a). 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. 22]) 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 2015.

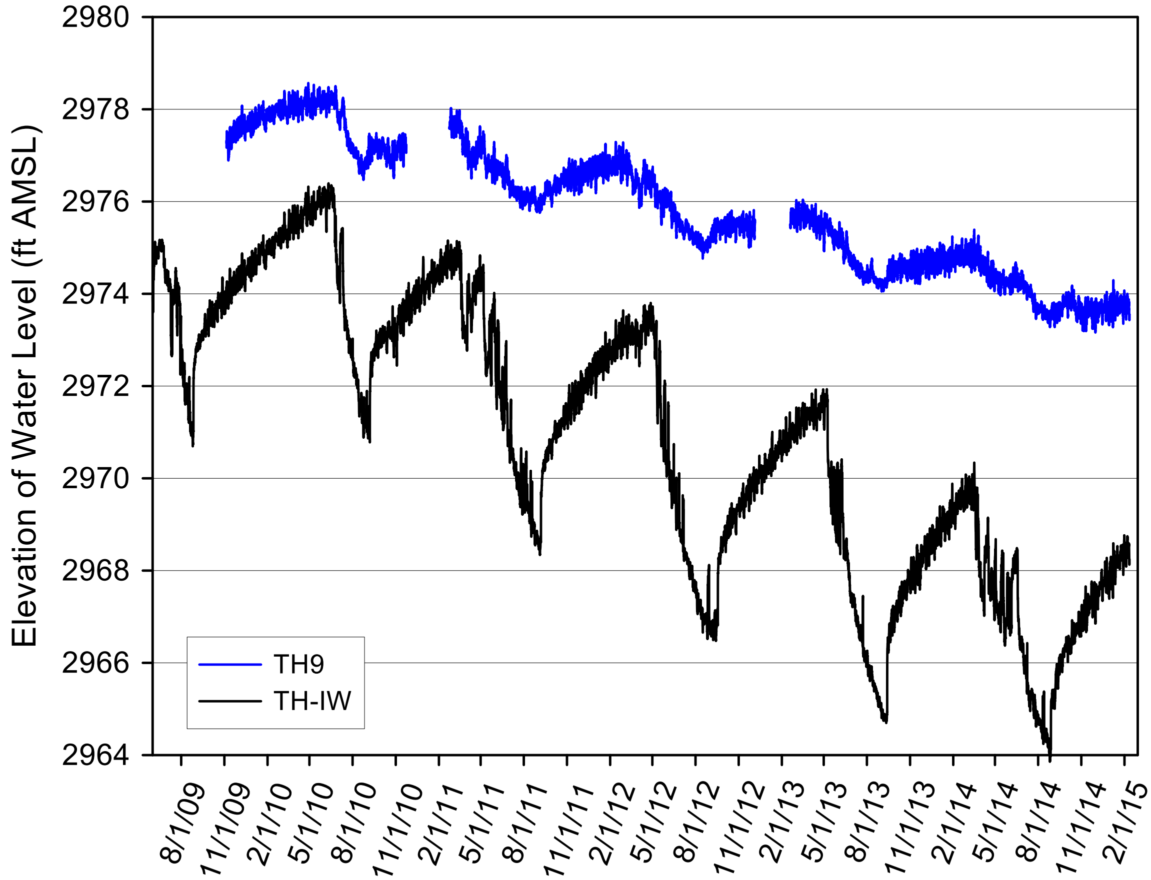


Figure 24a—Hydrograph comparison of Thomas index well and expansion well TH9—total data run to 2/11/15. TH9 is located approximately 1.5 miles northeast of the index well (0.75 miles north, 1.25 miles east).

The hydrograph at well TH11 also appears to be responding to many of the same pumping events as the Thomas index well (fig. 24b), but the responses are again more subdued and smoothed. Although similar, the pumping-induced response at TH11 is slightly greater than at TH9, as would be expected given it is closer to active pumping wells. A more detailed analysis and interpretation of the well TH11 hydrograph will be pursued in 2015.

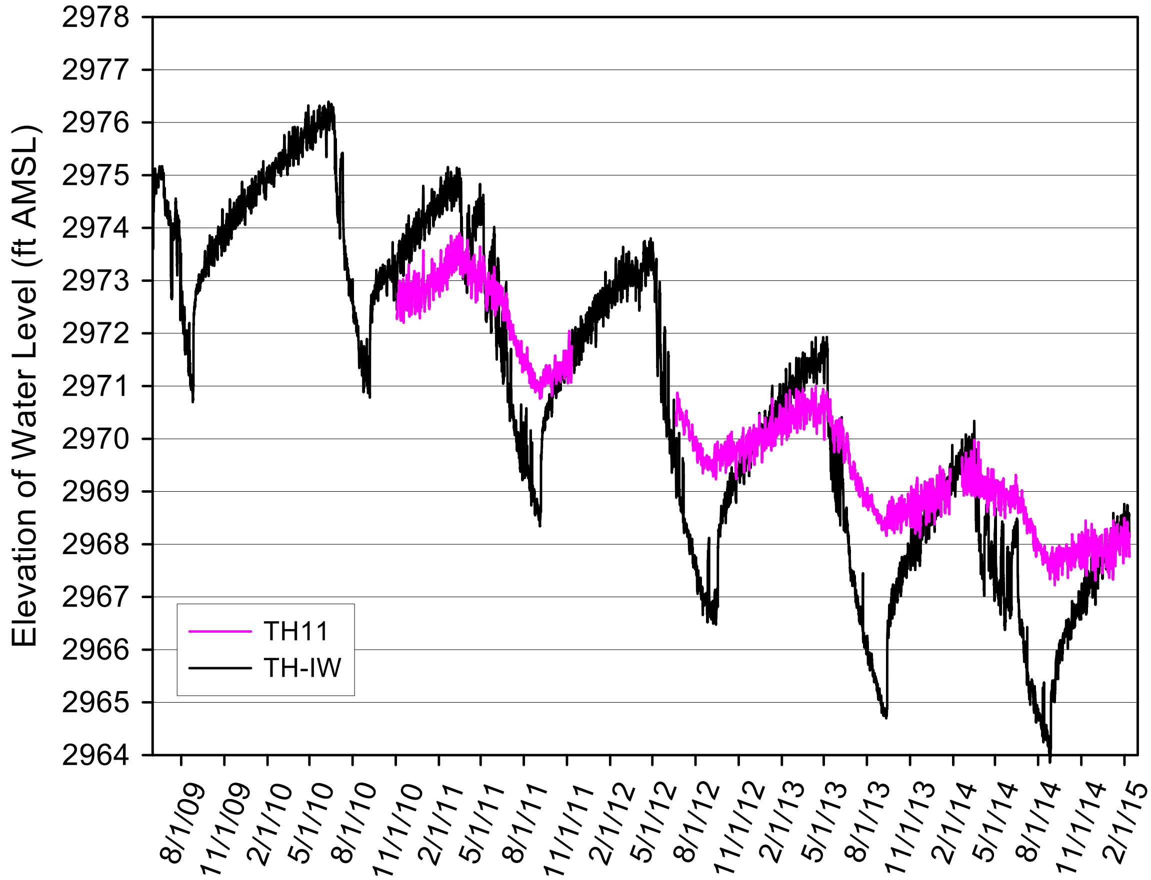


Figure 24b—Hydrograph comparison of Thomas index well and expansion well TH11—total data run to 2/11/15. TH11 is about 0.70 miles east-northeast of the index well (0.25 miles north, 0.75 miles east).

3.2.6. Haskell County Expansion Wells

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

3.2.7. Sheridan-6 LEMA Wells

Collaboration with GMD4 on the continuous monitoring of water levels at five observation wells within the Sheridan-6 (SD-6) Local Enhanced Management Area (LEMA) continued in 2014. By mid-year, the KGS formally took over the collection of water-level data for these wells, while GMD4 continues to maintain the sensors. Unlike the other index wells, the SD-6 wells have a transducer in the water column that is connected to a data logger on top of the well.

Analysis of prior data has indicated that all but one well have anomalous water-level spikes, primarily during the summer growing season, that appear to be related to high temperatures in the data logger housings. The KGS has been working with GMD4 to help mitigate this problem. In June 2014, miniature temperature sensors were placed inside the data logger housing at each of the five wells to measure temperature on five-minute intervals. As a result of earlier activities, which included painting the data logger housings white and shifting the position of the housings to reduce solar exposure, only two wells displayed anomalous water-level spikes in the summer of 2014.

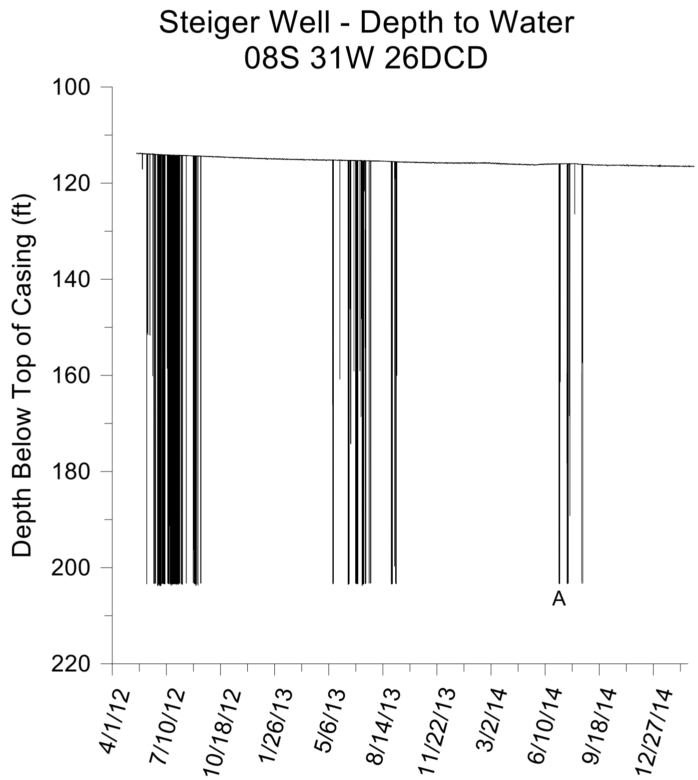
Figure 25a is a plot of depth to water versus time for the entire monitoring period at the Steiger well in the SD-6 LEMA; note the apparent abrupt large decreases in water level each summer. Figure 25b is an expanded view of the three-day period marked A on fig. 25a with the addition of the temperature data from inside the data logger housing. The water level appears to abruptly decrease for the period during which the data logger housing temperature was above 107 degrees F.

Figure 26 is a plot of depth to water versus time for the entire monitoring period at the Beckman well in the SD-6 LEMA. In this case, the data logger battery malfunctioned at least two times, producing gaps in the data record. In addition, there were anomalous water-level spikes that could have been produced by either data logger battery problems or the impact of temperature extremes on data logger operation.

We continue to monitor water levels in each well and the temperature in the data logger housing at each well. Given the problems we've had and are continuing to have with the equipment in the SD-6 LEMA wells, we anticipate replacing all of the existing monitoring equipment in 2015 with integrated pressure transducer/data logger units similar to those used at all the other index wells. These units remain submerged in the water column at all times and thus are not affected by surface temperature extremes. We will provide an interpretation of the SD-6 hydrographs in the 2015 annual report.

Hydrographs for all five LEMA wells up until the time of this report (March 6, 2015) can be viewed on the KGS website (www.kgs.ku.edu/HighPlains/lema/sd6.html); anomalous water-level spikes have been removed from those hydrographs.

a)



b)

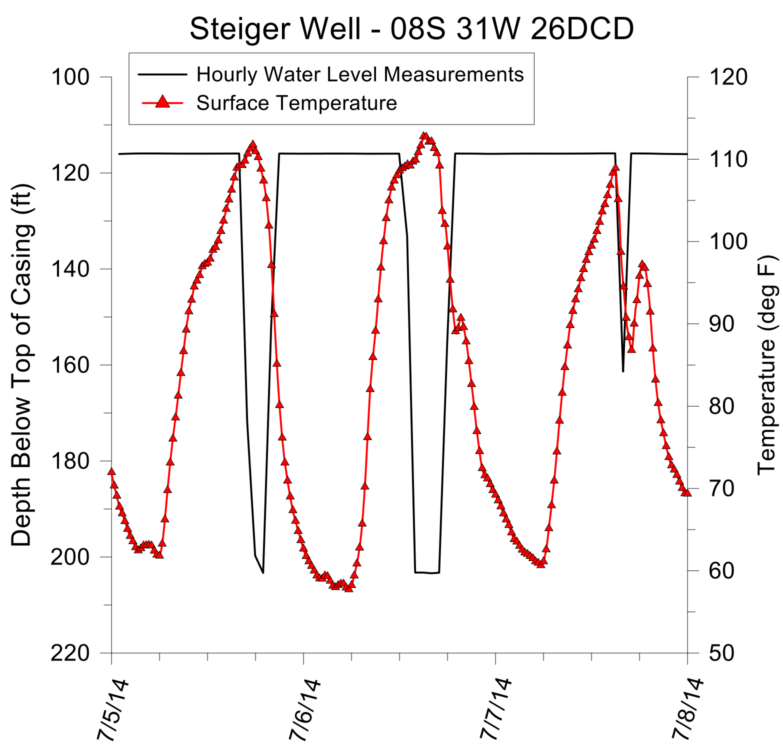


Figure 25—a) Steiger well hydrograph—total data run to 3/1/15. Note the large apparent water level changes each summer; b) Expanded view of Steiger well hydrograph for a three-day period in July 2014 (period marked A on upper plot) with data from temperature sensor in data logger housing. Frequency of temperature measurements is five minutes; symbols designate every fourth measurement.

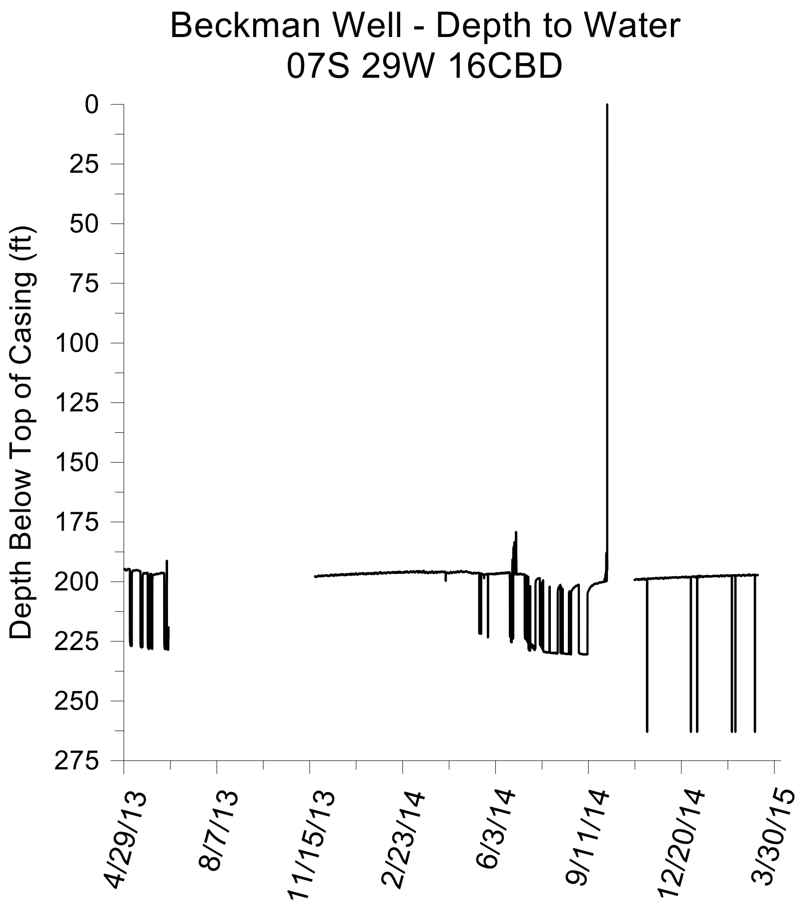


Figure 26—Beckman well hydrograph—total data run to 3/1/15. Gaps in data caused by malfunctioning data logger battery. Large abrupt changes in depth to water produced by either a malfunctioning data logger battery or temperature extremes.

4. Interpretation of Water-Level Responses

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

Significant effort has been expended over the course of this project to correct water-level measurements recorded by pressure transducers in the index wells. Common mechanisms beyond pumping that can affect the water level in a well include fluctuations in barometric pressure and tidal forces (earth tides). In previous project reports, earth-tide effects were shown to have a negligible impact on water-level measurements. The impact of changes in barometric pressure on water levels has been shown to be large enough to be of practical significance at one of the original index wells (Thomas County), the expansion wells in the vicinity of the Scott and Thomas index wells, the Rolla index well, and the Colby index well. In addition, we expect that some of the SD-6 LEMA wells will also be quite sensitive to fluctuations in barometric pressure. Given the expectation that the impact of barometric pressure will be large in unconfined portions of the HPA wherever the depth to water is on the order of or greater than that at the Thomas County index well (> 200 ft), the KGS developed an Excel spreadsheet to assess the nature of the relationship between barometric-pressure fluctuations and water levels and to remove the impact of barometric-pressure fluctuations from water-level measurements (Bohling et al., 2011). The nature of the relationship between barometric-pressure fluctuations and water levels is captured in the barometric response function (BRF) that is obtained as part of the spreadsheet calculations. In previous project reports, early efforts to extract information about site hydrostratigraphy from the BRF were described. In 2012 and 2013, initial work on getting more information from the BRFs began; it appears that it should be possible to get information from the BRFs about, among other things, the nature of the hydraulic connection between the well and the formation, the viability of annular seals, and an estimate of the bulk pneumatic diffusivity of the vadose zone. Little time was available for this work in 2014, so it was postponed until 2015. The 2015 annual report will therefore provide an update of this aspect of the project work.

4.2. Interpretation of Hydrographs from the Original Index Wells

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

<u>Haskell County</u>

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 2014 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 37.4 ft in height at the maximum observed drawdown for 2014 (water column height was likely considerably less in the immediate vicinity of the irrigation wells). This height was 1.4 ft less than at the maximum observed drawdown in 2013, but 2 ft greater than that in 2012; the increase over 2012 is undoubtedly a result of the court-ordered shutdowns described in section 3.1.1.1. 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 more water from the Dakota as the HPA becomes depleted in the area of the Haskell index well. However, as discussed in Section 6, the nature of the relationship between the Dakota aquifer and the HPA remains unclear.

Scott County

The 2014 water-level data helped refine the assessment of conditions in the vicinity of the Scott index well. Figure 27a, which is an update of the plot presented in the previous annual report, is a plot of drawdown versus the logarithm of duration of pumping for pumping periods beginning at A (2008), B (2009), C (2010), D (2011), E (2012), F (2013), and G (2014) 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). We originally tentatively interpreted the remaining portions of the plot as being affected by radial flow and aquifer boundaries. However, the data collected during the 2011 to 2014 pumping seasons have enabled us to reinterpret those portions of the plot. Figure 27b is a plot of drawdown versus the logarithm of duration of pumping for pumping periods beginning at D (2011), F (2013), and G (2014) on fig. 5 (2012 pumping period data are for a shorter interval so are not plotted). The coincidence of the 2011, 2013, and 2014 pumping period data indicates that the water-level changes are produced by pumping at the same well at essentially the same rate. 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 originally 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. 27b, similar to what was done earlier in this project using data from wells in the unconfined interval at the Haskell site (Butler et al., 2012; Butler, Stotler, et al., 2013).

The 2009 and 2010 pumping period data in fig. 27a are parallel to but earlier in time than the 2011–2014 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 28 shows the result after 2009 pumping times have been multiplied by 1.56 (* on fig. 28—if the first explanation is valid, the distance to the pumping well in 2009 is 0.8 that of the 2011–2014 pumping periods; if the second explanation is valid, the specific yield has increased by a factor of 1.56 between 2009 and 2011) and 2010 pumping times have been multiplied by 1.25 (** on fig. 28—if first explanation is valid, distance to 2010 pumping well is about 0.9 that of the 2011–2014 pumping periods; if second explanation is valid, specific yield increased by a factor of 1.25 from 2010 to 2011). After the time adjustments, the coincidence of the 2009–2014 pumping period data indicates that the aquifer responds as a homogeneous unit in the vicinity of the Scott index well and that decreases in saturated thickness during the monitoring period have had a very minor, if any, effect on the tranmissivity of the HPA in the vicinity of the Scott index well. However, the need for the time adjustment indicates that the specific yield likely increased as the water table fell. Thus, the Scott well can serve as a "sentinel" well for recognizing when decreases in saturated thickness are affecting aquifer properties. Assessment of water-level changes at the Scott index well will continue in 2015.

The 2013 annual report (Butler et al., 2014) presented an assessment of recovery data from three complete recovery seasons (2009–2010, 2011–2012, 2012–2013) and one continuing recovery season (2013–2014). Figure 29a presents an update of the recovery assessment with the complete 2013–2014 recovery season and the continuing 2014–2015 recovery (September 4 was used as the start of recovery for the 2014–2015 recovery). Note that the water levels during the 2014–2015 recovery are above previous years' recovery beginning at time A. In addition, the data become considerably noisier (maximum noise level is close to a foot late in the recovery) than previous years. After examining the record closely, we found that the water level and barometric pressure records paralleled one another after A, an indication that the vent tube in the gauge pressure transducer had become plugged. We therefore corrected all pressure transducer measurements after A on fig. 29a by subtracting the change in barometric pressure with respect to that at time A from the pressure transducer data. The resulting corrected record is shown in fig. 29b. The 2014–2015 recovery data now approximately overlie the data from previous years. We will remove the suspected plug from the vent tube later in the spring of 2015. The water use in 2009 and 2012 differed by about 22% (largest use difference for the years shown in fig. 29b); the durations of the 2009 and 2012 pumping periods differed by about 20%. Water-use data for 2014 are not yet available. The interpretation of the similarity of the recovery plots for four complete and one continuing recovery seasons, which hints at the possibility of inflow similar to that at the Thomas index well, will continue to be the focus of further work in 2015.

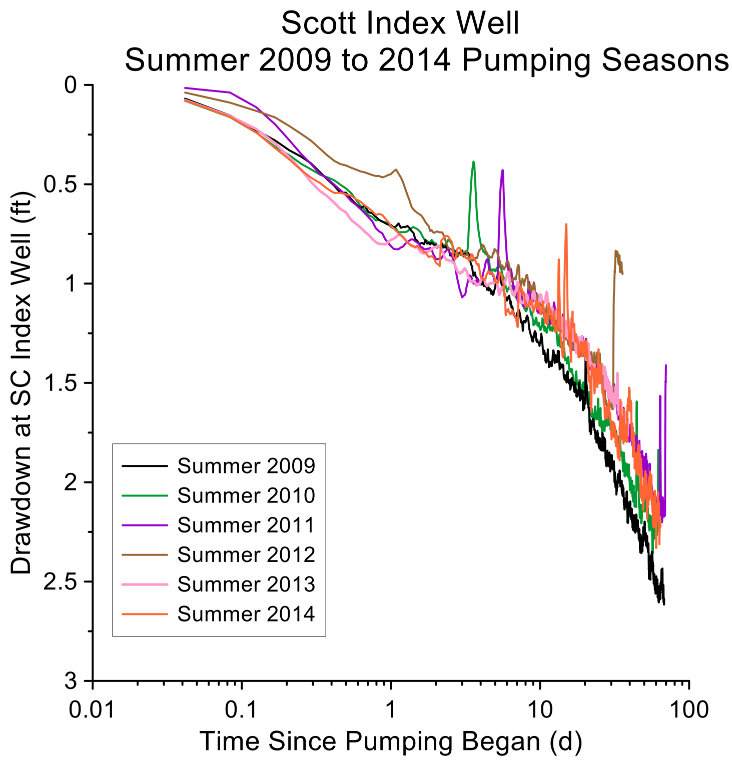


Figure 27a—Drawdown in the Scott index well versus the logarithm of pumping time for pumping periods beginning at points A (2008), B (2009), C (2010), D (2011), E (2012), F (2013), and G (2014) on fig. 5.

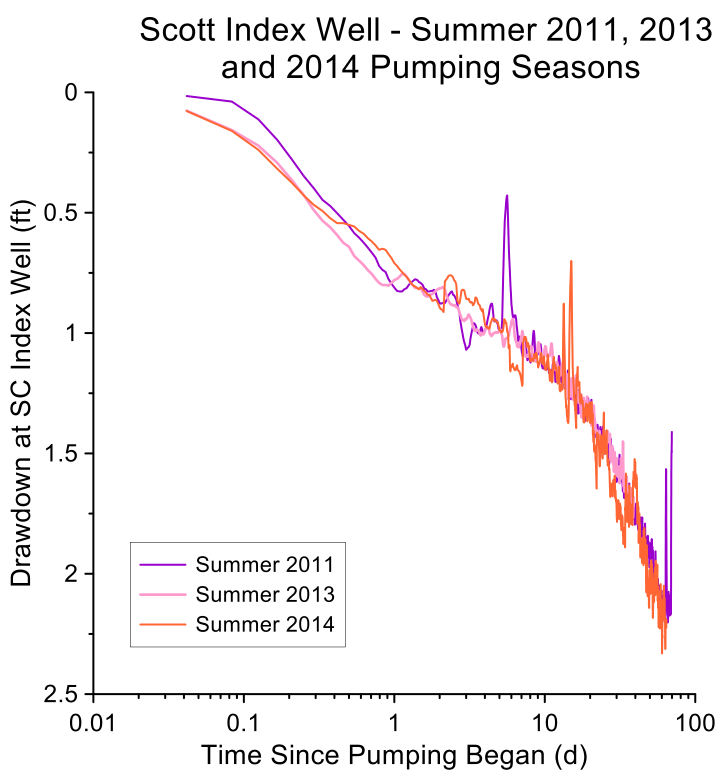


Figure 27b—Drawdown in the Scott index well versus the logarithm of pumping time for 2011, 2013, and 2014 pumping periods beginning at points D, F, and G, respectively, on fig. 5.

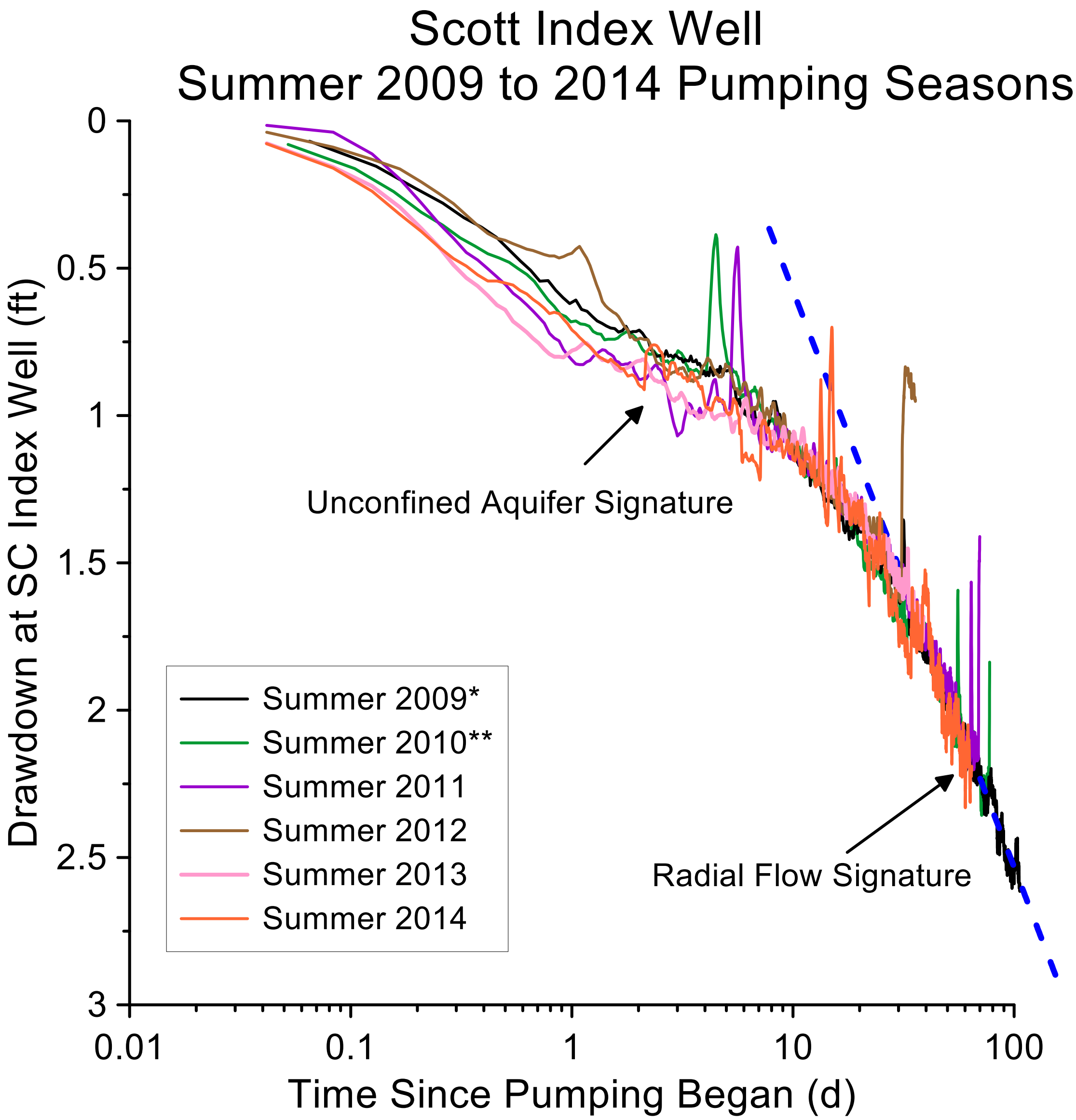


*Figure 28—Drawdown in the Scott index well versus the logarithm of pumping time for pumping seasons beginning at points B (2009), C (2010), D (2011), E (2012), F (2013), and G (2014) on fig. 5. * and **—pumping times modified as explained in text. 2008 pumping period not plotted because of noise produced by pumping cutoffs and restarts.*

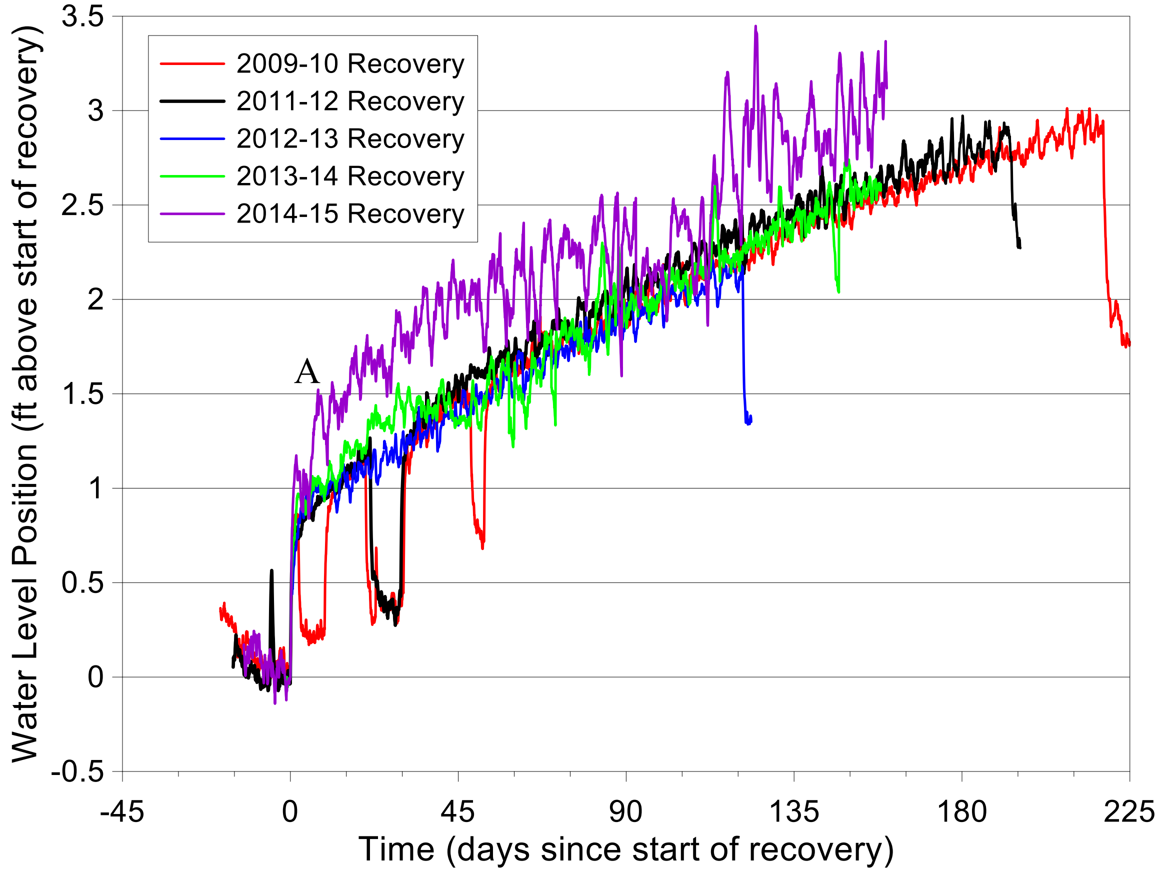


Figure 29a—Water levels in the Scott index well for the 2009–2010, 2011–2012, 2012–2013, 2013–2014, and 2014–2015 recovery periods. Recovery for the 2009–2010, 2011–2012, 2012–2013, 2013–2014 and 2014–2015 recovery periods calculated from points H, I, J, K, and L, respectively, on fig. 5. Note the separation between the 2014–2015 recovery and the previous years beginning at A.

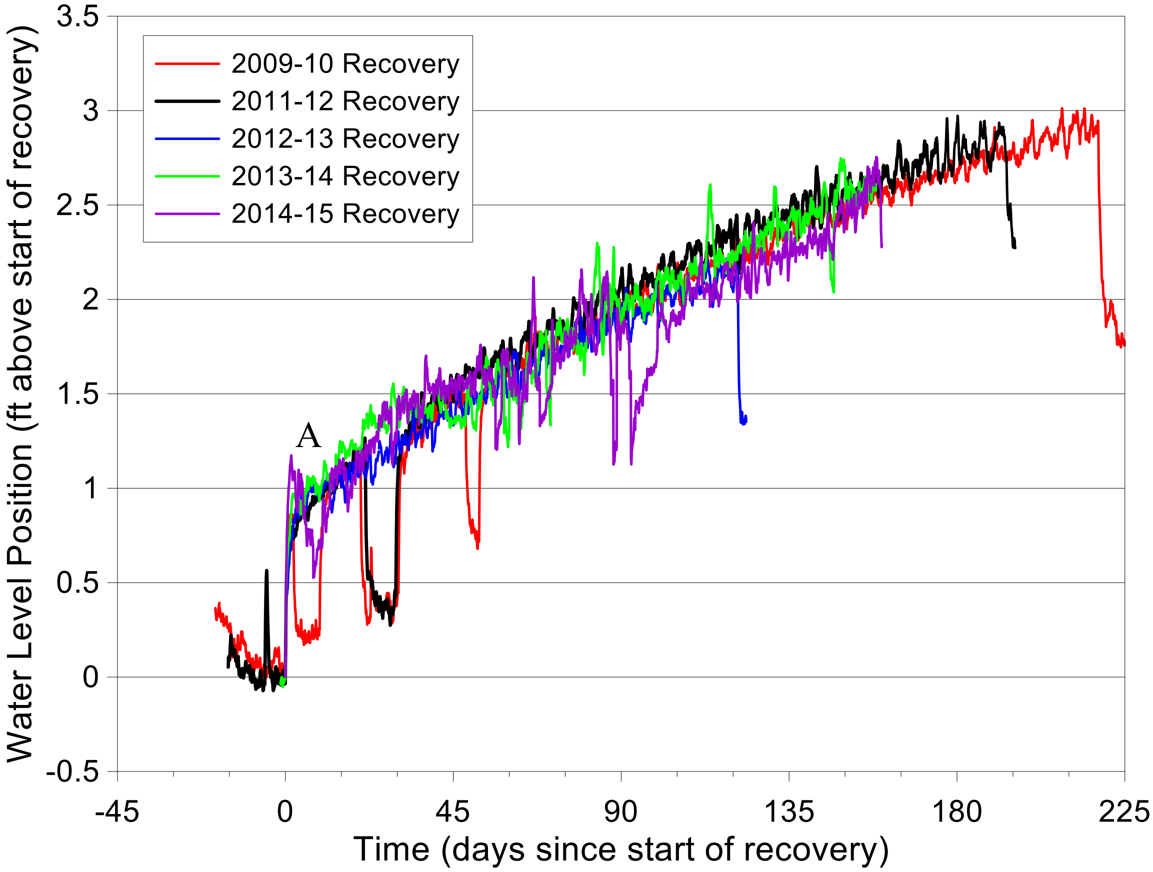


Figure 29b—Water levels in the Scott index well for the 2009–2010, 2011–2012, 2012–2013, 2013–2014, and 2014–2015 (corrected) recovery periods. Recovery for the 2009–2010, 2011–2012, 2012–2013, 2013–2014, and 2014–2015 recovery periods calculated from points H, I, J, K, and L, respectively, on fig. 5. Note that 2014–2015 recovery has been corrected for a plugged vent tube beginning at A as described in text.

Thomas County

The major findings regarding the water-level data from the Thomas index well were summarized in the publications described in the first paragraph of this section. The most important finding was that there appears to be a significant amount of inflow into the unconfined aquifer at the Thomas site. Further assessments of that possibility were carried out using the 2014 data.

An assessment of four complete and one continuing recovery seasons was presented in the 2013 annual report. Figure 30 presents an update of the recovery assessment with the results for the complete 2008–2009, 2009–2010, 2011–2012, 2012–2013 and 2013–2014 recovery seasons and the still continuing 2014–2015 recovery. The 2009 and 2012 pumping seasons bound the range of conditions (water use and pumping duration) observed during the monitoring period (table 6). Although the 2012 water use was 92% greater than that of 2009 and the irrigation season was close to 2.1 times longer, the rate of recovery following these irrigation seasons was essentially the same. The agreement between the superimposed recovery plots on fig. 30 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 2007–2008 and 2010–2011 recovery seasons are included, a further indication that a mechanism beyond pumping in the previous irrigation season is responsible for the rise of water levels during the recovery period.

In 2014, we developed a new approach for estimating the inflow into the HPA in the vicinity of the Thomas site. That approach is described in Section 5.9.

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

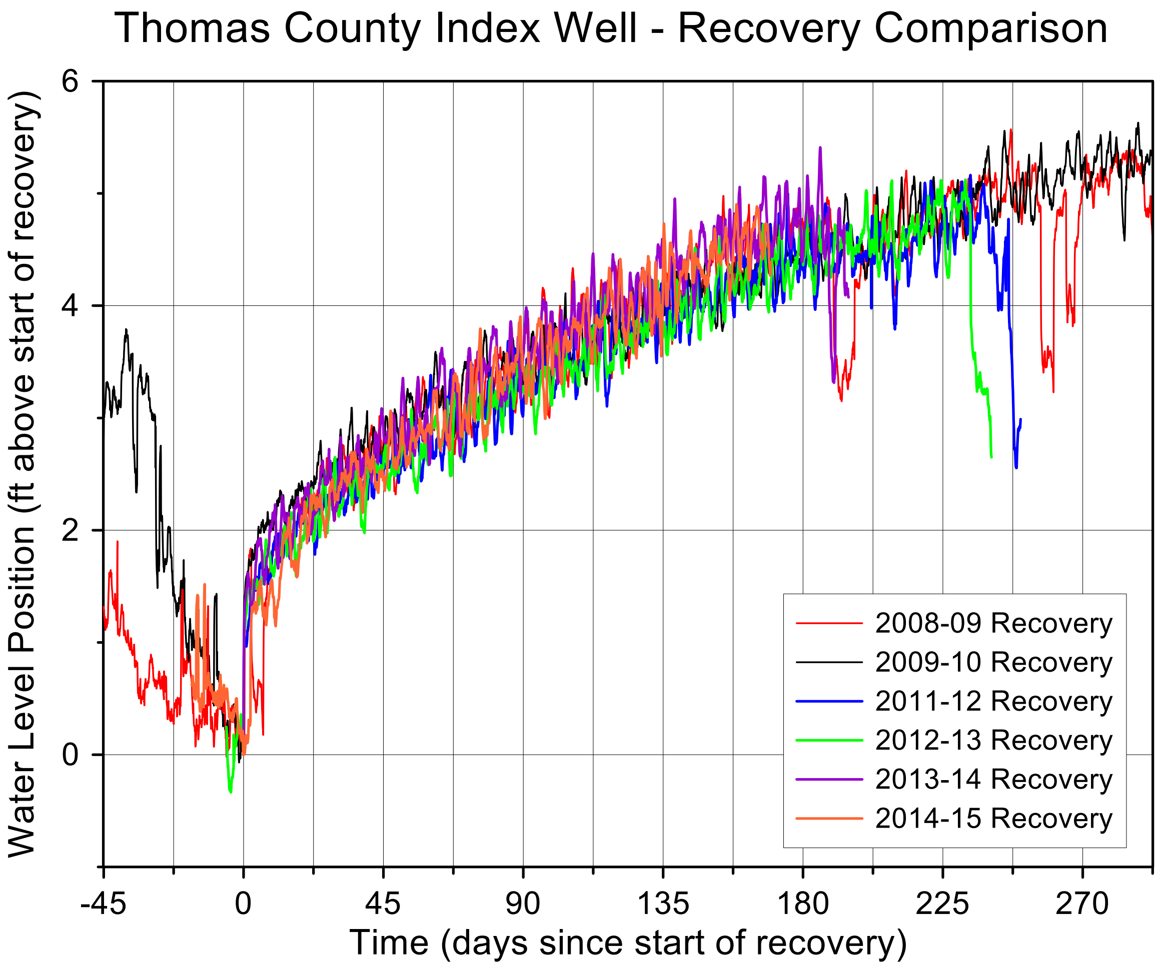


Figure 30—Water levels in the Thomas County index well for the 2008–2009, 2009–2010, 2011–2012, 2012–2013, 2013–2014, and 2014–2015 recovery periods. Recovery for the 2008–2009, 2009–2010, 2011–2012, 2012–2013, 2013–2014, and 2014–2015 recovery periods calculated from points A, B, C, D, E, and F, respectively, on fig. 7. Recovery period for 2010–2011 not included because of pumping during the early portions of that period.

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

5.1. *Introduction*

The measurement and interpretation of water-level changes at the index wells have provided an improved understanding of hydrologic responses at the local (section to township) scale in the HPA in western Kansas. These wells can also serve as an index of the character of the year-to-year water-level changes measured 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 can be valuable for management purposes. This section describes the continued advancements in this area.

The main driver of water-level changes in the HPA is the amount of water pumped for irrigation. The pumping volume is determined by the number of operating irrigation wells and the amount of water pumped from each well. The major drivers for the per-well amount are the type of crop, the additional water needed for crop growth above that provided by precipitation, and the irrigated area. In addition to the amount, the timing of precipitation relative to crop stage is also important. If the number of irrigation wells, the average mix of crops, and the irrigated area remain relatively constant, then the main factor controlling the annual pumping is the meteorological condition for a given year.

5.2. *Climatic Indices*

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

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. In last year's report, the persistent climatic conditions during 2008–2013 were represented by monthly values of the PDSI. Figure 31 updates the conditions through 2014. Conditions changed from near normal in 2008 across the three western climatic divisions (coinciding with GMDs 4, 1, and 3) to wet in 2009. Wet conditions continued through the first part of 2010 in western Kansas, then changed to somewhat dry during the latter portion of 2010. In west-central Kansas, the climate became drier in 2011 until the latter part of the year, when more rainfall brought the climate to near normal during the winter of 2011–2012. Severe drought started in the summer of 2011 in 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 2014 in northwest and southwest Kansas, although the trend was to less severe drought. In west-central Kansas, the divisional drought ended about halfway through 2014 and slightly wet conditions prevailed during the latter part of 2014.

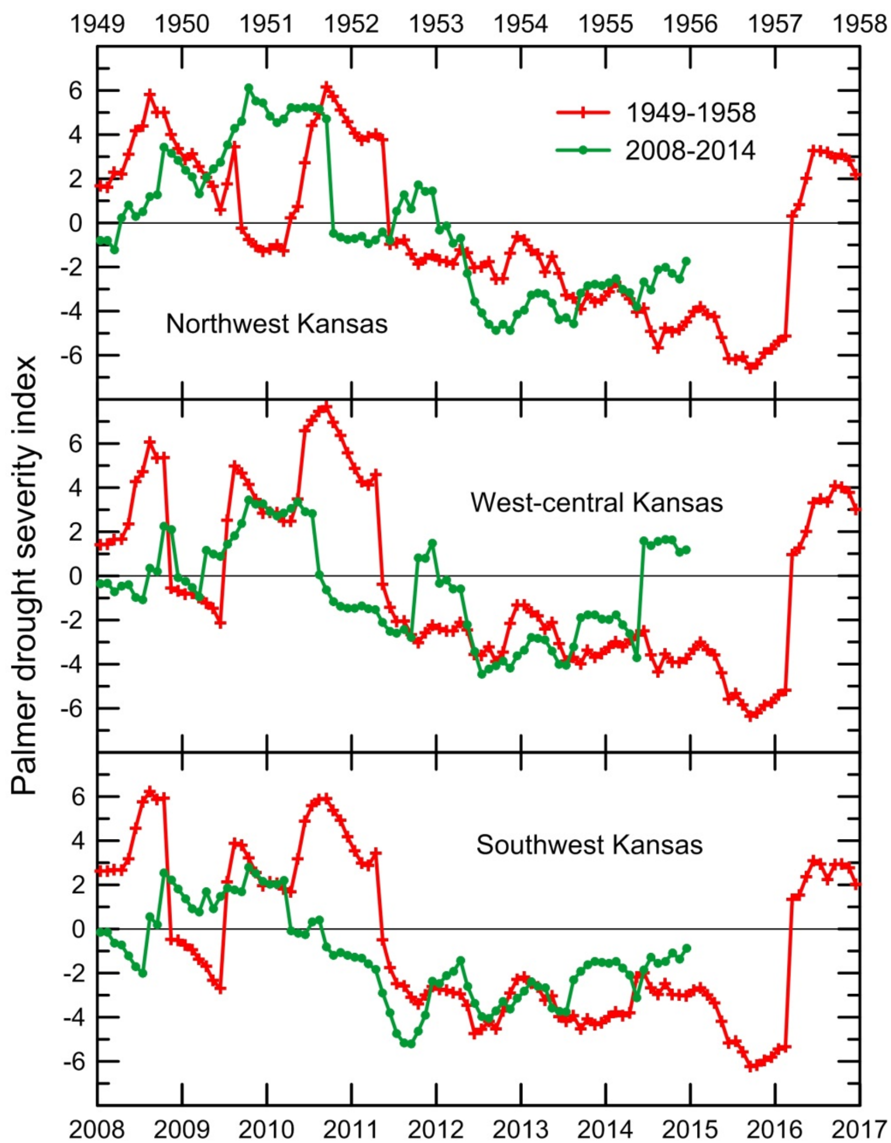


Figure 31—Comparison of monthly values of the Palmer Drought Severity Index (PDSI) for the three western climatic divisions of Kansas during 1949–1957 and 2008–2014. The monthly values are plotted as the middle of the month.

Figure 31 also includes comparison of the monthly PDSI values during 1949 through 1957, which included the drought of the 1950s, with those for 2008 through 2014. The years of 1949 through early 1952 included predominantly wet conditions on either side of a shorter period with normal to somewhat dry conditions. 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 climatic conditions 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 during 2011 through the first half of 2013 in southwest Kansas were either comparable to or worse than the drought during 1952–1954. The climatic conditions of the latter half of 2014 were not as dry in western Kansas as the latter half of 1955.

We have found that the nine-month October SPI is a good measure of the meteorological conditions that drive pumping from the HPA and that correlations between SPI and water-level changes are high for different areas of the HPA. Based on the nine-month SPI for October, the droughts of 2011 and 2012 in southwest Kansas were comparable to those for the first two years of the 1950s drought, 1952 and 1953 (fig. 32). The climatic conditions for 2012 were drier than for 1953 in both northwest and west-central Kansas. The conditions were less dry in 2013 than 1954 for all of western Kansas. The SPI indicates that the conditions were near normal for western Kansas during 2014 in comparison with dry for 1955 in northwest and west-central Kansas and near normal for southwest Kansas.

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 its 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 number of points of diversion in Thomas, Scott, and Haskell counties in 2013 were 1,112, 1,340, and 1,597, respectively. The number of points of diversion that were added after 1996 were 40, 25, and 0 for these three counties, respectively. Thus, for the period 1996–2013, the main driver for water-level changes in the HPA in western Kansas was the amount of pumping from each well.

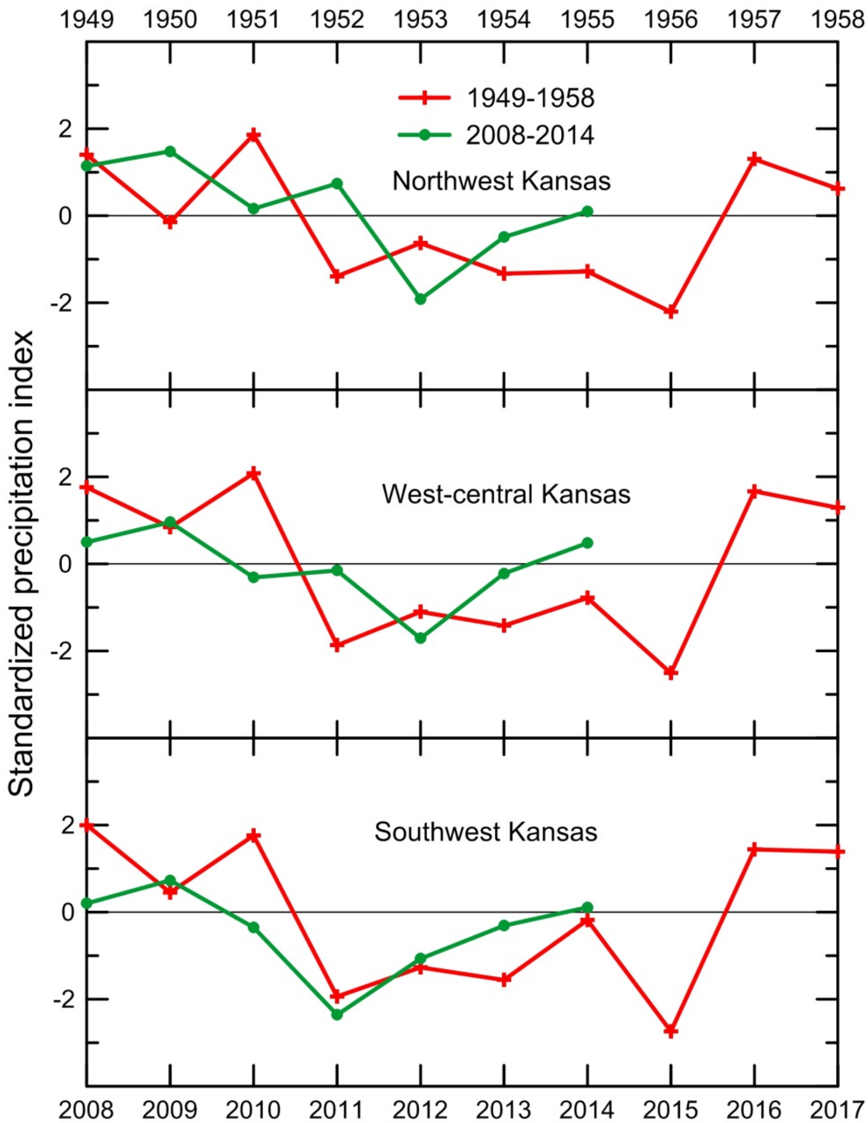


Figure 32—Comparison of the nine-month October SPI values for the three western climatic divisions of Kansas during 1949–1957 and 2008–2014. The nine-month October SPI correlates well with water-level changes in all three western GMDs.

5.4.1. Water-Level Change in the Groundwater Management Districts

The mean annual year-to-year changes in winter water-levels during 1996–2013 for the three western GMDs are displayed in fig. 33 based only on wells for which measurements were made during the winters of all years from 1996 to 2014. The values for 2014 were computed using the provisional data for the winter of 2015 for all wells for which data were available for each of the GMDs. 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 2014, the declines were substantially less than for the droughts of 2002 and 2012. The declines in 2014 were a little greater than the average for the 18 years of the 1996–2014 measurement period for GMDs 1 and 3 but a little less than average for GMD4.

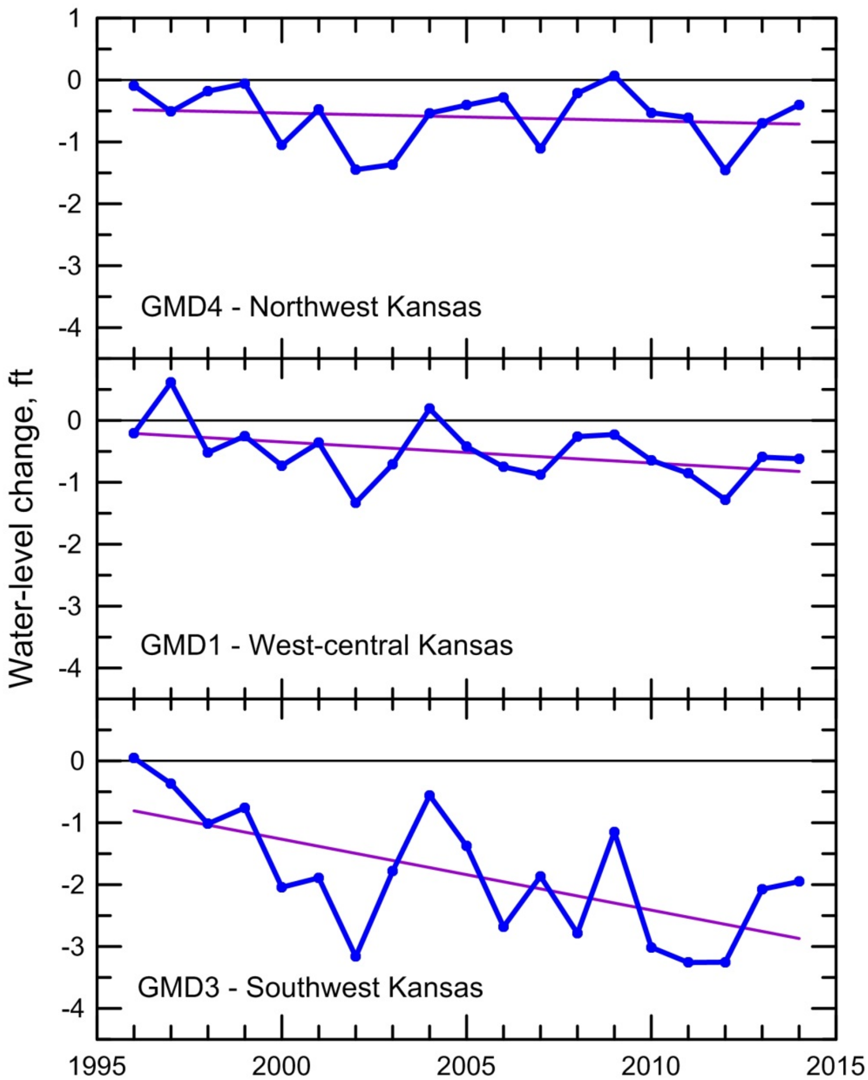


Figure 33—Mean annual water-level change in the HPA in the three GMDs in western Kansas during 1996–2014. The value for a particular year is the water-level difference between the following year and that year for continuously measured wells for 1996–2013 and between the provisional value for winter 2015 and the continuously measured wells in 2014 for the year 2014. The blue lines and points represent the mean annual water-level change and the purple line is the linear regression for the data.

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 2008 (see tables 3, 5, and 7). Figure 34 shows the annual year-to-year water-level changes for both the tape and transducer values for 2008–2014 (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 (except for the 2014 value as described in Section 5.4.1). 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 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 4.1 ft), and even greater at the Haskell index well (between -4.0 and -10.2 ft; a total absolute range of 6.1 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 2008–2014 (fig. 34). In contrast, the ranges in the annual water-level changes for the Thomas and Haskell index wells are substantially greater than the mean water-level changes for GMDs 4 and 3, respectively. The patterns in the annual water-level changes for the three index wells are generally similar to the patterns for the mean annual changes for the GMDs, especially for the Thomas and Scott index wells. This indicates that these index wells are generally representative of the regional water levels in the GMDs in which the wells are located. However, the 2014 water-level decline at the Scott County index well was enough lower than that of the GMD-wide decline that it could represent a significant difference. Although the changes in the water levels in the Haskell index well (the transducer values) showed increasing declines from 2009 to 2011 followed by smaller declines during 2011 to 2013 that are similar to the more muted changes for GMD3, the substantially larger decline in the index well water level in 2014 than in 2013 is substantially different from the nearly constant decline for that period for GMD3. This difference is related to the 18 days of pumping near the Haskell index well that ended December 15, 2014, and caused an interruption in the recovery of the water level at the index well.

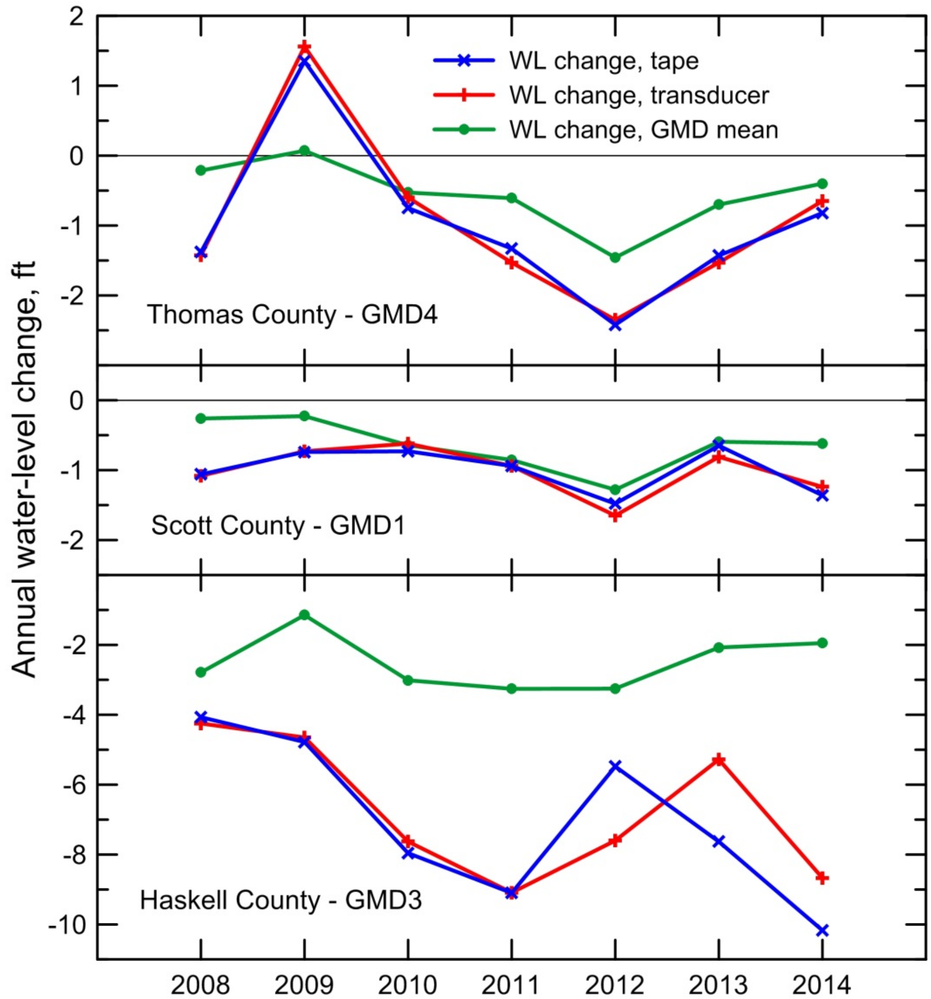


Figure 34—Annual winter water-level changes in the original three index wells and the mean annual changes in the three GMDs in western Kansas in which they are located. The value for a particular year is the water-level difference between the following year and that year. Note the difference in the y-axis scale for Haskell County versus that for Thomas and Scott counties; suspect 2013 tape measurement at the Haskell index well affected the 2012 and 2013 water-level change, 2014 water-level change affected by an 18-day pumping period ending on December 15, 2014.

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 nine-month October SPI correlates well with water-level changes in all three of the western Kansas GMDs (Whittemore et al., 2015 [see Appendix A]; Butler et al., 2014). 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 1996–2014 (fig. 35) show that the variations in water-level change mimic the variations in SPI.

As shown in last year's index well report, the correlations between water-level change and SPI are high; the coefficients of determination (R^2) for the 1996–2013 period were reported as 0.78, 0.71, and 0.78 for GMDs 4, 1, and 3, respectively (Butler et al., 2014). The revised climatic index data changed these correlation values by a small amount; the R^2 values for 1996–2013 are 0.74, 0.72, and 0.78 for GMDs 4, 1, and 3, respectively. All of these correlations are significant at P = 0.001. As indicated earlier, the 2014 data for water-level change for continuously measured wells in the GMDs are not yet available as of the time of this report. However, if the water-level changes for 2014 that involve the provisional 2015 measurements for all program wells in the GMDs are used for determining the correlations, the R^2 values for 1996–2014 are 0.74, 0.70, and 0.78 for GMDs 4, 1, and 3, respectively.

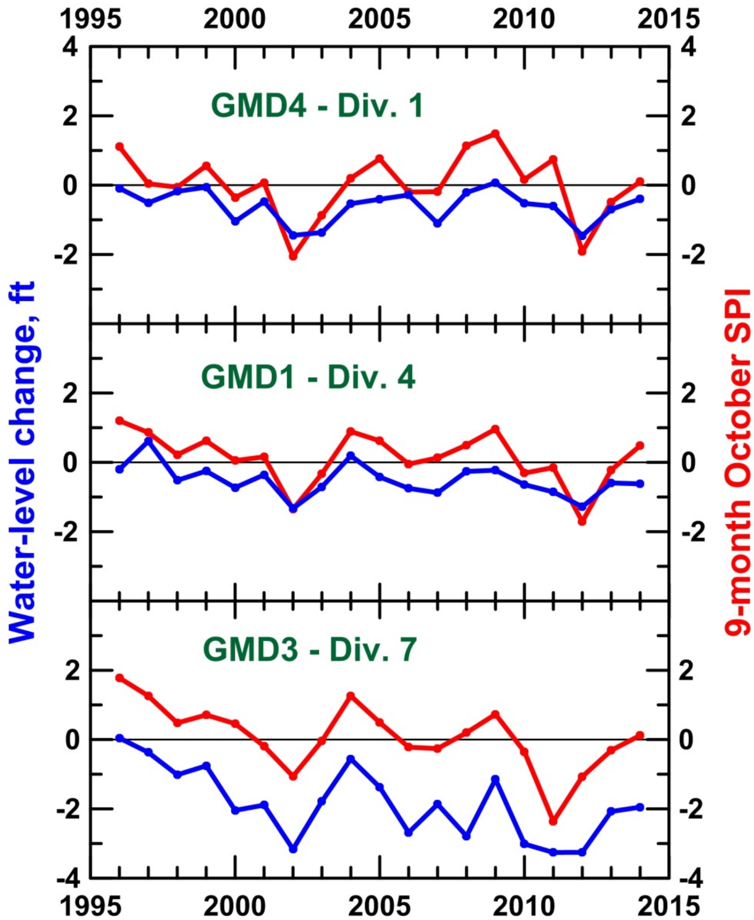


Figure 35—Variations in annual water-level changes for GMDs 4, 1, and 3 and the nine-month October SPI for climatic divisions 1, 4, and 7 during 1996–2014. The water-level changes are the same as shown in fig. 33.

5.5.2. Correlations for the Index Wells

In the previous annual report (Butler et al., 2014), we reported the monthly sums for the Palmer Z index and the duration and ending month for the SPI that give the optimum R^2 values for the climatic index and annual water-level change correlations for the index wells. Both climatic division (GMD area) and index-well-specific values of SPI were used in these correlations. The correlation with the SPI computed for the index location was substantially higher than the correlation with the climatic division SPI. The SPI for the index-well-specific location required calculation of an SPI coverage for each year followed by extracting the value for the SPI for the index well location from this coverage. The revision of the climatic dataset by the NCDC means that all of the SPI coverages would need to be recomputed to obtain the SPI values for the index well locations, a time-consuming process. For this year's report, we give the R^2 values for the correlations between the nine-month October SPI for the climatic division and the water-level change at the index well for 2008–2014 and compare them with the values for 2008–2013 (recalculated for the revised climate dataset) (table 22).

The correlations for the Thomas index well are essentially the same for the tape measurements for 2008–2013 and 2008–2014; the correlations for the transducer values are also similar for the two periods. In contrast, the correlations for both the tape and transducer measurements for the Scott and Haskell index wells are substantially lower for 2008–2014 than for 2008–2013. The cause of the lower correlation for 2008–2014 for the Haskell well is related to the 18-day pumping period during December 2014, which interrupted the water-level recovery as indicated earlier. The lower correlations for 2008–2014 for the Scott County index well suggest that some additional pumping might have occurred in comparison with past years in the area. The water-level decline for 2014 at the Scott County well is greater than expected for the climatic index; the 2014 decline for this well also is greater than the GMD1-wide water-level change as stated in the discussion of fig. 34. However, as described in Section 5.6.2 on correlation of water-level change with radar precipitation for the index wells, the main reason for the lower correlation for the addition of the 2014 data is probably the unusually wet June, which shifted the point for 2014 to a higher SPI value than expected based on the 2008–2013 regression.

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

A new indicator of climatic conditions driving pumping and water-level changes was tested this year: radar precipitation coverages. The Advanced Hydrologic Prediction Service of the National Weather Service provides spatial images and data coverages of radar precipitation for the United States (available at http://water.weather.gov/precip/). The radar precipitation data are compared to and adjusted using data from ground rainfall gauges. A brief description of the observation methods that apply to the general Kansas region follows (from the "About NWS Precip Analysis" tab on the above website):

> Observation Methods. East of the Continental Divide, RFCs derive the "Observed" precipitation field using a multisensor approach. Hourly precipitation estimates from WSR-88D NEXRAD are compared to ground rainfall gauge reports, and a bias (correction factor) is calculated and applied to the radar field. The radar and gauge fields are combined into a "multisensor field", which is quality controlled on an hourly basis. In areas where there is limited or no radar coverage, satellite precipitation estimates (SPE) can be incorporated into this multisensor field. The SPE can also be biased against rain gauge reports.

An example of a precipitation image from this website is shown in fig. 36 for annual precipitation during 2014. The data are displayed as a gridded field with a spatial resolution of approximately 4x4 km; the grid spacing as measured from the data for western Kansas is 2.57 mi north-south and 2.58 mi west-east. Coverages for radar precipitation data available from the website begin for the year 2005.

Table 22—Coefficients of determination (R^2) for the correlation of mean annual water-level changes at the three index wells with the nine-month October SPI (revised climatic dataset) for climatic divisions 1, 4, and 7 during 2008–2013 and 2008–2014.

Period	Index Well, WL Measurement Type, and SPI for Climatic Division	R^2
2008–2013	Thomas County, tape—Division 1	0.53
2008–2014	Thomas County, tape—Division 1	0.53[a]
2008–2013	Thomas County, transducer—Division 1	0.47
2008–2014	Thomas County, transducer—Division 1	0.46
2008–2013	Scott County, tape—Division 4	0.46
2008–2014	Scott County, tape—Division 4	0.17
2008–2013	Scott County, transducer—Division 4	0.50
2008–2014	Scott County, transducer—Division 4	0.33
2008–2013	Haskell County, tape—Division 7	0.50
2008–2014	Haskell County, tape—Division 7	0.16
2008–2013	Haskell County, transducer—Division 7	0.79[b]
2008–2014	Haskell County, transducer—Division 7	0.46

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

Although the image in fig. 36 displays the typical general increase in precipitation from west to east across Kansas, it also indicates the substantial spatial variation in precipitation within regions, such as climatic divisions and GMD areas. We thought that the ability of the dataset to show a more detailed variation in precipitation than the much more widely spaced precipitation stations used in the SPI computation would be valuable for representing climatic conditions at the index-well scale and also subunit scale for parts of GMDs. Therefore, we downloaded monthly radar precipitation data for all of the available years for the Kansas region (2005–2014; a total of 120 gridded coverages).

5.6.1. Correlations for the Groundwater Management Districts

We first determined correlations between the radar precipitation and annual water-level changes for the western three GMD areas to test whether these correlations were as good as those between SPI and water-level changes; this would validate whether the radar precipitation was a good regional indicator of the climatic conditions that drive pumping and water-level declines. We computed the spatial average precipitation from the monthly radar data for each of the areas of GMDs 1, 3, and 4. Then we calculated sums of different numbers and spans of the monthly average values to determine the optimum correlations in a similar manner as for the climatic indices used previously. Figure 37 shows graphs of monthly radar precipitation sums versus annual water-level change for the three western Kansas GMDs for 2005–2013 that give optimum correlations. Data for 2014 were not used because the water-level change for the continuously measured wells has not yet been computed. The R^2 value for GMD 4 is 0.80 for the sum of April through December radar precipitation (fig. 37a); in comparison, the R^2 for the revised nine-month October SPI for climatic division 1 versus water-level change for the same year period is 0.74. The R^2 value for GMD 1 is 0.73 for the sum of April through October radar precipitation (fig. 37b); in comparison, the R^2 for the revised nine-month October SPI for climatic division 4 versus water-level change for 2005–2013 is 0.79. The R^2 value for GMD 3 is 0.50 for the sum of January through November radar precipitation (fig. 37c); in comparison, the R^2 for the revised nine-month October SPI for climatic division 4 versus water-level change for 2005–2013 is 0.55. Thus, the correlations based on the radar precipitation for the regional GMD areas in western Kansas are comparable to those based on the SPI values for climatic divisions.

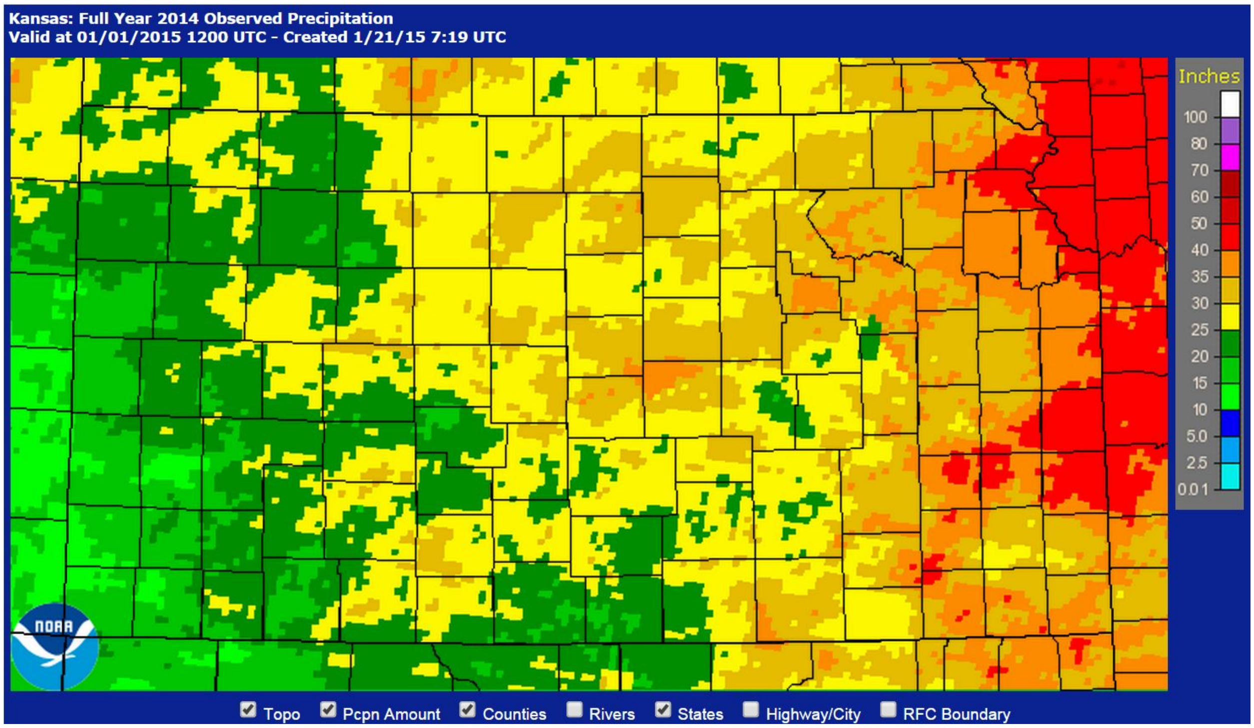


Figure 36—Radar precipitation image for Kansas for annual total during 2014. County lines are displayed in addition to the state boundary within the image area.

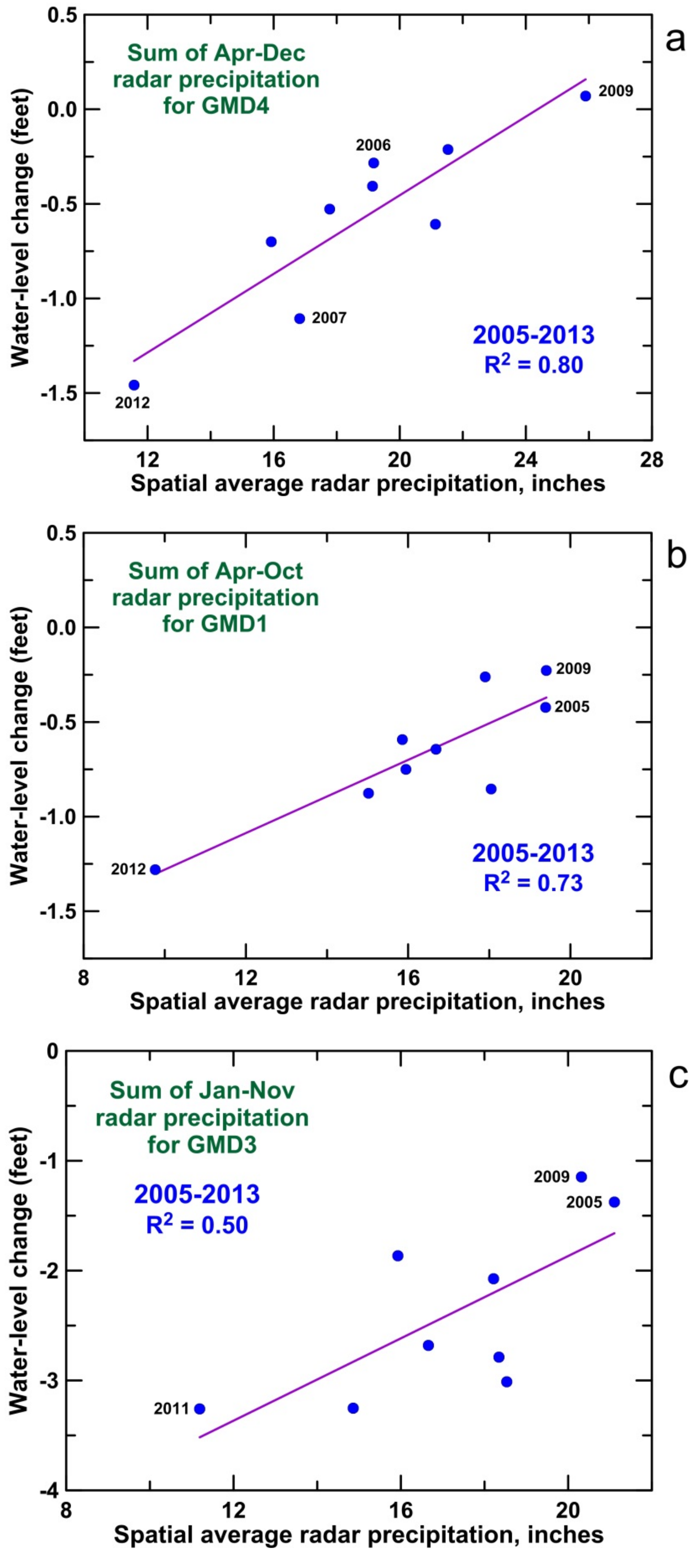


Figure 37—Correlation of mean annual winter water-level change during 2005–2013 for the three western Kansas GMDs with monthly sums of radar precipitation data for GMD areas.

5.6.2. Correlations for the Index Wells

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

The annual water-level changes are well correlated with both the nearest grid point and nine-grid-point mean of the March–December sum of monthly radar precipitation at the Thomas County index well for 2008–2014 (fig. 38). The nine-grid-point mean gives higher correlations than those for the nearest precipitation grid point. The R^2 values for the nine-grid-point data are greater than 0.9, meaning that more than 90% of the variation in the annual water-level change is explained by the variation in radar precipitation.

The annual water-level changes at the Scott County index well are well correlated with both the nearest grid point and nine-grid-point mean of the January–December sum of monthly radar precipitation at the well location for 2008–2013 (fig. 39). If the data for 2014 were included, the correlation would be substantially lower. The 2014 data do not appear to fit the general trend for 2008–2013. Examination of the monthly radar precipitation data shows that June 2014 had unusually high precipitation at the Scott index well site (8.91 in for the nearest point, 8.67 in for the mean of the nine grid points centered on the site). A monthly precipitation of 4–5 in less would probably have been sufficient for pumping not to have been needed for irrigation. If the 2014 point is shifted to the left by 4–5 in of precipitation in fig. 39, the point would be in the general band of points for the 2008–2013 data. However, part of the shift in the 2014 point could still be related to somewhat greater pumping during 2014 than expected for the climatic conditions for January–November due to low precipitation during the spring (April–May). This is similar to the greater water-level decline for the index well than that for the entire GMD1 area as discussed in Section 5.4.2 (see fig. 34). The transducer values for water-level change give appreciably higher R^2 values than the tape measurements for the 2008–2013 data; more than 90% of the variation in the annual water-level change based on transducer measurements is explained by the variation in radar precipitation.

The annual water-level changes at the Haskell County index well are well correlated with both the nearest grid point and nine-grid-point mean of the March–November sum of monthly radar precipitation at the well location for 2008–2013 (fig. 40). If the data for 2014 were included, the correlation would be greatly lower. The 2014 water-level decline is much greater than expected for the climatic conditions because the well was pumped for 18 days during December 2014 as described in Section 5.4.2. The transducer values for water-level change at the Haskell well give higher R^2 values than the tape measurements for the 2008–2013 data; more than 80% of the variation in the annual water-level change based on transducer measurements is explained by the variation in radar precipitation.

Table 23 summarizes the R^2 values for the correlations between annual water-level change at the index wells with radar precipitation. Table 24 summarizes the R^2 values for correlations with the nine-month October SPI computed for the index well site. The optimum correlations for the Thomas County index well are greater for both tape and transducer measurements of water-level changes versus radar precipitation (both the nearest point and nine-point mean) than versus the SPI for 2008–2013. The correlations for February–October radar precipitation at the Scott County index well with tape measurements during 2008–2013 are about the same as with the SPI; the correlations for the transducer measurements are greater for the radar precipitation (both optimum and February–October) than the SPI. For the Haskell County index well, the optimum correlations between both tape and transducer measurements of water-level change and radar precipitation were greater than those with SPI. Thus, radar precipitation data appears to be a better predictor of annual water-level change than SPI at the index wells for 2008–2013.

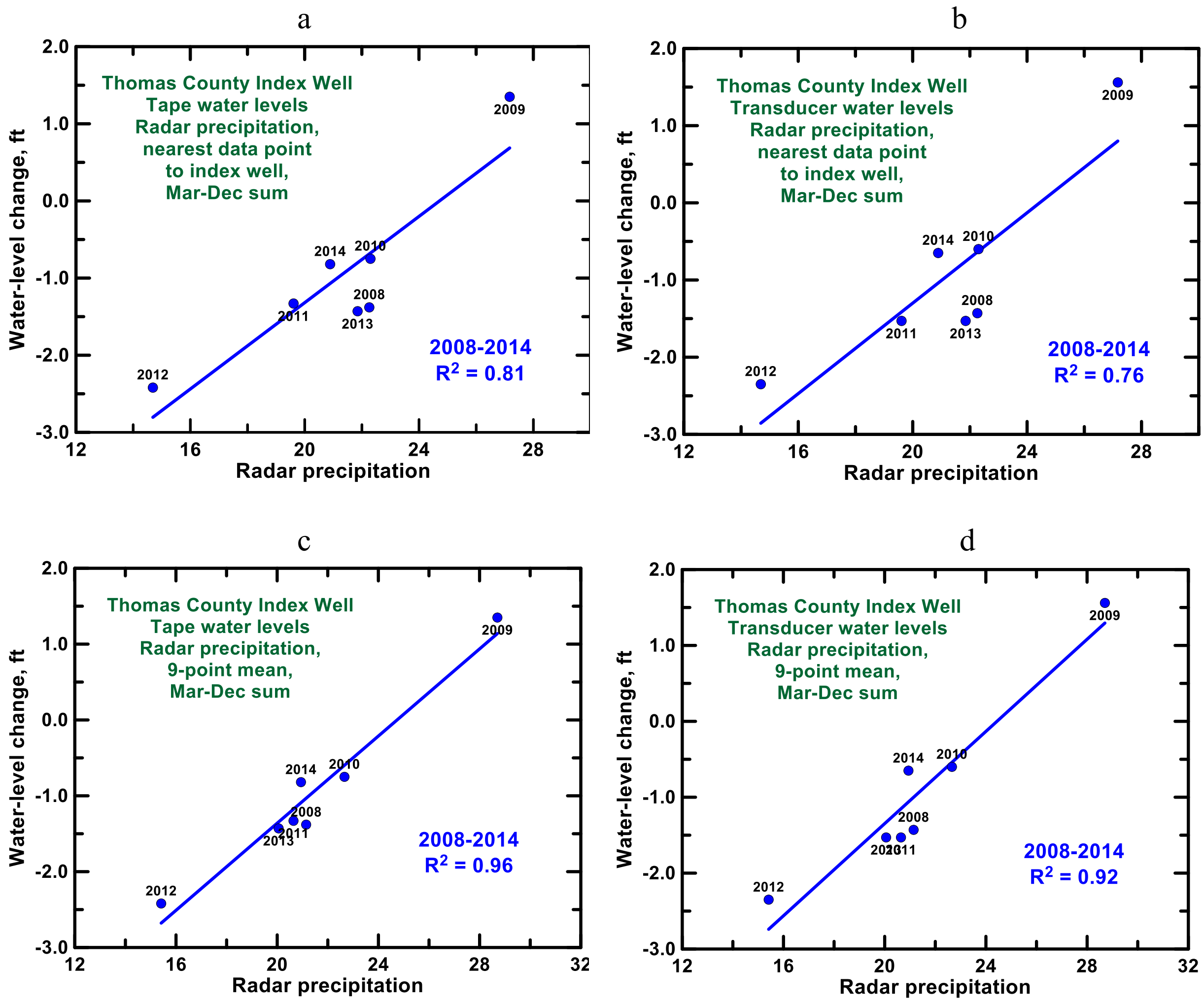


Figure 38—Correlation of annual water-level change (tape and transducer values) during 2008–2014 at the Thomas County index well with the sum of March–December radar precipitation at the grid point nearest the index well (a and b) and for the mean of the nine grid points centered on the index well (c and d).

Although the more specific indication of precipitation at the local scale by the radar data appears to be a generally better predictor than SPI calculated for the local scale, the radar data have a drawback: the influence of very heavy precipitation from local thunderstorms. This is shown by the low correlation for the 2008–2014 dataset for the Scott County well. An anomalously high precipitation amount for a month, such as June 2014 at the Scott County site, can introduce a larger variation in the climatic indicator than the more spatially averaged values for SPI, even those computed for the index well location, because the SPI is calculated from a series of widely distributed weather stations. The radar-detected precipitation for June 2014 at the Thomas County well was also high (5.86 in for the nearest grid point, 6.07 in for the nine-grid-point mean) but not as high as for the Scott County site. The R^2 for the 2008–2014 dataset for the water-level change and radar precipitation correlations for the Thomas County well are about the same as for the 2008–2013 dataset (table 23).

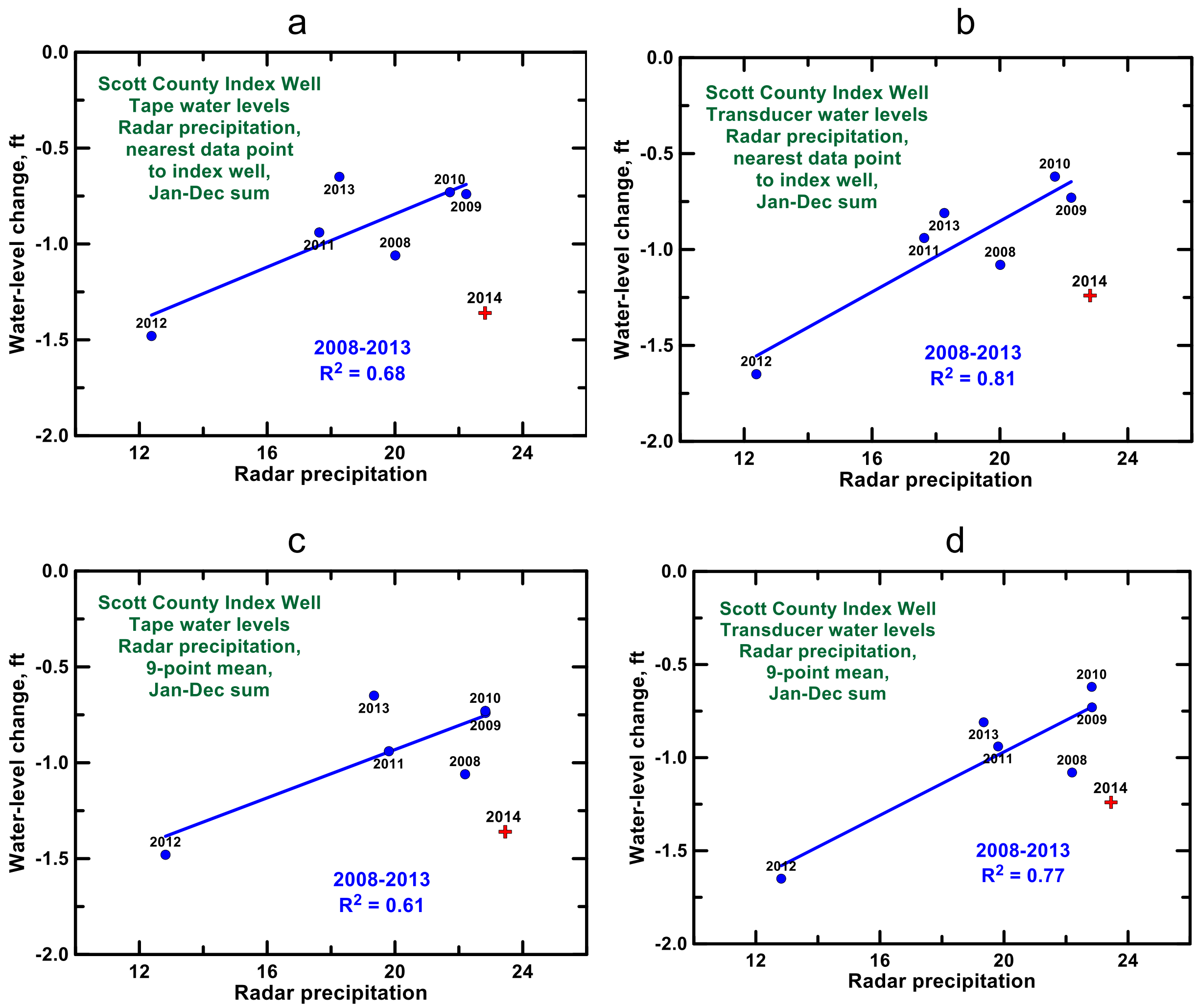


Figure 39—Correlation of annual winter water-level change (tape and transducer values) during 2008–2013 at the Scott County index well with the sum of January–December radar precipitation at the dataset grid point nearest the index well (a and b) and for the mean of the nine grid points centered on the index well (c and d). The point for 2014 is also shown in each graph.

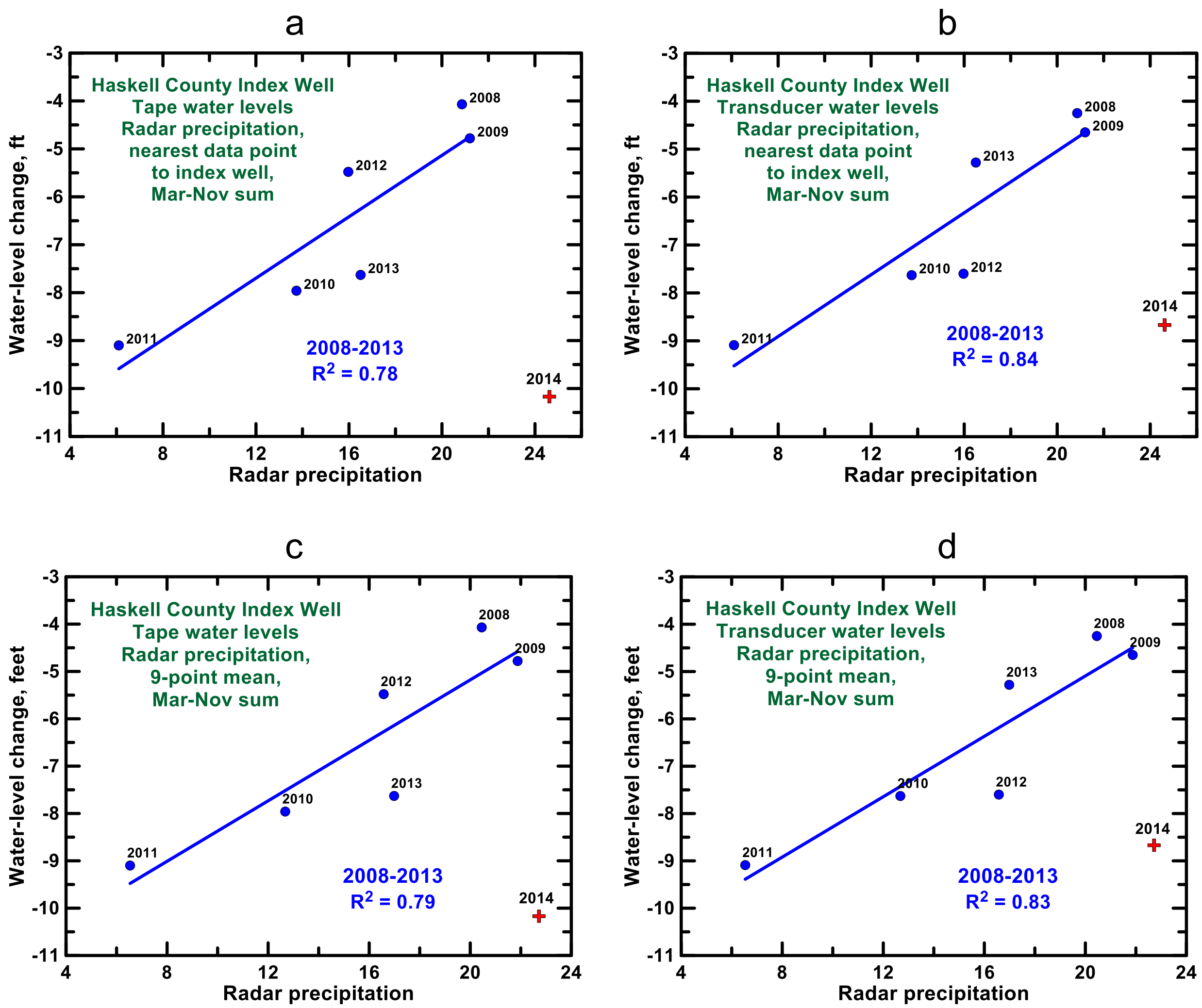


Figure 40—Correlation of annual winter water-level change (tape and transducer values) during 2008–2013 at the Haskell County index well with the sum of March–November radar precipitation at the grid point nearest the index well location (a and b) and for the mean of the nine grid points centered on the index well (c and d). The point for 2014 is also shown in each graph.

Table 23—Correlation (R^2 values) of annual water-level change with sum of monthly radar precipitation for the nearest grid point to the index well location and for the mean of the nine grid points centered on the index well for 2008–2013 and 2008–2014. The March–December sum for the Thomas County well is the optimum correlation based on transducer measurements for 2008–2014; the January–December and March–November sums for Scott and Haskell counties wells, respectively, are the optimum correlations for transducer values for 2008–2013. The February–October sum for 2008–2013 is for comparison with the nine–month October SPI in table 24. The statistical significance is dependent on the number of samples and thus is different for the 2008–2012 and 2008–2013 periods.

		Radar precipitation, nearest point		Radar precipitation, nine-point mean	
Annual period	**Monthly sum**	**Tape measurement**	**Transducer measurement**	**Tape measurement**	**Transducer measurement**
		Thomas County Index Well			
2008–2013	Mar–Dec	0.82[a]	0.78[a]	0.97[a]	0.94[a]
2008–2013	Feb–Oct	0.70[b]	0.67[b]	0.92[a]	0.90[a]
2008–2014	Mar–Dec	0.81[a]	0.76[a]	0.96[a]	0.92[a]
		Scott County Index Well			
2008–2013	Jan–Dec	0.65[b]	0.81[a]	0.61[b]	0.77[a]
2008–2013	Feb–Oct	0.67[b]	0.79[a]	0.64[b]	0.79[a]
2008–2014	Jan–Dec	0.18	0.43	0.21	0.49
		Haskell County Index Well			
2008–2013	Mar–Nov	0.78[a]	0.84[a]	0.79[a]	0.83[a]
2008–2013	Feb–Oct	0.80[a]	0.78[a]	0.81[a]	0.77[a]
2008–2014	Mar–Nov	0.06	0.20	0.13	0.29

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

Table 24—Correlation (R^2 values) of annual water-level change with the nine-month October SPI computed for the index well locations for 2008–2013.

	Correlation with nine-month October SPI	
Index well	**Tape measurement**	**Transducer measurement**
Thomas Co	0.71[a]	0.63[a]
Scott Co	0.67[a]	0.68[a]
Haskell Co	0.73[a]	0.77[b]

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

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

Last year's report showed statistically significant correlations between annual water use in the vicinity of the index well and annual water-level change for 2008–2012 at the Thomas, Scott, and Haskell counties sites. The R^2 values for the correlations were updated for new and revised water-use data and listed in table 25 for 2008–2013 (Thomas and Scott) and 2008-2012 (Haskell).

The water-level change and water-use correlations for 1-mi, 2-mi, and 5-mi radii water-use data are all statistically significant for the Thomas County index well. The larger the radius, the greater the correlation. Variations in the 5-mi radius water use explained more than 90% of the variation in annual water-level changes based on both tape and transducer measurements. The correlations for the Scott County index well are only significant for the 5-mi radius water use; the R^2 values for the tape and transducer measurements are at or close to 0.7. Graphs of the correlations for the 5-mi radius water use and transducer water-level measurements at the Thomas and Scott county sites are shown in fig. 41 (a and b). As stated in last year's report, 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 most impacting the water levels at these sites but could represent more uniform water use for each year than a smaller area (lessening the effect of reporting errors, etc.).

Although the water level and water use correlation for tape measurements at the Haskell County index well and the 1-mi radius water use for 2008–2012 is statistically significant ($R^2 = 0.81$, table 25), no correlation was found for the 2008–2013 data. The probable error in the tape measurement for 2012 might have produced an artificially high correlation for the five data points. Figure 41c displays the distribution of points and linear regression for the 2008–2013 data sets based on transducer-measured water levels and the 1-mi water use radius. The substantial scatter in the points could be related to the relatively small range in annual water-level changes when compared to the very large irrigation season water-level decline (more than 100 ft) and the sensitivity of water levels in the confined aquifer at the location to even short periods of pumping outside the main irrigation season.

Table 25—Correlation (R^2 values) of annual use around the index wells with annual water-level changes (tape and transducer measurements) in the index wells for 2008–2013 for Thomas and Scott counties and 2008–2012 for Haskell County.

	Tape measurements			Transducer measurements		
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	0.76[a]	0.78[b]	0.92[b]	0.77[b]	0.81[b]	0.94[b]
Scott Co	0.36	0.53	0.70[a]	0.48	0.51	0.68[a]
Haskell Co	0.81[b]	0.11	0.24	0.37	0.26	0.29

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

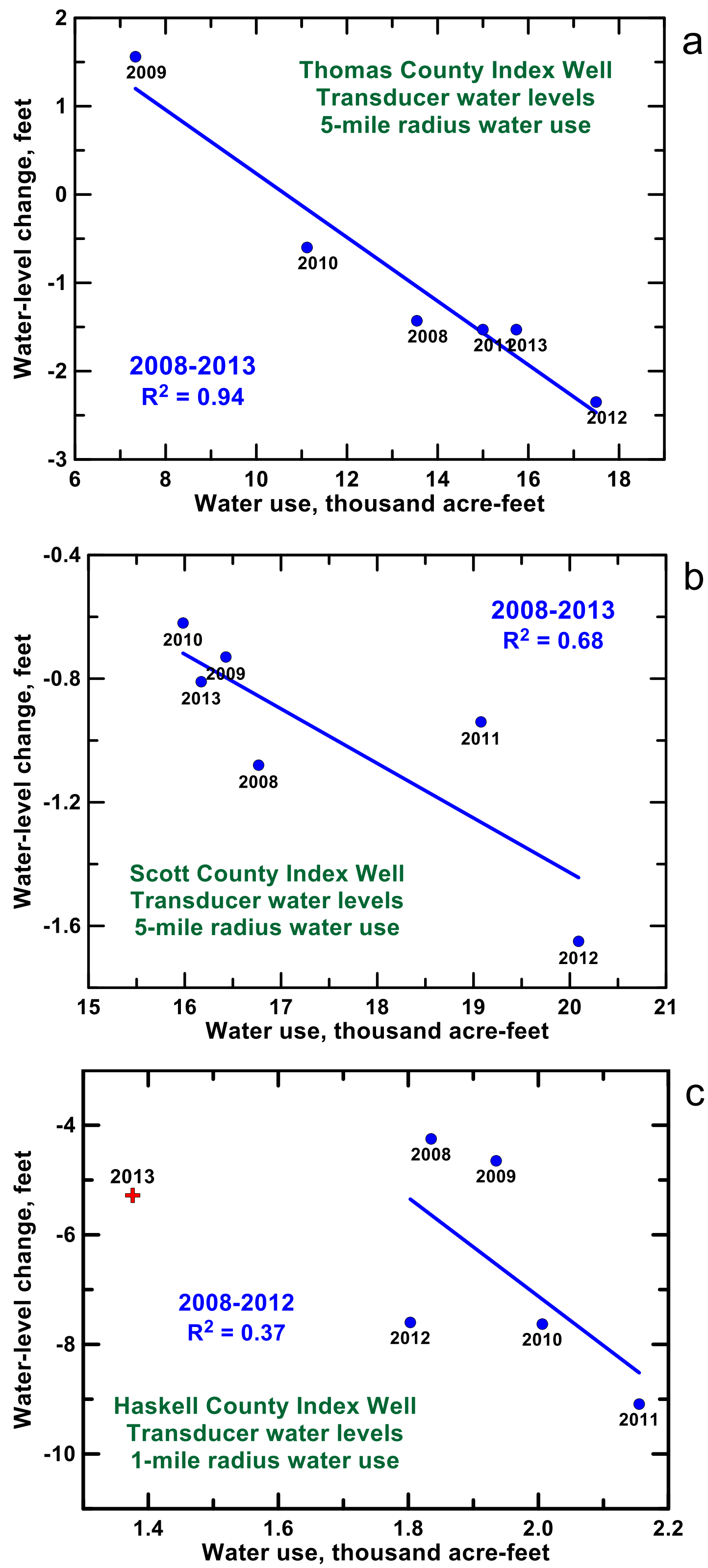


Figure 41—Correlation of annual water-level changes based on transducer measurements in the index wells versus annual water use within a 5-mi radius for the Thomas and Scott counties wells during 2008–2013 and within a 1-mi radius for the Haskell County well during 2008–2012.

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

Annual water use and radar precipitation are highly correlated for the Thomas and Scott counties index wells (table 26). The R^2 values for the February–October radar precipitation are higher than for the nine-month October SPI calculated for the index well site for 2008–2012 (table 27). The R^2 values for radar precipitation during 2008–2013 are generally lower than those for the 2008–2012 dataset (table 26).

The highest R^2 value for the 2008–2013 dataset at the Thomas County well is for the correlation of the nine-grid-point mean and water use within a 5-mi radius (table 26, fig. 42a). The nine-grid-point mean represents an area of 59.6 mi^2 in comparison to the areas of 12.6 mi^2 for a 2-mi radius and 78.5 mi^2 for a 5-mi radius. However, the correlation between water use within a 1-mi radius (3.14 mi^2) and radar precipitation at the nearest grid point to the well (representing an area of 6.63 mi^2) is nearly as high. The highest R^2 value for the 2008–2013 dataset at the Scott County well is for the correlation of water use within a 1-mi radius and radar precipitation at the nearest grid point (table 26, fig. 42b).

Table 26—Correlation (R^2 values) of annual water use with the February–October sum of monthly radar precipitation for the nearest grid point to the index well location and for the mean of the nine grid points centered on the index well for 2008–2012 and 2008–2013. The statistical significance is dependent on the number of samples and thus is different for the 2008–2012 and 2008–2013 periods.

	Radar precipitation, nearest point			Radar precipitation, nine-point mean		
Annual period	**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 County Index Well			
2008–2012	0.97[a]	0.94[a]	0.93[a]	0.90[a]	0.93[a]	0.98[a]
2008–2013	0.67[b]	0.66[b]	0.70[b]	0.80[a]	0.83[a]	0.91[a]
			Scott County Index Well			
2008–2012	0.90[a]	0.32	0.96[a]	0.82[b]	0.22	0.92[a]
2008–2013	0.87[a]	0.31	0.85[a]	0.80[a]	0.22	0.79[a]
			Haskell County Index Well			
2008–2012	0.74[b]	0.33	0.46	0.75[b]	0.30	0.45
2008–2013	0.22	0.24	0.39	0.25	0.24	0.44

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

The correlations between water use within a 1-mi radius at the Haskell County index well and the sum of February–October radar precipitation at the nearest grid point or a nine-grid-point mean around the well are statistically significant for 2008–2012 (table 26). The R^2 values for these correlations are substantially greater than for the correlation between water use and the nine-month October SPI computed for the index well site (table 27). Figure 42c displays the correlation for radar precipitation at the nearest grid point. The point for 2013 in fig. 42c indicates why the correlations for 2008–2013 are so much lower than for 2008–2012. The much smaller amount of pumping during 2013, which was due to the court-ordered shutdown of pumping at two nearby wells (see section 3.1.1.1), does not fit the general relationship of water use and precipitation that prevailed during 2008–2012.

Table 27—Correlation (R^2 values) of annual water use around the index wells with the nine-month October SPI computed for the index well locations for 2008–2012.

	Correlation with nine-month October SPI		
Index well	**Water use, 1-mi radius**	**Water use, 2-mi radius**	**Water use, 5-mi radius**
Thomas Co	0.65	0.53	0.64
Scott Co	0.82[a]	0.21	0.77[a]
Haskell Co	0.58	0.49	0.60

[a] Significant at P = 0.05

The effect of a longer period of a monthly sum of radar precipitation on correlations between water use and precipitation at the index wells was examined to see whether the longer period would remove some of the effects of anomalously high precipitation for individual months. Table 28 lists the correlations for an annual sum of radar precipitation. Comparison of the results in tables 26 and 28 indicate that the R^2 values for the annual total precipitation are lower for the Thomas and Scott index wells than for the February–October sum for 2008–2012, but higher for both wells for the 2008–2013. The R^2 values for annual precipitation are a little lower than those for the February–October sum for 2008–2012 at the Haskell County index well. Thus, both the period of February–October, which is similar to the SPI period of nine months ending in October, and the annual total precipitation appear to be appropriate for the correlation of water use with radar precipitation; the optimum correlation depends on the particular span of years. Somewhat different monthly sums may give somewhat higher correlations for particular combinations of water use radius and radar precipitation area (nearest grid point or multiple grid-point means) but these are probably partly due to the randomness of data distribution for the low number of years in the correlation. As the number of data years increases for the index wells, more definitive determinations of optimum correlations could be obtained, just as for the 19 years of data currently available for the GMD-wide datasets (1996–2014).

Table 28—Correlation (R^2 values) of annual water use with the annual sum (January–December) of monthly radar precipitation for the nearest grid point to the index well location and for the mean of the nine grid points centered on the index well for 2008–2012 and 2008–2013. The statistical significance is dependent on the number of samples; the break between P = 0.01 and P = 0.05 may be different for the same R^2 and number of samples due to rounding of R^2 values.

	Radar precipitation, nearest point			**Radar precipitation, nine-point mean**		
Annual period	**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 County Index Well			
2008–2012	0.96[a]	0.88[a]	0.90[a]	0.88[a]	0.87[a]	0.95[a]
2008–2013	0.75[b]	0.70[b]	0.76[b]	0.83[a]	0.83[a]	0.92[a]
			Scott County Index Well			
2008–2012	0.84[a]	0.29	0.90[a]	0.72[b]	0.19	0.83[a]
2008–2013	0.84[a]	0.29	0.75[b]	0.72[b]	0.16	0.67[b]
			Haskell County Index Well			
2008–2012	0.72[b]	0.33	0.45	0.72[b]	0.30	0.45
2008–2013	0.24	0.25	0.42	0.27	0.25	0.42

[a] Significant at P = 0.01

[b] Significant at P = 0.05

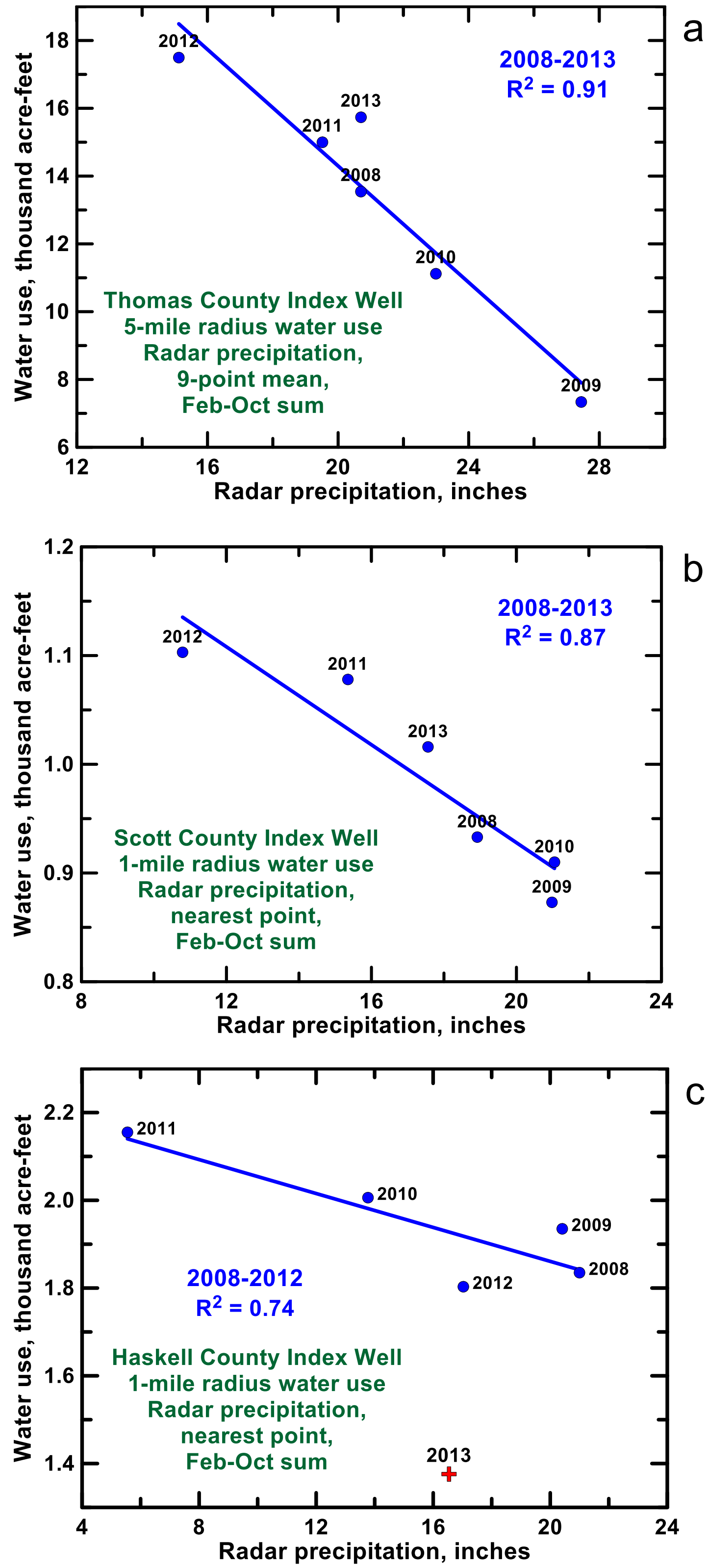


Figure 42—Correlation of annual water use with radar precipitation at the index wells in Thomas and Scott counties for 2008–2013 and Haskell County for 2008–2012.

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

In the previous sections and in the previous work of this project that led to the Whittemore et al. (2015) publication in Appendix A, we have found a linear relationship between annual water-level change and water use. In this section, we develop the theoretical support for this relationship.

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

Water Volume Change in Aquifer = Net Inflow - Pumping (1)

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

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

where:

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

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

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

where a and b are constants (slope and intercept of best-fit line, respectively).

Equation (3) indicates that, given the conditions noted in the previous paragraph, a plot of ΔWL versus Q should be linear, which is what we have found in our analyses of 1996–2013 annual water-level changes in GMD4 (Whittemore et al., 2015—see Appendix A) and in the analyses of water-level changes at the index wells discussed in the previous sections.

Thus, it appears that we should be able to estimate the S_y and I of any particular area of an aquifer from the slope (a) and intercept (b) of the best-fit line to the ΔWL versus Q plot. More importantly, we can also use the equation to estimate the impact of proposed pumping reductions on annual water-level changes in a theoretically defensible manner. Finally, equation (3) provides a very rapid means of predicting future water-level changes for a given annual pumping; the annual pumping for a projected climatic condition can be estimated using the relationships discussed in the previous sections and Whittemore et al. (2015—see Appendix A).

5.9.1. Application to Thomas County Index Well

Figure 43a is the ΔWL versus Q plot for a circular area with a 5-mi radius centered on the Thomas County index well. The average annual water-level change over the area is approximated by the annual water-level change at the index well, while the water use is the total reported annual water use for that area. As shown in fig. 43a, the equation for the best-fit line through these data is:

$$\Delta WL = 3.46 - 0.33Q \tag{4}$$

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

$$S_y = (Area*0.33)^{-1} \tag{5}$$

Given the area of 50,265 acres, $S_y = 0.06$, which is the specific yield for a sand, clay, and silt mixture (majority sand with lesser amounts of clay and silt).

Given this S_y, we can estimate I from the intercept (3.46):

$$I = 3.46*S_y \tag{6}$$

In this case, $I = 0.21$ ft/yr or 2.5 inches/yr.

We can also calculate the reduction in average annual water use that would have been required to have had no change in water level over the 2008–2013 monitoring period. The average reported use for this period was 13,370 ac-ft and the water use at $\Delta WL = 0$ can be calculated from equation (4) as 10,485 ac-ft. Thus, a 22% reduction in average annual water use would have produced essentially stable water levels over the monitoring period.

Equation (4) can be used to predict future annual water-level changes for a given reported water use assuming that the slope and intercept do not change with time. However, that assumption could be questionable under the following conditions:

a) Continuing aquifer depletion—as the saturated thickness diminishes, S_y could change, which would cause a change in the slope and intercept parameters in equation (4). However, the S_y change would likely be gradual and not great. Probably the maximum change we could expect at the scale of this example is a factor of two. The small and medium dashed lines in fig. 43b are the ΔWL vs. Q plots for a factor of two decrease and increase in S_y, respectively. It likely would be difficult to pick up such a change for some time unless the reported water use was near the upper end of the historical range. Note that the Q at $\Delta WL = 0$ remains unchanged as it is solely a function of I;

b) Changing climatic conditions—As climatic conditions change, inflow into the area would likely change. Most projections indicate drier conditions in the future. The large dashed line in fig. 43b is the ΔWL vs. Q plot for a factor of two decrease in I assuming no change in S_y. This change should be more readily detectable than a change in S_y as the line shifts downward to the left while retaining its original slope. Changes in climatic conditions could also result in changes in the duration and the onset and/or end of the pumping season. However, as long as the water-level measurements are taken at about the same time as current measurements and three or so months from the end of the pumping season, this should not produce scatter in the plot much beyond what we currently observe.

c) Changes in irrigation return flow—irrigation return flow and irrigation enhanced recharge could be significant contributors to the inflow into this area. If so, the inflow would likely decrease over time, regardless of climatic conditions, because of the transition to more efficient irrigation practices.

Three additional factors that could be responsible for the scatter in fig. 43a are:

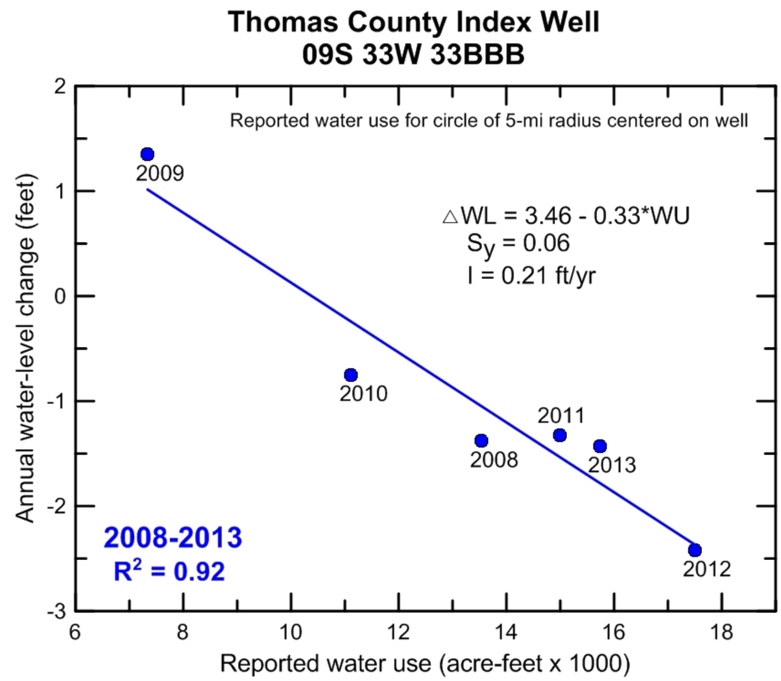
a) Changes in atmospheric pressure—changes in atmospheric pressure can produce up to a foot change in water level at the Thomas index well and elsewhere in western Kansas where the water table is well more than 100 ft below land surface. Considerable "noise" can be introduced into the ΔWL data if the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

b) Measurement error—error in reported Q, in particular, can produce considerable scatter.

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

The ΔWL vs. Q plots in Whittemore et al. (2015—see Appendix A) use the average annual water change over a certain area. In this section, we have used the annual water-level change at the Thomas County index well in place of an areal average. Although this approximation of the areal average may not have a big impact on the slope of the best-fit line, it likely would alter the intercept and thus could affect the I estimate somewhat.

a)



b)

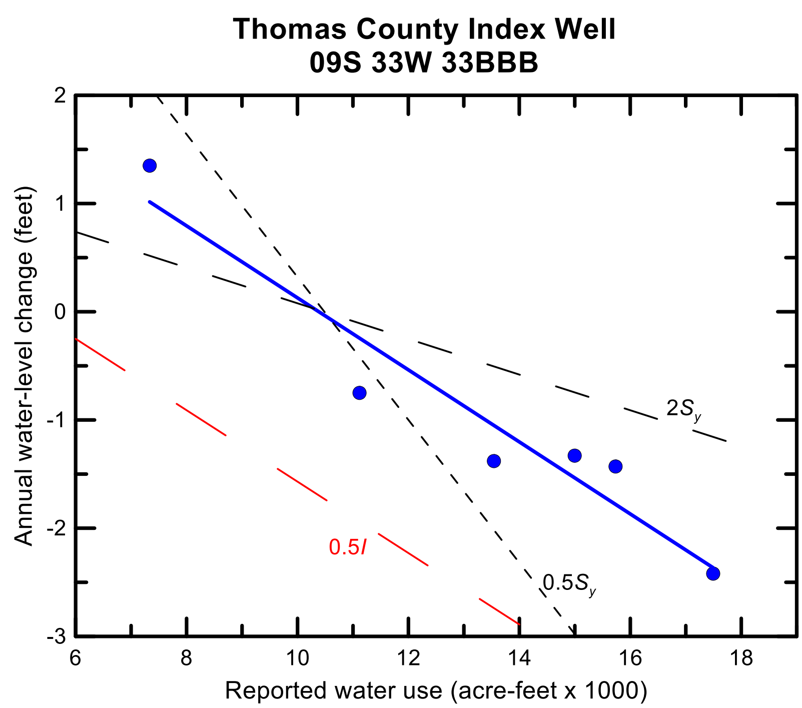


Figure 43—a) Reported water use versus annual water-level change at the Thomas County index well plot for the monitoring period (2008–2013; reported water use for 2014 not yet available). Solid line is the best-fit line with a slope of 0.33 and intercept of 3.46. b) Sensitivity of water use versus annual water-level change at the Thomas County index well to changes in specific yield (S_y) and net inflow (I); small and medium dashed lines indicate plot for a factor of two decrease and increase in S_y, respectively, and large dashed line indicates plot for a factor of two decrease in I.

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

The index well program report for 2013 listed a plan to assess in 2014 the effect of the Dakota aquifer on water levels in the vicinity of the Haskell County index well and the direction of possible leakage between the HPA and the Dakota aquifer. Water-level records in the KGS online database WIZARD were examined in the four township block surrounding the Haskell County site for wells identified or estimated to be completed in the Dakota aquifer and nearby wells completed in the HPA. This identification/estimation was based on data obtained during studies for the Dakota aquifer bulletin published by the KGS in 2014 (Whittemore et al., 2014); the investigations included examination of publications, WWC5 well logs, and other information such as well depths in the water rights information system (WIMAS) to determine or estimate wells that are completed only or partially in the Dakota aquifer.

No records indicate that any wells are completed solely in the Dakota aquifer in the area of the Haskell County index well. In the four township block around the Haskell index well, three wells for which water-level data exist in WIZARD appear to be partially completed in Dakota sediments (as well as in the HPA). The water-level elevations at these locations were compared to the water-level elevations of nearby wells completed only in the HPA to assess whether there appeared to be any significant difference in water levels that might suggest flow from the Dakota aquifer upward into the HPA or from the HPA down into the Dakota.

An irrigation well located at T. 28 S., R. 30 W., 17BAB, in Gray County, with a well depth of 541 ft was estimated to have a yield of 30% from the Dakota aquifer and 70% from the HPA based on the WWC5 record (web ID 444043) and water right no. 3877. The WIZARD ID for this well is 373709100374702. The water-level depth was 258.92 ft on January 6, 2015; based on a surface elevation of 2,813 ft, this depth gives a water-level elevation of 2,554.08 ft.

An irrigation well at T. 27 S., R. 31 W., 24CDD, in Haskell County, with a well depth 383 ft, was estimated to have a yield of 10% from the Dakota aquifer with the rest from the HPA based on the WWC5 record (web ID 28160) and water right no. 6281. The WIZARD ID for this well is 374044100395002. The water-level record is for 1991–2015. The water-level elevation on January 6, 2015, was 2,561.9 ft based on a water-level depth of 259.77 ft and a land surface elevation of 2,821.67 ft. This well is a replacement for an older well at the site that had a completion depth of 206 ft, which would have only been in the HPA, and a water-level record for 1964–1990. The water-level elevation in the old well on January 30, 1990, was 2,659.72 ft based on a surface elevation of 2,818 and a water-level depth of 158.28 ft. In comparison, the replacement well had a water-level elevation of 2,659.47 ft on January 16, 1991, based on a water-level depth of 162.2 ft. The difference in water-level elevations between 1990 and 1991 was 0.25 ft. This difference could most easily be interpreted as a water-level decline from one year to the next at the location, rather than a difference between water levels in the Dakota aquifer and the HPA.

Another irrigation well in the index well area that might include a very small amount of yield from the Dakota aquifer is located at T. 28 S., R. 31 W., 19AAA, in Haskell County, with a completion depth of 600 ft, a WWC5 record (web ID 415284), and water right no. 13393. However, it is difficult to determine how much, if any, groundwater is derived from the Dakota aquifer in this well; the log indicates that the completed well ends in yellow clay overlain by "fine to medium sand and gravel–brown rock mixed." The yellow clay suggests that the brown rock is probably gravel eroded from Dakota strata rather than Dakota bedrock. The water-level elevation in this well was 2,543.83 ft on January 7, 2015, based on a surface elevation of 2,930 ft and a water-level depth of 386.17 ft.

The Haskell County index well, located at T. 27 S., R. 31 W., 36BDC, is approximately 3.5 miles to the south-southeast of the first irrigation well described above (estimated 30% Dakota yield) and a little less than 2 mi south of the second well (estimated 10% Dakota yield). The elevation of the water table in the index well on January 6, 2015, was 2,535.29 ft. WIZARD contains water-level data for three irrigation wells screened only in the HPA in the four block township around the index well:

1. Location T. 27 S., R. 31 W., 09CDB, Haskell County, well depth 430 ft, surface elevation 2,816 ft, water-level depth 252.3 ft on January 6, 2015, water-level elevation 2,563.7 ft;
2. Location T. 28 S., R. 31 W., 35CCB, Haskell County, well depth 312 ft, surface elevation 2,863 ft, water-level depth 272.5 ft on January 5, 2015, water-level elevation 2,590.5 ft;
3. Location T. 28 S., R. 30 W., 24BAB, Gray County, well depth 429 ft, surface elevation 2,804 ft, no water level for 2015 but the water level was 288.6 ft on January 14, 2014, giving a water-level elevation of 2,515.4 ft.

The water-level elevations in January 2015 in the two irrigation wells that appear to have some yield from the Dakota aquifer (2,554.08 ft and 2,561.9 ft) range from about 47 ft above to 36 ft below the January 2014 and 2015 water-level elevations of the wells screened only in the HPA (index well and three irrigation wells). The maximum difference in the water-level elevations of the HPA-only wells is 75 ft. These values, along with the observations for the old irrigation well and its replacement discussed above indicate that there is no clear evidence for the water level in the Dakota aquifer near the Haskell County index well to be either substantially above or below the water level in the HPA. The best way to determine the relative water levels in the Dakota and HPA aquifers and, therefore, the direction of vertical groundwater flow between the two aquifers in northeast Haskell County would be to install a monitoring well completed only in the Dakota aquifer near the existing index well.

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 collected from the three original 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, and the border index wells in Morton, Stevens, and Seward counties were sampled in 2014. 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. Similar data will be available by the end of 2015 from drilling projects completed in 2014 near the Scott index well and Cimarron index well sites. Last year's index well report focused on sources and age of water near the three original index wells (Butler et al., 2014); this year, the focus is on the new information obtained in Morton, Stevens, and Seward counties.

The four southern border well locations were the focus of intense study by the USGS 14–15 years ago as part of the National Aquifer Water Quality Assessment (NAWQA) program (e.g., McMahon, 2001; McMahon et al., 2004; McMahon et al., 2007). In 1999–2000, a total of 14 wells were installed at these four locations (13 screened within the HPA). Two wells are located near Rolla, four each near Hugoton and Liberal, and three near the Cimarron River in southeast Seward County. A fourth well at the Cimarron site is screened in Permian rock units. Each monitoring location installed during the NAWQA project contained at least one water-table well and one well deeper in the aquifer, providing vertical information about fluid flow within the aquifer. Two of the four monitoring locations are located in rangeland (Rolla, Cimarron) and two near irrigated fields (Hugoton, Liberal). Nine of the thirteen original HPA wells were resampled in 2014; by 2014, the water table had dropped below the shallowest well at Hugoton. Thus, 75% of the viable HPA wells were resampled in 2014. The earlier work provided baseline geochemical and groundwater age information across and within this transect of HPA wells. By resampling these wells (15 years later), we can assess the original estimates of recharge rates and travel times within the aquifer and refine conceptual models concerning recharge pathways.

Geochemical changes from the original sampling in 1999–2000 (McMahon et al., 2004) to 2014 were small (table 29). Total-dissolved solids (TDS), nitrate (NO_3), and chloride (Cl) concentrations are discussed in detail to demonstrate the overall stability. In 2014, NO_3-N concentrations ranged between 1.77 and 5.74 mg/L; in 1999–2000, the range was 1.90 to 5.71 mg/L. In six of the wells, values increased by 1.1% or less (within the analytical uncertainty); in the remaining three wells, NO_3 concentrations decreased between 3.5% and 7.5%. Rolla was the only site where NO_3 concentrations were highest in water sampled from the shallowest well (NO_3 concentrations were also highest at this site compared with other sites). Chloride concentrations were low in all but one of the wells. Excluding the Cimarron site, in 2014, Cl concentrations ranged between 7.92 and 23.4 mg/L, compared with 9.22 to 19.9 mg/L in water sampled from the same wells in 1999–2000. The changes in concentration varied between an 11.6% decrease and an 8.1% increase, with five wells exhibiting a decreased Cl concentration and two wells exhibiting an increased concentration. The highest values by far were recorded at the Cimarron site; here, concentrations ranged between 52.7 and 1,800 mg/L in 2014, compared with 52.5 and 1,860 mg/L in 1999–2000. Very little change was observed between 1999 and 2014; differences of -1.6 to + 0.2% were observed, which are within analytical uncertainty. The deepest well has the highest concentration, a reflection of the influence of deeper and more saline water in the Permian strata. Higher Cl concentrations were recorded near the water table compared with the next deepest well in the HPA at every site except Rolla in both 1999–2000 and 2014.

Stable isotope values in the HPA samples were heavier (less negative values) in this southern tier of counties than elsewhere in the Kansas HPA (fig. 44), following a trend previously observed from Thomas to Haskell counties (Butler et al., 2014). Similar to the Haskell site, isotopic values were heaviest in water sampled from the shallowest wells and became lighter with depth. The largest change with depth was observed at the Liberal site (2.3‰ over 410 ft), next was the Cimarron site (1.6‰ over 270 ft), Hugoton (0.8‰ over 480 ft), and finally Rolla (0.5‰ over 170 ft). The rate at which isotopic composition decreased per foot was roughly the same at the two easternmost sites (Liberal and Cimarron, 0.0056 and 0.0059‰/ft) compared with Rolla (0.0029‰/ft) and Hugoton (0.0017‰/ft). Slightly heavier isotopic values were observed in the shallowest wells from west to east (Rolla to Liberal: -7.9 to -7.0‰). This trend was interrupted at the Cimarron site (-7.4‰). At the Hugoton site, excepting the water-table well, values were essentially the same between 313 and 617 ft below the ground surface. The stable isotopic composition (δ^2H, $\delta^{18}O$) exhibited very little change from 1999–2000 to 2014. The most significant changes were observed at the Rolla site, where $\delta^{18}O$ values changed between 0.7 and 1.3%; values at the remaining sites were all within 0.4% between the two sampling events (just outside of analytical uncertainty).

The isotopic trends from samples collected through the index well program provide useful information about recharge conditions across the Kansas HPA. Waters recharging into the HPA in northern Kansas reflect a cooler climate and/or higher elevation than in southern Kansas. The surface elevations of the three original index wells decrease from north to south (3,188 ft, 2,967 ft, and 2,838 ft at the Thomas, Scott, and Haskell counties sites, respectively). The surface elevations of the new index wells near the Oklahoma border decrease from west to east (3,375 ft, 3,100 ft, 2,821 ft, and 2,529 ft at the Rolla, Hugoton, Liberal, and Cimarron sites, respectively). The much lighter isotopic composition of the water at the Thomas County well than at the comparable depth at the Rolla site (which is at a higher elevation) suggests that the north-south location is more important than the elevation control on the isotopic composition. Likewise, at any one site, isotopic values decrease with depth, also indicating recharge during a cooler climate or higher elevation for water found deeper in the aquifer. Water found deeper in the aquifer is older than shallower water and has likely recharged earlier and significantly up-gradient and at a higher elevation than that of the sample location, while the shallower water tends to be more locally recharged. The relatively small decrease in isotopic values observed for the near water-table samples from west to east between Rolla and Liberal (+0.9‰ for $\delta^{18}O$), which could be related to elevation, is much less than the overall vertical change (e.g., 2.0 ‰ for $\delta^{18}O$ at Liberal). This suggests that the earlier age of deeper water recharged farther to the west and during slightly cooler climates than at present is a more important control than present-day surface elevation. As additional stable and radioactive isotopic data are collected, the age, climate, and elevation of the recharge to HPA at different depths and locations will become clearer.

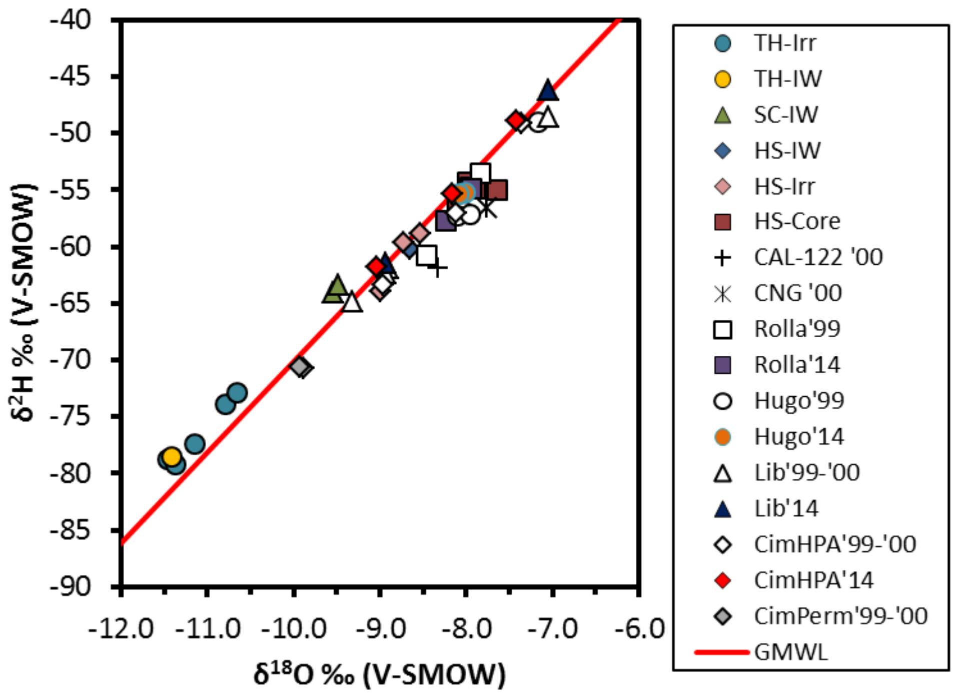


Figure 44—Stable isotopic composition ($\delta^{18}O$ vs. $\delta^{2}H$) for High Plains aquifer water and underlying Permian strata. Sample locations are abbreviated: TH = Thomas County, SC = Scott County, HS = Haskell County, CAL-122 = Haskell County, CNG = Cimarron National Grasslands, Hugo = Hugoton, Lib = Liberal, CimHPA = Cimarron High Plains aquifer, CimPerm = Cimarron Permian strata, Irr = irrigation well, IW = index well, Core = pore water. Data for samples collected in 1999–2000 are published in McMahon et al. (2004).

Although the geochemistry and isotopic compositions were little changed from 1999 to 2014, more significant changes were observed in the radioactive carbon content (^{14}C). In 2014, a younger fraction of water was sampled in the shallowest wells at every site except Hugoton (the water table well at Hugoton could not be sampled in 2014). The largest difference was observed at Cimarron. No significant change was observed for water from any of the deeper wells.

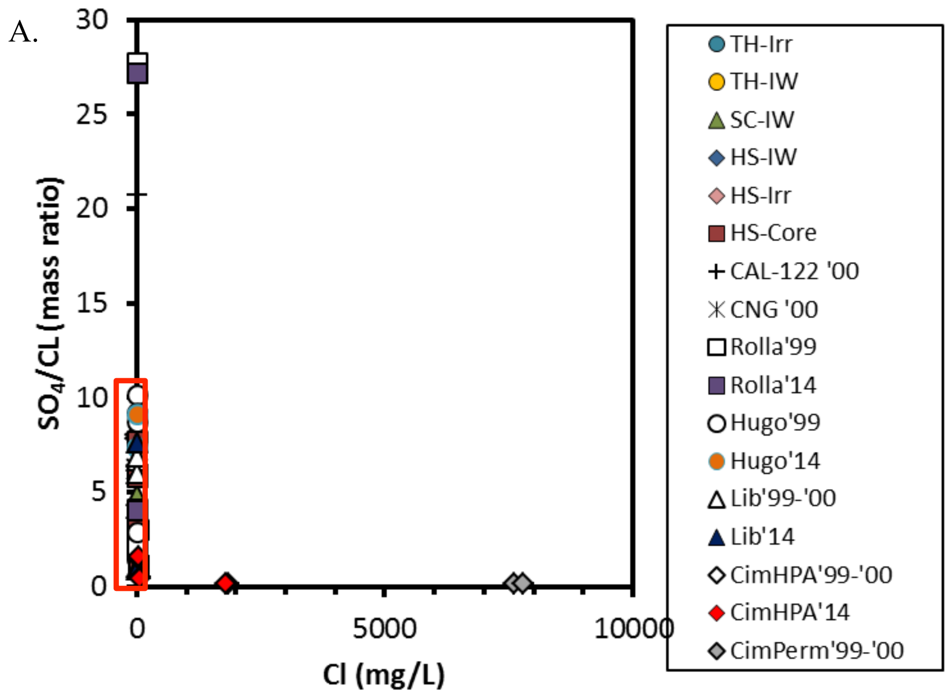
Nitrate and Cl concentrations are often used to aid in establishing residence times and recharge rates in aquifers like the HPA. In regions where climatic conditions have been semi-arid during recent time, Cl and NO_3 naturally concentrate in the unsaturated zone through evapoconcentration. As a result, Cl and NO_3 concentrations are often highest in water-table wells; this is certainly the case for Cl at Hugoton, Liberal, and the upper wells at Cimarron (those unaffected by the Permian bedrock aquifer) and for NO_3 at the Rolla site.

In last year's report, deeper sources of water from the underlying Dakota aquifer to the HPA were explored (Butler et al., 2014). As discussed in that report, the sulfate (SO_4) concentration in the Dakota aquifer is commonly greater than Cl in the freshwater portions of the aquifer due to oxidation of pyrite often present in the fine-grained Dakota deposits. This results in a distinctly different water quality between the two aquifers, with HPA water that is mixed with Dakota water having higher TDS concentration and higher SO_4/Cl ratios. Such trends were observed at the Haskell County site but were absent or negligible at the Scott and Thomas counties sites.

With the expansion of the index well program, wells are now being sampled in an area where the Dakota formation is absent beneath the HPA. In the area of the border index wells, the HPA overlies units of Permian age. The water in these formations can have significantly higher TDS and Cl contents than either the Dakota or HPA in the area where Dakota aquifer strata are in contact with the HPA in southwest Kansas. Sulfate concentrations, while elevated compared with the Dakota and HPA, make up a significantly smaller portion of the TDS than Cl in the strata underlying the Cimarron well site, resulting in a low SO_4/Cl ratio compared with Dakota waters. Farther to the west, the Permian strata underlying the HPA can have relatively high SO_4 concentrations that can be greater than Cl, resulting in a high SO_4/Cl ratio.

In the border well area, the influences of Permian strata are readily observed (fig. 45). With the exception of the Cimarron site, SO_4/Cl ratios increase with depth. The deepest monitoring wells at the Rolla, Hugoton, and Liberal sites all have high SO_4/Cl ratios and higher TDS, indicating inputs from Permian strata in areas with anhydrite or gypsum dissolution. The Rolla and CAL-122 site (located in Haskell County) have the highest SO_4/Cl ratios. On the other hand, the easternmost site, Cimarron, exhibited a low SO_4/Cl ratio with increasing TDS with depth. This indicates the strong influence of the underlying Permian strata in an area where halite dissolution is occurring and is a more important control on groundwater chemistry than anhydrite or gypsum dissolution.

Although inputs from deeper units can supplement water to the HPA, the quality of water in the bedrock underlying parts of the HPA is usually substantially lower than in the HPA. One concern of rapid extraction of freshwater is the encroachment of lower quality water, degrading the overall quality of water available for irrigation. The deepest wells would obviously see this change first. The deep wells were not a target of sampling this year at the Liberal and Hugoton sites (nearest to substantial areas of irrigation). Water quality higher in the aquifer column was not observed to have degraded from 1999 to 2014. At the Rolla and Cimarron sites, both located in rangeland, water quality in the deep aquifer was essentially unchanged from 1999 to 2014.



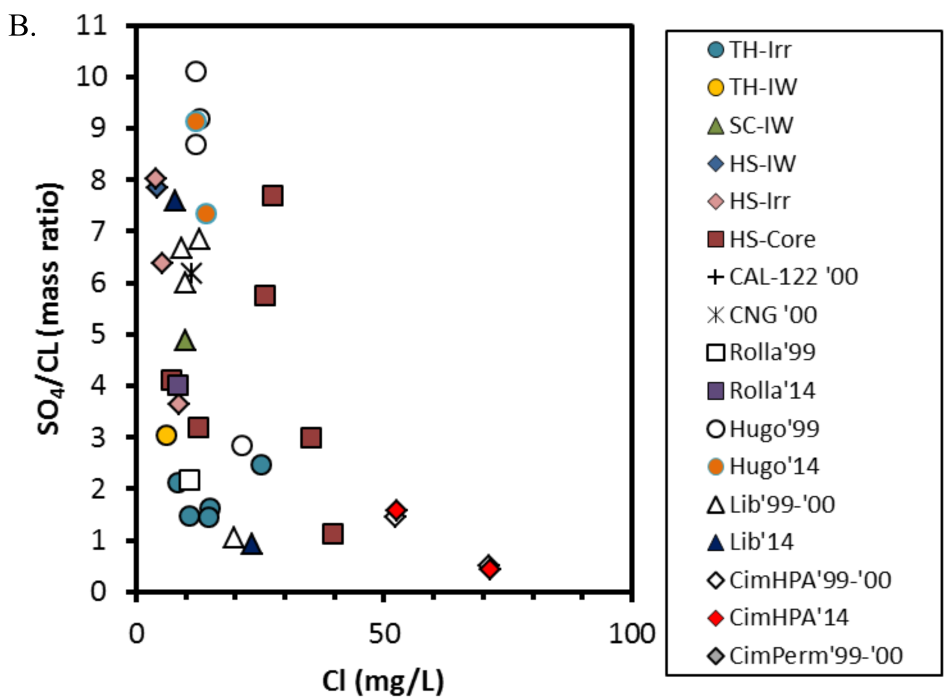


Figure 45—Comparison of SO_4/Cl ratio versus Cl concentration in water from the index wells, nearby irrigation wells, and core samples. A) All samples, B) expanded box section. Abbreviations in the legend are as in fig. 44.

Table 29—Geochemical data for the border index well sites. Dissolved constituents are reported in mg/L.

Well name	Sample date	DIC	Ca	Mg	Na	K	Cl	SO4	Br	NO3-N	3H (TU)	δ^2H ‰	$\delta^{18}O$ ‰	$\delta^{13}C$ [DIC] ‰	^{14}C[DIC] (pMC)
Central High Plains aquifer															
CAL-122	7/10/00	190	126	22.1	27.6	6.6	13.1	272	0.23	0.24	1.5	-62	-8.3	-	-
CNG	7/25/00	206	62.1	12.6	23.9	2	11.3	70.1	0.11	1.22	<0.3	-57	-7.8	-4.6	65.09 ± 0.60
Rolla															
193	8/30/99	220	42.9	6.56	42.5	4.3	10.6	23.1	0.07	5.71	0.3	-54	-7.8	-5.0	73.05 ± 0.59
193	11/24/14	202	65.2	8.84	17.3	1.7	8.42	33.7	0.09	5.74		-55	-7.9	-8.6	78.0 +/- 0.3
366	8/30/99	187	133	41.6	47.8	3.5	15.6	432	0.15	2.27	<0.3	-61	-8.5	-5.4	21.12 ± 0.29
366	11/24/14	184	122	39.4	47.3	3.1	14.1	383	0.16	2.29		-58	-8.2		
Hugoton															
140	8/29/99	261	39.3	11.7	74.3	8.2	21.3	60.5	0.13	2.21		-49	-7.2	-	-
313	8/29/99	193	70.5	21.4	19.8	3.5	12.1	122	0.14	2.56	<0.3	-57	-8.0	-7.2	14.51 ± 0.21
313	11/24/14	191	65.9	20.9	19.4	3	12	109	0.15	2.61		-55	-8.0	-9.1	14.0 +/- 0.1
495	8/28/99	206	63.7	19	19.8	3.1	12.1	105	0.14	2.51	<0.3	-57	-8.1	-6.6	19.03 ± 0.28
495	11/24/14	188	65.6	19.3	20.4	2.8	14.1	104	0.14	2.56		-55	-8.1		
617	8/28/99	203	66.9	19.2	20.2	3.1	12.8	117	0.14	2.3	<0.3	-57	-8.0	-6.0	20.26 ± 0.26
Liberal															
160	8/27/99	264	38.5	34.5	17.9	3.5	19.9	21.1	0.1	1.9	< 0.3	-49	-7.0	-5.8	38.76 ± 0.36
160	11/25/14	260	38.7	35.5	20	3.0	23.4	21.8	0.15	1.77		-46	-7.0	-9.3	42.7 +/- 0.2
319	8/27/00	220	44.1	23.8	25.3	3.5	9.22	61.5	0.1	3.15	< 0.3	-62	-8.9	-6.8	15.08 ± 0.21
319	11/25/14	218	43.3	24.1	25.2	2.8	7.92	60.2	0.09	3.23		-61	-8.9		
436	8/26/99	207	41.7	22.6	26.4	3.9	9.93	59.6	0.1	3.07	< 0.3	-62	-8.9	-6.9	11.44 ± 0.26
570	8/26/99	237	46.9	24.1	36.1	3.9	12.8	87.4	0.1	2.37	<0.3	-65	-9.3	-6.2	9.80 ± 0.18
Cimarron															
65	9/1/99	201	54.5	14.1	48.7	4.7	71.3	36.5	0.08	2.06	4.4	-49	-7.4	-6.3	67.53 ± 0.62
65	11/25/14	203	62.3	15.7	37.6	3.0	71.5	31.7	0.09	1.79		-49	-7.4	-8.9	77.2 +/- 0.3
210	8/31/99	211	66.9	18.7	41.8	3.5	52.5	76.8	0.14	3.07	<0.3	-57	-8.1	-6.0	40.46 ± 0.49
210	11/25/14	203	67.7	18.9	42.4	3.1	52.7	83	0.12	3.13		-55	-8.2		
336	9/1/99	199	300	148	761	10.6	1861	261	0.42	2.3	<0.3	-63	-9.0	-7.6, -	10.36 ± 0.2
336	11/25/14	183	289	145	755	9.5	1804	240	0.81	1.98		-62	-9.0		
Upper Permian-Pennsylvanian aquitard															
Cimarron															
436	8/31/99	117	778	430	3839	18	7622	1268	0.26	0.39	<0.3	-71	-9.9	-8.0	10.75 ± 0.19
436	10/18/00	119	749	430	4046	20	7800	1278	1.36	0.32	0.3	-71	-9.9	-8.0	5.10 ± 0.11

8. Spin-Offs and Related Research

In 2014, complementary research furthered the work of the project.

8.1. Haskell County NSF Project

In the summer of 2010, the National Science Foundation (NSF) awarded a $381,000 grant to the KGS to study the subsurface stratigraphic framework, sedimentary facies, and chronostratigraphy of the Ogallala Formation and overlying units. The Kansas Water Office and the Bureau of Reclamation provided additional funding to this project. 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 Butler et al., 2014). In 2014, additional holes were drilled across the HPA in Norton County, Scott County, Meade County, and along the Cimarron River in Haskell County. The stratigraphy and geochemical and isotopic characteristics of vadose zone fluids are currently being determined.

8.2. Kansas Water Resources Institute Grants

<u>Investigation of recharge to the High Plains aquifer, northwestern Kansas</u>

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 in Butler et al. [2014]). The results of this work indicated a near-surface layer of loess (~30 ft thick) significantly delays downward flow of water at the location studied, despite the study location beneath an irrigated circle. Further study indicated the unsaturated zone water in the subsurface layer between the pre-development and modern day water table is remnant HPA water that has not fully drained. At the very high end, it was estimated that water takes a minimum of 300 years to flow through the unsaturated zone to the pre-development water table (Katz, 2014). Thus, the results of the work indicate other recharge pathways, such as focused recharge beneath ephemeral streams and playas, could be much more important and should be explored.

<u>Getting the information modelers need: Extracting hydrostratigraphic information from drillers' logs</u>

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. Development of this model, encompassing a 15 mile x 15 mile region centered on the index well, continued in 2014, along with further work on development of log-based aquifer property distributions for use in a groundwater flow model developed for GMD1. In addition, a more detailed assessment of drillers' logs in a smaller area around the Thomas County index well was begun. Figure 46 depicts the drillers' logs from 52 wells in a 6 mi x 6 mi area centered on the index well in terms of the permeability category associated with the dominant sediment type in each logged interval. These logs are being examined in detail to determine whether they provide evidence for lateral confinement of the deeper high-permeability units in the index well, at depths corresponding to recent water levels, thus supporting the interpretation of the index well water-level record as indicative of lateral confinement (Butler, Stotler, et al., 2013).

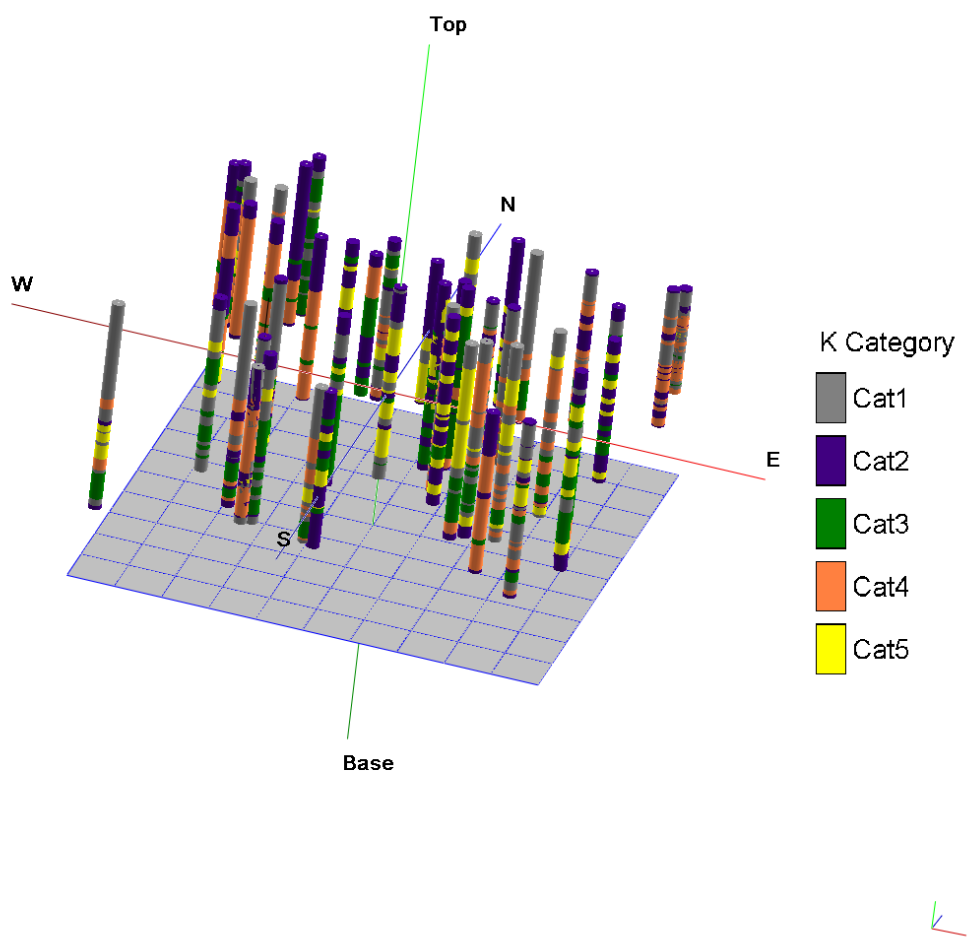


Figure 46—Hydraulic conductivity category (1 for lowest permeability materials to 5 for highest) associated with dominant sediment type in each interval contained in drillers' logs for 52 wells in a 6-mi x 6-mi region centered on the index well (vertical axis runs through it). The average vertical length of the logs is about 250 feet. Logs run from land surface to maximum logged depth, usually corresponding to bedrock. Current water levels are in the lower portion of the sequence, in the lowermost high permeability interval (yellow) in the index well.

9. Summary of 2014 Accomplishments and Plans for 2015

9.1. 2014 Accomplishments

- Continued collection and processing of data. Telemetered data from the original three index wells have continued to be served on the web, and downloads have been used for analysis and presentations. Data collection and analysis from the Thomas and Scott expansion wells have continued.
- Continued collection and processing of data from the index wells along the Kansas-Oklahoma border (border wells). Telemetered data from two wells at the Hugoton site and two wells at the Liberal site are now served on the web. Downloads from all wells have been used for analysis and presentations. Provided initial interpretation of the hydrographs from the four border well sites. Monitoring of two depths at the Liberal and Hugoton sites allowed the determination of the direction of pumping-induced groundwater flow.
- Added two index wells (Colby and Belpre) to the network. Telemetered equipment has been installed at both wells and data will shortly be available on the web.
- Added five monitoring wells in the Sheridan-6 LEMA to the network. Sensors are being manually downloaded quarterly.
- Continued detailed analysis of hydrographs at all three original index well sites.
- Continued assessment of the information that can be acquired from an analysis of the water-level response to changes in barometric pressure.
- Continued comparison of transducer data with the results of the annual water-level network.
- Continued analysis of climatic indices and their relationship to annual water-level changes measured at the index well and across the western three GMDs.
- Initiated an analysis of the utility of radar precipitation data for use in relationships with annual water-level change and water use in the vicinity of the index wells.
- Continued assessment of relationship between precipitation, annual water-level change, and annual water use in the three western GMDs.
- Developed the theoretical support for the relationship between annual water-level change and reported water use in the HPA.
- Assessed 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.
- Continued integration of program data into the digital Kansas High Plains Aquifer Atlas (Fross et al., 2012).
- Gave presentations about the index well program to KWO, DWR, GMD personnel, among others.

9.2. Planned Activities, 2015

- Continue monitoring and processing of water-level data from the three original index wells and the expansion wells in their vicinity, the border index wells, the new Colby and Belpre index wells, the Sheridan-6 index wells, and any other data sets that we can find.
- Continue detailed analysis of hydrographs from the three original index wells and the expansion wells in their vicinity, the border index wells, the Colby and Belpre index wells, the Sheridan-6 index wells, and any other data sets that we can find.
- Assess recovery and pumping for 2014 and 2015 periods.
- Continue to seek new wells to add to the network.
- Drill three new index wells in GMD1; install sensors and telemetry equipment at each well.
- Continue interpretation of geochemical results to assess age(s) and source(s) of groundwater in the vicinity of each index well.
- If possible, collect and analyze water samples from irrigation wells in the vicinity of all of the index wells.
- Continue progression toward improving end-user capabilities for broader implementation of the index well program.
- Continue assessment of the information that can be acquired from hydrograph inspection.
- Continue assessment of the information that can be acquired from an analysis of the water-level response to changes in barometric pressure.
- Continue to cooperate with GMD4 on interpretation of monitoring data from the Sheridan-6 index wells.
- Continue assessment of the relationships among climatic indices, radar precipitation data, annual water-level change, and annual water use in the HPA.
- Further develop theoretical support for relationships among annual water-level change, annual water use, and climatic conditions.
- Integrate information from drillers' logs in the vicinity of the Thomas and Scott index wells into interpretation of water-level responses in those areas.

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.
- Relationship between the Dakota aquifer and the HPA in southwestern Kansas.

10. References

Bohling, G. C., Jin, W., and Butler, J. J., Jr., 2011, Kansas Geological Survey barometric response function software user's guide: Kansas Geological Survey, Open-File Report 2011-10, 27 p. Available online at http://www.kgs.ku.edu/HighPlains/OHP/index_program/brf.html (accessed April 2, 2015).

Buddemeier, R. W., Stotler, R., Butler, J. J., Jr., Jin, W., Beeler, K., Reboulet, E., Macfarlane, P. A., Kreitzer, S., Whittemore, D. O., Bohling, G., and Wilson, B. B., 2010, High Plains aquifer calibration monitoring well program: Third year progress report: Kansas Geological Survey, Open-File Report 2010-3, 117 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2010/OFR10_3/index.html (accessed April 2, 2015).

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

Butler, J. J., Jr., Stotler, R., Whittemore, D. O., Reboulet, E., Bohling, G. C., and Wilson, B. B, 2012, High Plains aquifer calibration monitoring well program: Fifth year progress report: Kansas Geological Survey, Open-File Report 2012-2, 93 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2012/OFR12_2/index.html (accessed April 2, 2015).

Butler, J. J., Jr., Whittemore, D. O., Bohling, G. C., Reboulet, E., Stotler, R. L., and Wilson, B. B., 2013, High Plains aquifer index well program: 2012 annual report: Kansas Geological Survey Open-File Report 2013-1, 116 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2013/OFR13_1/index.html (accessed April 2, 2015).

Butler, J. J., Jr., Whittemore, D. O., Reboulet, E., Stotler, R. L., Bohling, G. C., Olson, J. C., and Wilson, B. B., 2014, High Plains aquifer index well program: 2013 annual report: Kansas Geological Survey Open-File Report 2014-1, 90 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2014/OFR14_1/index.html (accessed April 2, 2015).

Fross, D., Sophocleous, M. A., Wilson, B. B., and Butler, J. J., Jr., 2012, Kansas High Plains Aquifer Atlas: Kansas Geological Survey, available online at http://www.kgs.ku.edu/HighPlains/HPA_Atlas/index.html (accessed April 2, 2015).

Harlow, R. H., 2013, Depositional and paleoclimatic evolution of the Cenozoic High Plains succession from core: Haskell Co., Kansas: M.S. Thesis, Department of Geology, University of Kansas, Lawrence, 124 p.

Hayes, M. J., Comparison of major drought indices: National Drought Mitigation Center, Lincoln, Nebraska, http://drought.unl.edu/Planning/Monitoring/ComparisonofIndicesIntro.aspx (accessed April 2, 2015).

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

Katz, B. S., 2014, Analysis of chemical storage and transit times to characterize water movement through a thick unsaturated zone overlying the High Plains aquifer, northwestern Kansas, MS Thesis, Department of Geology, University of Kansas, Lawrence, 53 p.

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

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

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

McMahon, P. B., Böhlke, J. K., and Christenson, S. C., 2004, Geochemistry, radiocarbon ages, and paleorecharge conditions along a transect in the central High Plains aquifer, southwestern Kansas, USA: Applied Geochemistry, v. 19, no. 11, p. 1,655–1,686.

McMahon, P. B., Dennehy, K. F., Bruce, B. W., Gurdak, J. J., and Qi, S. L., 2007, Water-quality assessment of the High Plains Aquifer, 1999–2004: U.S. Geological Survey Professional Paper 1749, 136 p.

National Climatic Data Center, U.S. Palmer drought indices: http://www.ncdc.noaa.gov/oa/climate/research/prelim/drought/palmer.html (accessed April 2, 2015).

Stotler, R., Butler, J. J., Jr., Buddemeier, R. W., Bohling, G. C., Comba, S., Jin, W., Reboulet, E., Whittemore, D. O., and Wilson, B. B., 2011, High Plains aquifer calibration monitoring well program: Fourth year progress report: Kansas Geological Survey Open-File Rept. 2011-4, 185 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2011/ OFR11_4/KGS-OFR-2011-4.pdf (accessed April 2, 2015).

Whittemore, D. O, Butler, J. J., Jr., and Wilson, B. B., 2015, Assessing the major drivers of water-level declines: New insights into the future of heavily stressed aquifers, Hydrological Sciences Journal (in press).

Whittemore, D. O., Macfarlane, P. A., and Wilson, B. B., 2014, Water resources of the Dakota aquifer in Kansas: Kansas Geological Survey Bulletin 260, 60 p. Available online at http://www.kgs.ku.edu/Publications/Bulletins/260/index.html (accessed April 3, 2015).

Young, D. P., Buddemeier, R. W., Butler, J. J., Jr., Jin, W., Whittemore, D. O., Reboulet, E., and Wilson, B. B., 2008, High Plains aquifer calibration monitoring well program: Year 2 progress report: Kansas Geological Survey, Open-File Report 2008-29, 54 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2008/OFR08_29/index.html (accessed April 2, 2015).

Young, D. P., Buddemeier, R. W., Whittemore, D. O., and Reboulet, E., 2007, High Plains aquifer calibration monitoring well program: Year 1 progress report on well installation and aquifer response: Kansas Geological Survey, Open-File Report 2007-30, 44 p. Available online at http://www.kgs.ku.edu/Hydro/Publications/2007/OFR07_30/index.html (accessed April 2, 2015).

11. Appendix A: Assessing the Major Drivers of Water-Level Declines: New Insights into the Future of Heavily Stressed Aquifers

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ASSESSING THE MAJOR DRIVERS OF WATER-LEVEL DECLINES: NEW INSIGHTS INTO THE FUTURE OF HEAVILY STRESSED AQUIFERS

Donald O. Whittemore, James J. Butler, Jr., and Blake B. Wilson

ABSTRACT
The major driver of water-level changes in many heavily stressed aquifers is irrigation pumping, which is primarily a function of meteorological conditions (precipitation and potential evapotranspiration). Correlations among climatic indices, water-level changes, and pumping can thus often be used to assess the impact of climatic and anthropogenic stresses. The power of this simple, first-order approach, which captures the primary excitation-response relationships driving aquifer behavior, is demonstrated for the High Plains aquifer in the central United States (Kansas). Regional correlations between water-level changes and climatic indices indicate a repeat of the most severe drought on record would more than double water-level decline rates. More importantly, correlations between water-level changes and reported pumping reveal that practically feasible pumping reductions should stabilize water levels, at least temporarily, over much of the aquifer in Kansas. This example illustrates that when uncertainty obscures process-based modeling projections, simple approaches such as described here can often provide insights of great practical value.

KEY WORDS: groundwater levels; climatic index; groundwater pumping; High Plains aquifer

INTRODUCTION

The question of what the future holds for heavily stressed aquifers is of great societal interest. This is particularly true in areas that are prone to or have recently experienced severe droughts, such as the Great Plains region of the United States (US). Changes in water levels have long served as a measure of an aquifer's response to anthropogenic and climatic stresses. Records of past changes, however, just tell us where we have been; the more critical issue is where we are going.

Approaches for forecasting water-level changes have ranged from extrapolation of past trends (e.g., Fig. 7 in Buchanan *et al*. 2009) to process-based modeling (e.g., Anderson and Woessner 1991). Intermediate between these two end members are data-based methods of varying degrees of complexity that are focused on exploiting relationships between water-level changes and potential drivers of those changes (e.g., Adamowski and Chan 2011, Chen *et al*. 2002, Gurdak *et al*. 2007, Sahoo and Jha 2013). A subset of these intermediate methods is based on correlations between water-level changes and possible causative factors (e.g., Chen *et al*. 2004). If these relatively simple correlation-based approaches can explain most of the observed changes, they can serve as valuable tools for rapid, first-order assessment of an aquifer's response to various pumping and climatic scenarios. One such approach is discussed here and applied to a portion of one of the world's largest aquifer systems, the High Plains aquifer (HPA) of the central US.

The HPA extends over portions of eight states in the Great Plains region of the US (Fig. 1) and provides irrigation and, to a much lesser extent, drinking, stock, and industrial water supplies that account for nearly one quarter of the nation's annual groundwater use (Maupin and Barber 2005). Much of the aquifer system, however, appears to be on a fundamentally unsustainable path. Large pumping-induced declines (Stanton *et al.* 2011), which have been the focus of recent articles in the popular media (e.g., Wines 2013), indicate that current rates of withdrawals cannot be sustained; the projected trajectory of climate change further exacerbates the situation (e.g., Rosenberg *et al.* 1999, 2003, Brunsell *et al*. 2010, Logan *et al*. 2010).

The main driver of water-level changes in the HPA is the amount of water pumped for irrigation (comprising approximately 95% of total pumped in 2005 [Kenny *et al.* 2009]). Irrigation is primarily needed to supplement precipitation for fall-harvested row crops, so pumpage is concentrated in the summer growing season. The volume of irrigation pumpage is determined by the number of wells and the amount pumped per well. For a given hydrostratigraphic configuration, the primary controls on the per-well amount include the area irrigated, meteorological conditions (i.e. precipitation and potential evapotranspiration), crop type, and regulatory (water-right) allocation. If the number of wells, irrigated area, crop mix, and water-right allocation remain relatively constant, then the main factor controlling pumping is the meteorological conditions for a given year.

Climatic indices provide a good measure of meteorological conditions, especially how precipitation deviates from historic norms. Commonly used indices include the Palmer Drought Severity Index (PDSI), the Palmer Z Index, and the Standardized Precipitation Index (SPI). 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 a similar monthly index developed to evaluate short-term moisture conditions in crop-producing areas; the PDSI, in comparison, was developed to monitor longer-term wet and dry spells (Heim 2002). The SPI was created to quantify precipitation deficits and surpluses (normalized by long-term records) over time intervals of practical relevance for water resources (McKee *et al.* 1993). Although there are a number of other climatic indices, such as the recently proposed Standardized Precipitation Evapotranspiration Index (Vincente-Serrano *et al.* 2010), these have not been as widely used as the Palmer indices and SPI. Monthly values of PDSI, Palmer Z Index, and SPI (for various intervals) are available online for climatic divisions of US states (National Climatic Data Center, 2014).

The major objective of this paper is to demonstrate how relationships among climatic indices, water-level changes, and reported water use can be simply and quickly exploited to develop new insights into the future of heavily stressed aquifers. The focus is on the relatively data-rich portion of the HPA in the state of Kansas, but the general procedure should be widely applicable. This approach is not envisioned as a replacement for process-based modeling. However, in cases where uncertainty produced by limited data and incomplete mechanistic descriptions may obscure process-based modeling projections, simple approaches such as that described here, which capture the primary excitation-response relationships driving large-scale system behavior, can be of great practical value.

THE HIGH PLAINS AQUIFER IN KANSAS

The HPA extends over the western third and the south-central parts of the state of Kansas (Fig. 1) and is overlain by five groundwater management districts (GMDs). The areas of the three western districts (from north to south, GMDs 4, 1, and 3) coincide well with the western three (1, 4, and 7, respectively) of the state's nine climatic divisions; the areas of GMDs 2 and 5 (henceforth, GMDs 2&5) in south-central Kansas are predominately located within climatic division 8 and will be considered together for the purposes of this work (Fig. 1). A climatic division is an area of relatively uniform climatic characteristics for which climatic data are reported monthly by the National Climatic Data Center (NCDC, 2014); the divisions were created in 1950 and correspond to the Crop Reporting Districts of the United States Department of Agriculture. The three western Kansas climatic divisions are characterized by semi-arid conditions, while the south-central Kansas climatic division is characterized by a more sub-humid climate.

Groundwater levels in the Kansas HPA have been measured annually in an extensive well network for several decades. The network currently consists of about 1400 wells distributed approximately evenly over the aquifer (Miller *et al.* 1999, Bohling and Wilson 2012). The measurements are made during the winter when irrigation wells are typically not operating. In the mid-1990s, the Kansas Geological Survey took over primary responsibility for managing the measurement program; the data collected since that time (1996) are utilized here.

Data from the Kansas well network can be used to calculate spatial averages of the annual changes in water level for each of the GMD regions for 1996-2012 (where the value for a particular year represents the average difference between the winter water-level measurements in that year and the following year). The patterns of the annual changes for the western three GMDs are relatively similar, showing declines in most years (Fig. 2a). The infrequent small annual rises primarily represent greater aquifer recovery at the time of the winter water-level measurement (result of less water use and/or earlier cessation of pumping in the previous irrigation season) rather than recharge of same-year precipitation (depth to the water table in these areas is substantial and the estimated mean annual recharge is small {<1-2 cm under natural [non-irrigated] conditions} due to relatively low mean annual precipitation [40-58 cm] and high evapotranspiration [Fross *et al.* 2012]). The much more frequent and substantial annual rises in water levels in south-central Kansas (GMDs 2&5) do mainly reflect recharge of same-year precipitation because the mean annual precipitation is greater (58-84 cm) and the average depth to water is much less. The patterns of annual changes observed in the 1996-2012 data are also observed in long-term hydrographs from wells in the GMDs. The HPA in the three western GMDs has been so heavily stressed by pumping since the 1950s that the vast majority of hydrographs show substantial declines over the last half century, indicating that the aquifer is being mined. Declines are appreciably less in GMDs 2&5; the hydrographs fluctuate substantially from year to year but with a much smaller long-term trend than farther west, reflecting pumping activity as well as aquifer recharge and stream-aquifer interactions.

Development of the Kansas HPA and expansion of irrigated cropland was substantial during the middle part of the 20th century. However, since the mid-1990s, the irrigated area and crop types in Kansas have not changed appreciably (Rogers and Lamm 2012) and the number of water-right permitted irrigation wells has increased only slightly (≈6%). In addition, Hendricks and Peterson (2012) found that irrigation pumping in Kansas for 1992-2007 varied little in response to fluctuations in energy prices. Thus, the main driver for water-level changes in the Kansas HPA during this period was the pumping induced by meteorological conditions.

CORRELATION OF WATER-LEVEL CHANGE WITH CLIMATIC INDICES AND WATER USE

Climatic indices

Temporal variations in mean annual water-level changes parallel the temporal variations in climatic indices for the GMD areas (e.g., Fig. 2a). This implies a high degree of correlation between the water-level changes and the climatic indices, which is confirmed by linear-regression analyses (Fig. 2b, Table 1). Although irrigation pumping is expected to be tied most closely to conditions during the growing season (typically May through early September), some of the best correlations were obtained for a range of months exceeding the growing season for the PDSI and Palmer Z Index, and for 9-month and 12-month SPI values (Table 1). This is thought to be partly related to pre-planting irrigation to increase soil moisture and, where the water table is shallow, recharge of same-year precipitation and stream-aquifer interactions. Although the Palmer indices, which incorporate precipitation and temperature, and involve calculations of evapotranspiration (ET) and soil moisture, give high correlations with water-level changes, the SPI gives correlations nearly as high as or higher than those for the Palmer indices (Table 1). This indicates that precipitation variations are the main climatic driver of water-level change across the Kansas HPA. However, the mechanisms that produce the high correlation with precipitation vary across the Kansas HPA. In the western Kansas GMDs, except for during and shortly after a precipitation event, pumping of groundwater is essentially continuous throughout the irrigation season (e.g., Figures 2 and 3 of Butler et al. [2013]). Thus, precipitation controls when the pumps are operating, and therefore is an indirect control on water levels. In the south-central Kansas GMDs, this mechanism is supplemented by recharge of recent precipitation; in those areas, precipitation has both a direct and indirect control on water levels. More efficient use of water (irrigation done only during critical periods of high ET demand) would likely improve the correlations involving the Palmer indices in all the GMDs.

The focus of this paper is on the correlation with the SPI, not just because it is the simplest of the common climatic indices, but it is also the only climatic index that gives coefficient of determination (R^2) values greater than 0.7 for all of the GMD areas of the Kansas HPA. The period of the SPI index that produces the optimum correlation with annual water-level changes differs slightly among the three western GMDs. In order to facilitate comparisons, the SPI, 9-month, October index is used here for the three western GMDs. The slight decreases in the correlations for GMDs 4 and 3 (Table 1) resulting from use of this form of the SPI are not of practical importance. A different index (SPI, 12-month, December) is used for the GMDs 2&5 area, which is characterized by greater precipitation and recharge of same-year precipitation.

The correlations between the SPI and the annual water-level changes are high for all of the GMD areas, but the correlation is somewhat weaker for GMD1 (Table 1). The likely explanation for this lower correlation, which undoubtedly explains a considerable portion of the spread observed in all the correlation plots (Fig. 2b), is the distribution of rainfall within the period covered by the SPI. For example, if the circled outlier point in Fig. 2b (water-level change of +0.19 m and an SPI of 0.86) is removed from the GMD1 data, the R^2 for the correlation increases from 0.71 to 0.80. Precipitation in GMD1 for that year (1997) was higher than the 1996-2012 average for the three months when irrigation water demand by crops is generally the highest (June-August). Thus, pumping was likely considerably less than expected for the typical irrigation season and concentrated much earlier in the season, leading to a year-on-year increase in winter water levels. Also, the distribution of the rainfall was such that the SPI value was not as high as it would have been if the precipitation had been more evenly distributed throughout the 9-month period.

Water use

Since 1978, Kansas has required non-domestic water users to obtain a water right. Starting in the early 1980s, water-right holders were required to submit annual water-use reports; quality control of the reported data began in 1990. Variations in annual water-level change are generally of opposite sign of those of water use during 1996-2012 (Fig. 3a), as would be expected. Correlations of annual water-level changes with reported water use during 1996 to 2012 for GMDs 4 and 2&5 are high, although not quite as high as with the SPI; the correlation for GMD3 is statistically significant but substantially lower than that with the SPI, whereas that for GMD1 is not statistically significant (Fig. 3b, Table 2). If the circled outlier value (2007 - water-level change of +0.86 m and water use of 0.72×10^9 m^3) is removed from the data for GMDs 2&5, the R^2 improves to 0.88, a remarkably high correlation; that outlier is again a result of the distribution of precipitation during the growing season. The most likely explanation for the weaker correlations between water-level changes and water use for GMDs 1 and 3 is the greater use of less-accurate meters (e.g., duration-of-pumping versus flow-rate meters) in those districts. A second explanation is downward trends in the annual water-level change data that are not consistent with the water use data. GMD3 has a downward trend in the annual water-level change data but no trend in water-use data. If a linear trend is removed from the water-level change data, the correlation increases from 0.32 to 0.56 (statistically significant at the P=0.01 level). A likely explanation for the downward trend is that it is a product of changes in hydrostratigraphic conditions, specifically decreasing specific yield and/or increasing aquifer compartmentalization (as has been reported elsewhere for the western Kansas HPA [Butler et al., 2013]). Such hydrostratigraphic changes with depth are not unexpected in this portion of the HPA as the sedimentary sequence transitions from one dominated by sands and gravels (channel deposits) to one dominated by clays and silts (inter-channel deposits) as discussed by Butler et al. (2013). An additional possibility for the weaker correlation in GMD3 is that the Arkansas River valley and surface irrigation districts fed by the river provide supplemental irrigation water that is not available in the other districts. GMD1 has downward trends in both water-level change and water-use data. If linear trends are removed from both data sets, the correlation increases from an R^2 of 0.07 to 0.47 (statistically significant at the P = 0.01 level). The downward trend in the water-level change data is again thought to be a product of changing hydrostratigraphic conditions, while the downward trend in the annual pumping is likely due to diminishing transmissivity with decreasing saturated thickness (i.e. the drawdown produced by the lower transmissivity limits pumping at individual wells). Neither GMD4 nor GMDS 2&5 have trends in water-level change that are inconsistent with the water use data.

Variations in SPI are generally of opposite sign of those of water use during 1996-2012 (Fig. 4a), as would also be expected. Correlations of SPI with reported water use for GMDs 4 and 2&5 are high, although not as high as with annual water-level change; the correlation for GMD3 is statistically significant but substantially lower than that with water-level change, whereas that for GMD1 is not statistically significant (Fig. 4b). As for the relationship between water-level change and water use described above, if the water-level change data are detrended, the R^2 values for GMDs 1 and 3 increase.

In general, the water-level data set has the least uncertainty of the three data types considered here because the data set is based on annual measurements taken at the same time of the year at the same location in a regular network across the HPA. The climatic data set is expected to have greater uncertainties because measurement locations are fewer in number and less regularly distributed than the water-level data, and different temporal patterns in precipitation can give similar climatic index values for a particular period. Given the time frame of this assessment, changes in measurement methods for climatic data and in the duration and intensity of rainfall events are not expected to introduce significant uncertainty relative to that produced by the number and distribution of measurement locations and the distribution of precipitation during the period characterized by SPI values. The data set with the greatest uncertainty is reported water use. The relative uncertainties in the three data sets are reflected in the general relative order of correlation strength among the data sets: highest for SPI versus water-level change, followed by water use versus water-level change, and lowest for water use versus SPI.

PREDICTION OF FUTURE WATER-LEVEL CHANGES

The strength of the correlations discussed in the previous section indicates that these relationships can be exploited to develop insights into the HPA response to various future scenarios. We demonstrate the value of this approach through an assessment of the predicted response to the cases of extended drought, continuation of average climatic conditions, and reductions in pumping. Given the illustrative nature of this paper, the predicted responses are presented without confidence intervals, i.e. response should be considered the mean response for the defined conditions.

Extended drought

The 1930s and 1950s had the longest and most severe years of recorded drought in Kansas (Paulson *et al.* 1991). Although the 1930s drought extended for a longer period than that for the 1950s, the 1950s drought included years (particularly 1956) with the most severe drought conditions since record keeping began in 1895. The SPI values for past drought periods can be used in the regression equations of Table 1 to predict annual water-level declines for each of the GMD areas. Applying this procedure to a drought of the same length (five years) and intensity of the 1950s drought, which occurred prior to widespread irrigation pumping in the Kansas HPA, yields total water-level declines of 2.01 m, 2.05 m, 5.06 m, and 5.07 m for GMDs 4, 1, 3, and 2&5, respectively (Table 3). The mean annual declines predicted for a repeat of the 1950s drought range from 1.8 to 2.6 times those observed during 1996-2012 for the three western GMDs, and even greater for GMDs 2&5. A repeat of this extended drought would clearly have an extremely deleterious impact on conditions in the Kansas HPA.

Global climate models project that winter precipitation will increase slightly in western Kansas but spring precipitation will decrease and summer precipitation will decrease even more (Brunsell *et al.* 2010). These projections indicate that lower SPI values will be more common in the coming decades and that the frequency of droughts similar to that of the 1950s may increase. The above assessment indicates that such conditions will likely lead to an acceleration of water-level declines across all portions of the HPA in Kansas.

Average climate

The zero value for a climatic index indicates average (historic [since 1895 for Kansas] norm) conditions. The water-level change at the zero value thus provides insight into how pumping is affecting water levels under conditions that would be considered neither wet nor dry for a particular area. The annual water-level changes at the zero SPI value are negative (water-level declines) for all GMDs during 1996-2012: -0.18 m for GMD4, -0.17 m for GMD1, -0.58 m for GMD3, and -0.28 m for GMDs 2&5 (zero intercept values in regression equations in Table 1). The declines for the three western GMDs are not unexpected because the natural recharge to the HPA in these areas is very small relative to the amount of pumping (Fross et al. 2012), i.e. the aquifer is being mined under average climatic conditions.

GMDs 2&5 are attempting to manage their areas on a long-term sustainable basis, so the 0.28 m/yr decline is surprising. However, the actual decline rate over 1996-2012 was much less (0.07 m/yr) because the climatic conditions for this period were slightly wetter than average (historic norm). The 1996-2012 mean of the SPI index for GMDs 2&5 is 0.47, which is on the wet side of normal. In contrast, the SPI means for climatic divisions 1, 4, and 7 are very close to zero (-0.01, 0.11, and 0.08, respectively) for this same period. This implies that, should the mean of future climatic conditions be closer to an SPI of zero for GMDs 2&5, unexpected water-level declines could occur even during normal meteorological conditions. The annual water-level data (Fig. 2a) and hydrographs from continuously monitored wells (e.g., Fig. 3 in Butler *et al.* [2011]) are consistent with this projection, as both indicate that GMDs 2&5 are dependent on substantial but infrequent recharge events to sustain water levels. A decrease in the frequency of such events would lead to further declines even without the onset of drought conditions.

Reductions in pumping

Given that water-level declines are expected to continue across the Kansas HPA under average climatic conditions, there is growing interest in reducing pumping to extend the "usable lifetime" of the aquifer. The key question is how much reduction is needed to significantly moderate the declines. A new management framework, the Local Enhanced Management Area (LEMA), was established by the Kansas Legislature in 2012 to allow the adoption of locally generated management plans that are supported by regulatory oversight (Kansas Department of Agriculture 2013). In January 2013, the first LEMA was established in a 256-km^2 area within GMD4; the management plan calls for a reduction in average annual pumping of about 20% over a period of five years in the hope that that would produce a significant reduction in the rate of water-level decline.

An obvious question is what percentage reduction would produce a stabilization of water levels across the entire GMD4 area. If, as in GMD4, reliable water-use (groundwater pumping) data are available, then the water use versus annual water-level change relationship (Table 2) can be utilized to assess this issue. The approach (Table 4) yields a pumping reduction of 22%, which is quite close to the target reduction for the first LEMA in Kansas. Thus, it appears that a practically feasible reduction in annual pumping would have kept water levels (in terms of the regional average) at approximately the same level from 1996 to 2012. However, the reduction is much smaller than expected for long-term sustainability. This finding suggests that there is a previously unrecognized inflow to the HPA within GMD4 and is consistent with the recent interpretation of hydrographs from some continuously monitored wells in that area (e.g., Butler *et al.* 2013). The source of the inflow and its expected duration are the focus of ongoing investigations; it likely is a short-term phenomenon related to irrigation return flow or delayed drainage from the unsaturated zone created by water-level declines.

The pumping reduction required to stabilize water levels for GMDs 2&5 can be calculated in a similar manner. Given that climatic conditions have been slightly wetter than the historic norm in this area for 1996-2012, a pumping reduction of approximately 3% from the average for that period would produce near-stable water levels (Table 4). However, if climatic conditions had been the historic average for this period, a larger pumping reduction (17%) would be required for stabilization (calculation based on a water-level change of +0.28 m to achieve stable water levels at an SPI value of zero using approach of Table 4).

The poor correlations between water use and annual water-level change preclude the direct application of the regression for assessing reduction impacts for GMDs 1 and 3. However, an approximate approach can be applied to GMD1 by recognizing that a reduction in water use is equivalent (in terms of its impact on water-level changes) to the occurrence of a wetter period (i.e. greater SPI value) and then determining that equivalence using data from GMD4. This approach can be justified by the high degree of similarity between the linear regressions for water-level change versus SPI for GMDs 1 and 4 (Table 1), which is undoubtedly due to the similarities in irrigated crops and irrigation practices in these two adjacent GMDs. The 22% water use reduction in GMD4 is equivalent to a SPI change of 1.30 (-0.01 to 1.29 – Table 5a). If the same relationship between percentage pumping reduction and SPI change is assumed, the strong correlation between climatic indices and annual water-level change for GMD1 can be exploited to assess the impact of a pumping reduction for GMD1. Using the same SPI change as in GMD4, an annual water-level increase of 0.04 m is obtained for GMD 1 (Table 5b). Thus, a reduction in annual pumping of about 20% would have likely kept the average of water levels in GMD1 at approximately the same level for the entire period. The dissimilarity between the linear regressions for water-level change versus SPI for GMDs 3 and 4 preclude the application of this approach to GMD3.

The reductions in pumping that would stabilize groundwater levels can be used to estimate mean annual recharge rates to the HPA in GMDs 1 and 4 because groundwater discharge to streams in these areas has been insignificant over the last few decades. Dividing the volume of pumping that would stabilize groundwater levels by the GMD area gives mean recharge rates of 4.7 cm/yr and 3.3 cm/yr for GMDs 1 and 4, respectively, which are three to four times greater than other estimated recharge values for these GMDs (e.g., Fross et al., 2012).

These rates represent the volume of pumping averaged over the entire GMD area. In actuality, the pumping volume is concentrated in those areas where the pumping occurs (and where most of the water-level measurements are made); use of the area of influence of the pumping wells in the recharge calculation would lead to a substantially larger recharge rate. A similar approach cannot be used to estimate the mean annual recharge in GDMs 2&5 because of the large amount of groundwater discharge to streams in those areas.

CONCLUSIONS

The major driver of water-level changes in many heavily stressed aquifers is the amount of water pumped for irrigation. Thus, correlations among climatic indices, changes in water levels, and reported water use can often serve as valuable tools for assessing an aquifer's response to various climatic and development scenarios. Projections of future climatic conditions can be defined in terms of climatic indices; these indices can then be used in a linear regression (climatic index versus annual water-level change) to assess an aquifer's likely response to those conditions. The magnitude of the intercept of the regression can shed light on aquifer sustainability at average climatic conditions under current pumping practices. If water-use (groundwater pumping) data are available for at least a portion of the area or nearby areas, pumping versus annual water-level change regressions can be used to develop difficult-to-obtain insights into the impact of pumping reductions on the rate of water-level declines. Even when pumping data are not available, some sense of the magnitude of pumping reductions required to significantly moderate declines can be obtained by recognizing that the aquifer response to a pumping reduction would be similar to the response to a wetter climatic period.

This simple approach has great potential for widespread application, especially for aquifers that have been fully developed (little change in area irrigated by groundwater). That potential is demonstrated through an application to a portion (state of Kansas) of the High Plains aquifer (HPA) in the central United States. The high correlation between average annual water-level changes and climatic indices across the HPA in Kansas during the last two decades confirms that pumping is primarily a function of the meteorological conditions (precipitation and potential evapotranspiration) for a given year. A precipitation-based climatic index can explain as much of the variation in water-level changes as more involved indices that incorporate potential evapotranspiration and soil moisture because of current pumping practices (near-continuous pumping during the irrigation season). These correlations indicate that a repeat of the most severe drought over the last century would have an extremely deleterious impact on the Kansas portion of the HPA under current pumping practices, as such a drought would more than double the mean rate of water-level decline. Given the potential for increased drought frequency in the coming decades, the prospects for sustaining the current rates of pumping in this portion of the HPA are not bright. Even under a future characterized by a continuation of average (historic norm) climatic conditions, water levels will continue to decline 0.2-0.6 m annually under current pumping practices. However, a key finding of this assessment is that practically feasible pumping reductions (≈20%) would likely stabilize water levels, at least in the short term, over much of the Kansas HPA (Groundwater Management Districts 1, 2, 4, and 5). Although in western Kansas this stabilization may largely be a product of enhanced recharge produced by past inefficient irrigation practices or of delayed drainage from the unsaturated zone produced by water-level declines, and thus only of limited duration, it could help extend the usable lifetime of the resource and serve as a bridge to an economy based on a different mix of agricultural practices.

The correlations used here involve quantities averaged or summed over relatively large geographical areas. Thus, given the strength of these correlations, it is possible that similar correlations involving climatic indices and the large areal averages of water-level change determined from gravity measurements of the GRACE satellite mission (e.g., Famiglietti *et al*. 2011, Strassberg *et al.* 2007) could provide important insights for many heavily stressed regional aquifer systems.

In closing, we must emphasize that the approach outlined here is not envisioned as a replacement for process-based modeling. Rather, it should be viewed as a complementary tool for rapid, first-order assessment of an aquifer's future in the face of continuing anthropogenic and climatic stresses. Such assessments should prove to be of considerable practical value for those responsible for the management of declining groundwater resources.

Figure captions

Fig. 1. Map of the High Plains aquifer in the US and Kansas (inset). Kansas inset also shows groundwater management district (GMD – colored lines) and climatic division (dashed) boundaries (modified from Butler *et al.* 2013).

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Table captions

Table 1. Optimum[a] and utilized[b] (bolded) correlations of mean annual water-level changes for GMDs with climatic indices for coinciding climatic divisions during 1996-2012.

Table 2. Coefficients of determination (R^2) and linear regression equations for correlation of mean annual water-level changes with reported water use during 1996-2012 for the GMD areas[a].

Table 3. SPI values for given year and predicted water-level declines calculated using the regression equations in Table 1 for a drought of the same length and intensity of that of the 1950s.

Table 4. Steps for calculating pumping reduction to obtain stable water levels (water-level change of zero) for GMD4 and GMDs 2&5 during 1996-2012 using water-level and water-use regression equations in Table 2.

Table 5. Steps for calculating average annual water-level decline for 21.7% reduction in pumping in GMD1 based on SPI change for this reduction in GMD4 for 1996-2012.

References

Adamowski, J. and Chan, H. F., 2011. A wavelet neural network conjunction model for groundwater level forecasting. *Journal of Hydrology*, 407, 28-40.

Anderson, M.P, and Woessner, 1991. *Applied groundwater modeling: Simulation of flow and advective transport*. Academic Press, 381 pp.

Bohling, G.C. and Wilson, B.B., 2012. *Statistical and geostatistical analysis of the Kansas High Plains water-table elevations, 2012 measurement campaign*. Lawrence, KS: Kansas Geological Survey, Open-File Report 2012-16.

Buchanan, R.C., Buddemeier, R.R., and Wilson, B.B., 2009. *The High Plains aquifer*. Lawrence, KS: Kansas Geological Survey, Public Information Circular 18. Available from: www.kgs.ku.edu/Publications/pic18/index.html [accessed 22 Aug 2014].

Brunsell, N.A., *et al*., 2010. Seasonal trends in air temperature and precipitation in IPCC AR4 GCM output for Kansas, USA: evaluation and implications. *International Journal of Climatology,* 30, 1178-1193.

Butler, J.J., Jr., *et al*., 2011. New insights from well responses to fluctuations in barometric pressure. *Ground Water,* 49 (4), 525-533.

Butler, J. J., Jr., *et al*., 2013. Interpretation of water-level changes in the High Plains aquifer in western Kansas, *Groundwater,* 51 (2), 180-190.

Chen, Z., Grasby, S.E., and Osadetz, K.G., 2002. Predicting average annual groundwater levels from climatic variables: an empirical model. *Journal of Hydrology*, 260, 102-117.

Chen, Z., Grasby, S.E. and Osadetz, K.G., 2004. Relation between climate variability and groundwater levels in the upper carbonate aquifer, southern Manitoba, Canada. *Journal of Hydrology* 290, 43-62.

Famiglietti, J.S., *et al*., 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophysical Research Letters*, 38, L03403, doi: 10.1029/2010GL046442.

Fross, D., *et al*., 2012. *Kansas High Plains Aquifer Atlas* [online]. Lawrence, KS: Kansas Geological Survey. Available from: www.kgs.ku.edu/HighPlains/HPA_Atlas/index.html [accessed 22 Aug 2014].

Gurdak, J.J., *et al*., 2007. Climate variability controls on unsaturated water and chemical movement, High Plains aquifer, USA. *Vadose Zone Journal*, 6 (2), 533-547, doi:10.2136/vzj2006.0087.

Heim, Jr., R. R., 2002. A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society*, 83, 1149-1165.

Hendricks, N.P. and Peterson, J.M., 2012. Fixed effects estimation of the intensive and extensive margins of irrigation water demand. *Journal of Agricultural and Resource Economics*, 37 (1), 1-19.

Kansas Department of Agriculture, 2013. *Local Enhanced Management Areas (LEMA)* [online]. Topeka, KS. Available from: agriculture.ks.gov/divisions-programs/dwr/managing-kansas-water-resources/local-enhanced-management-areas/lists/lemas/sheridan-county-6-lema [accessed 22 Aug 2014).

Kenny, J.F., *et al*., 2009. *Estimated use of water in the United States in 2005.* Washington, D.C.: U.S. Geological Survey Circular 1344, 60 p.

Logan, K. E., *et al*., 2010. Assessing spatiotemporal variability of drought in the U.S. central plains. *Journal of Arid Environments*, 74**,** 247–255. DOI: 10.1016/j.jaridenv.2009.08.008.

Maupin, M.A. and Barber, N.L., 2005. *Estimated withdrawals from principal aquifers in the United States, 2000.* Washington, D.C.: U.S. Geological Survey, Circular 1279, 46 p.

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

Miller, R. D., Buchanan, R.C. and Brosius, L., 1999. *Measuring water levels in Kansas*. Lawrence, KS: Kansas Geological Survey, Public Information Circular 12. Available from: http://www.kgs.ku.edu/Publications/pic12/pic12_1.htm [accessed 22 Aug 2014].

National Climatic Data Center, 2014. www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp [accessed 22 Aug 2014].

Palmer, W.C., 1965. *Meteorological drought*. Washington, D.C.: U.S. Weather Bureau, NOAA Library and Information Services Division, Research Paper No. 45.

Paulson, R.W., *et al*., 1991. *National water summary 1988-89: hydrologic events and floods and droughts*. Washington D.C.: U.S. Geological Survey, Water-supply Paper 2375.

Rogers, D. H. and Lamm, F.R., 2012. Kansas irrigation trends. *Proceedings 24th Annual Central Plains Irrigation Conference*, p. 1-15, 21-22 Feb 2012, Colby, KS,. Available from: www.ksre.ksu.edu/irrigate/OOW/P12/Rogers12Trends.pdf [accessed 22 Aug 2014].

Rosenberg, N. J., *et al*., 1999. Possible impacts of global warming on the hydrology of the Ogallala aquifer region. *Climatic Change*, 42, 677–692.

12.

Rosenberg, N. J., *et al*., 2003. Integrated assessment of Hadley Centre (HadCM2) climate change projections on agricultural productivity and irrigation water supply in the conterminous United States I. Climate change scenarios and impacts on irrigation water supply simulated with the HUMUS model. *Agricultural and Forest Meteorology*, 117*,* 73–96.

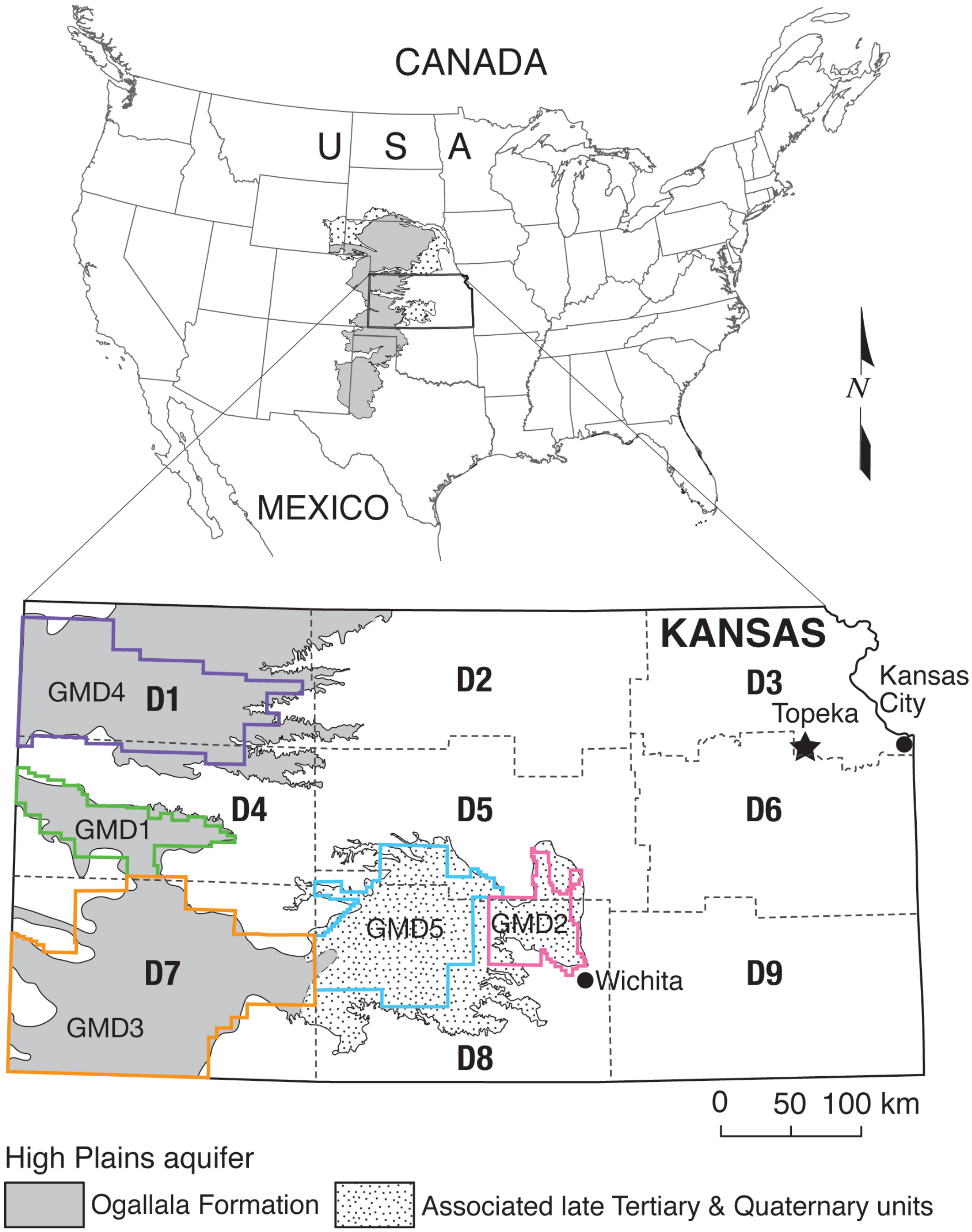
Sahoo, S., and Jha, M.K., 2013. Groundwater level-prediction using multiple linear regression and artificial neural network techniques: a comparative assessment. *Hydrogeology Journal*, 21(8), 1865-1887, DOI 10.1007/s10040-013-1029-5.

Stanton, J. S, *et al*., 2011. *Selected approaches to estimate water-budget components of the High Plains, 1940 through 1949 and 2000 through 2009*. Washington, D.C.: U. S. Geological Survey, Scientific Investigations Report 2011-5183.

Strassberg, G., Scanlon, B.R., and Rodell, M., (2007). Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from the High Plains Aquifer (USA). *Geophysical Research Letters*, 34, L14402, doi:10.1029/2007GL030139.

Vicente-Serrano, S.M., Begueria, S., and Lopez-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, 23, 1696-1718.

Wines, M., 2013. Wells dry, fertile plains turn to dust. *New York Times*, 20 May. Available from: www.nytimes.com/2013/05/20/us/high-plains-aquifer-dwindles-hurting-farmers.html?hp&_r=0 [accessed 22 Aug 2014].



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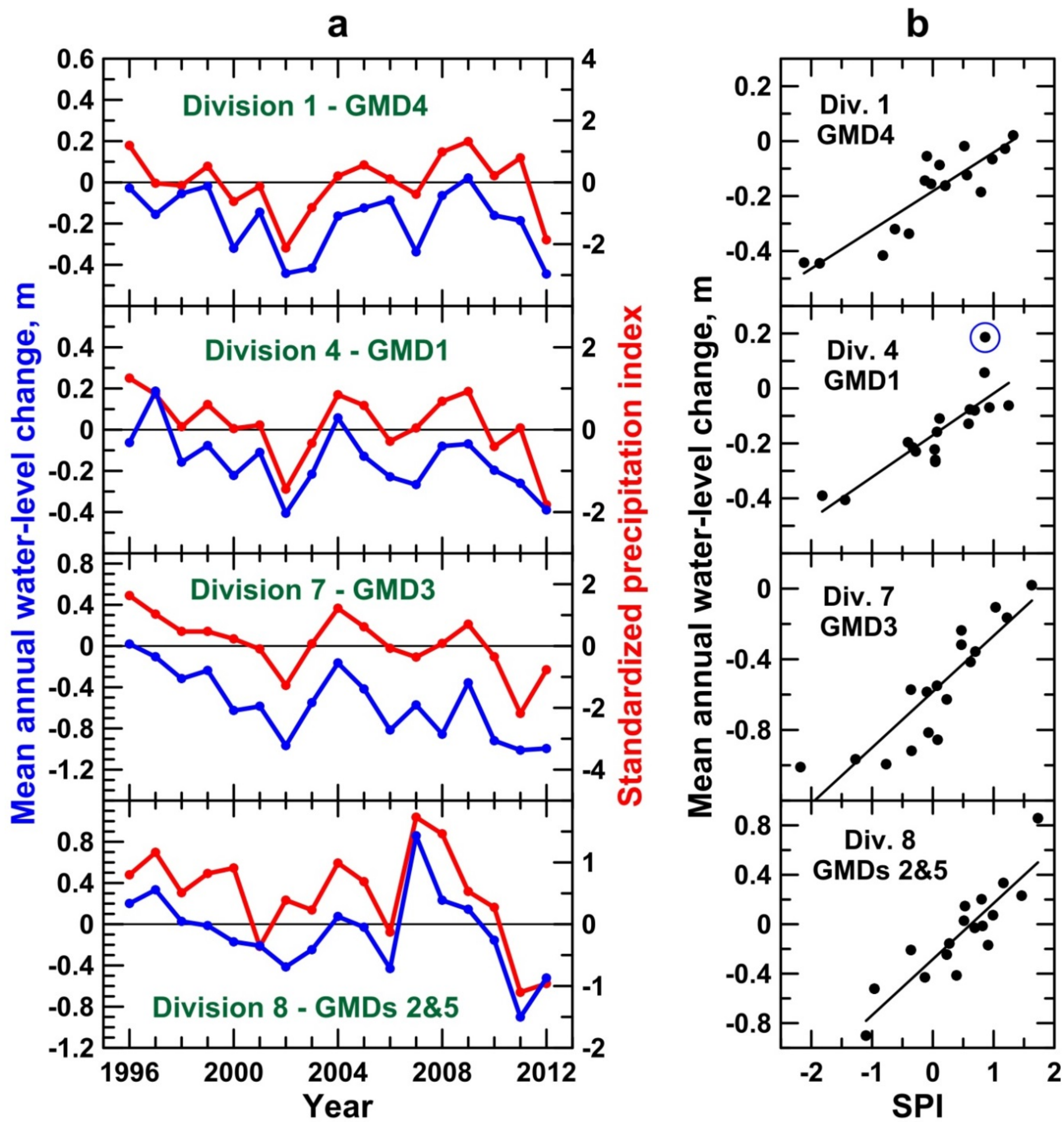

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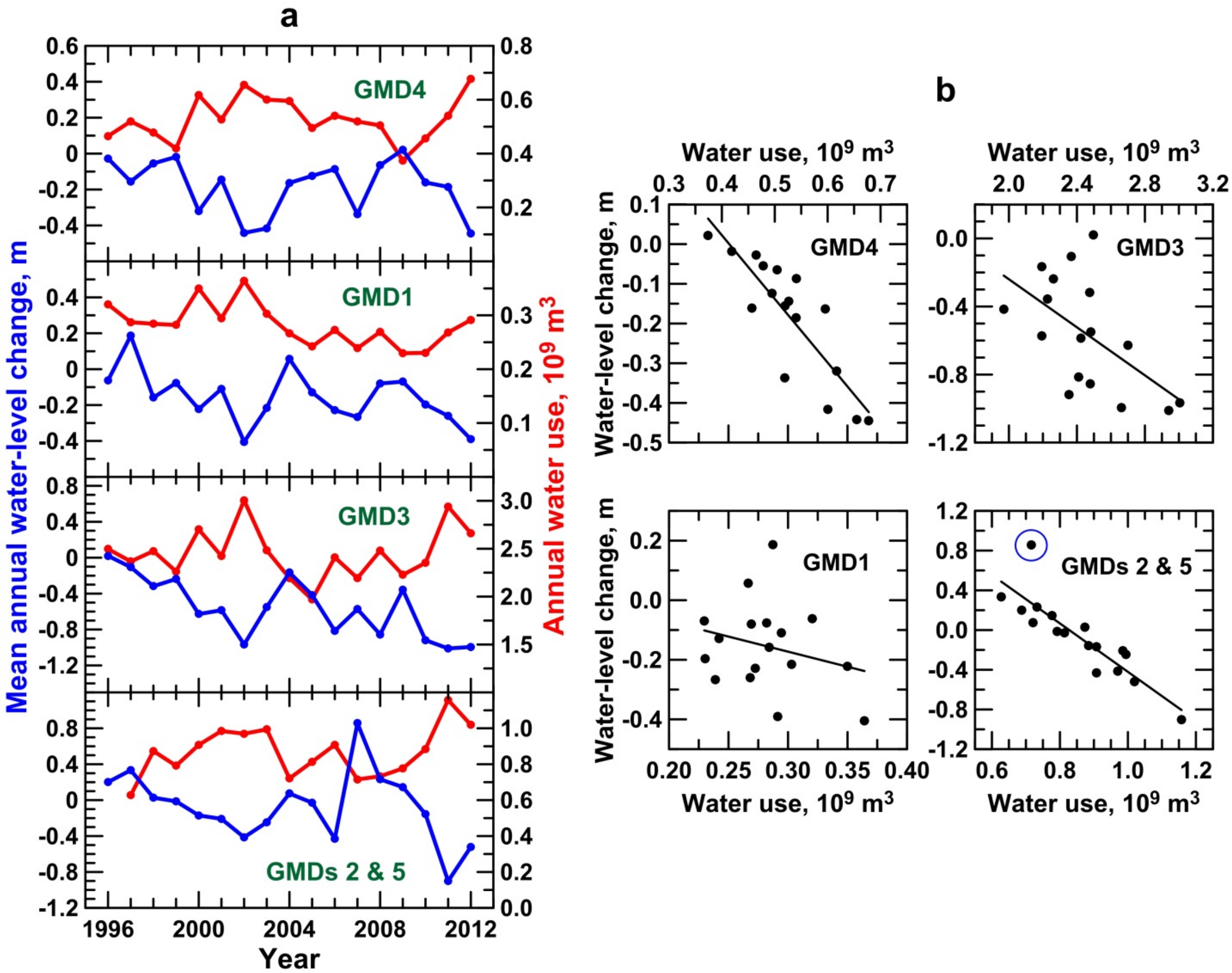

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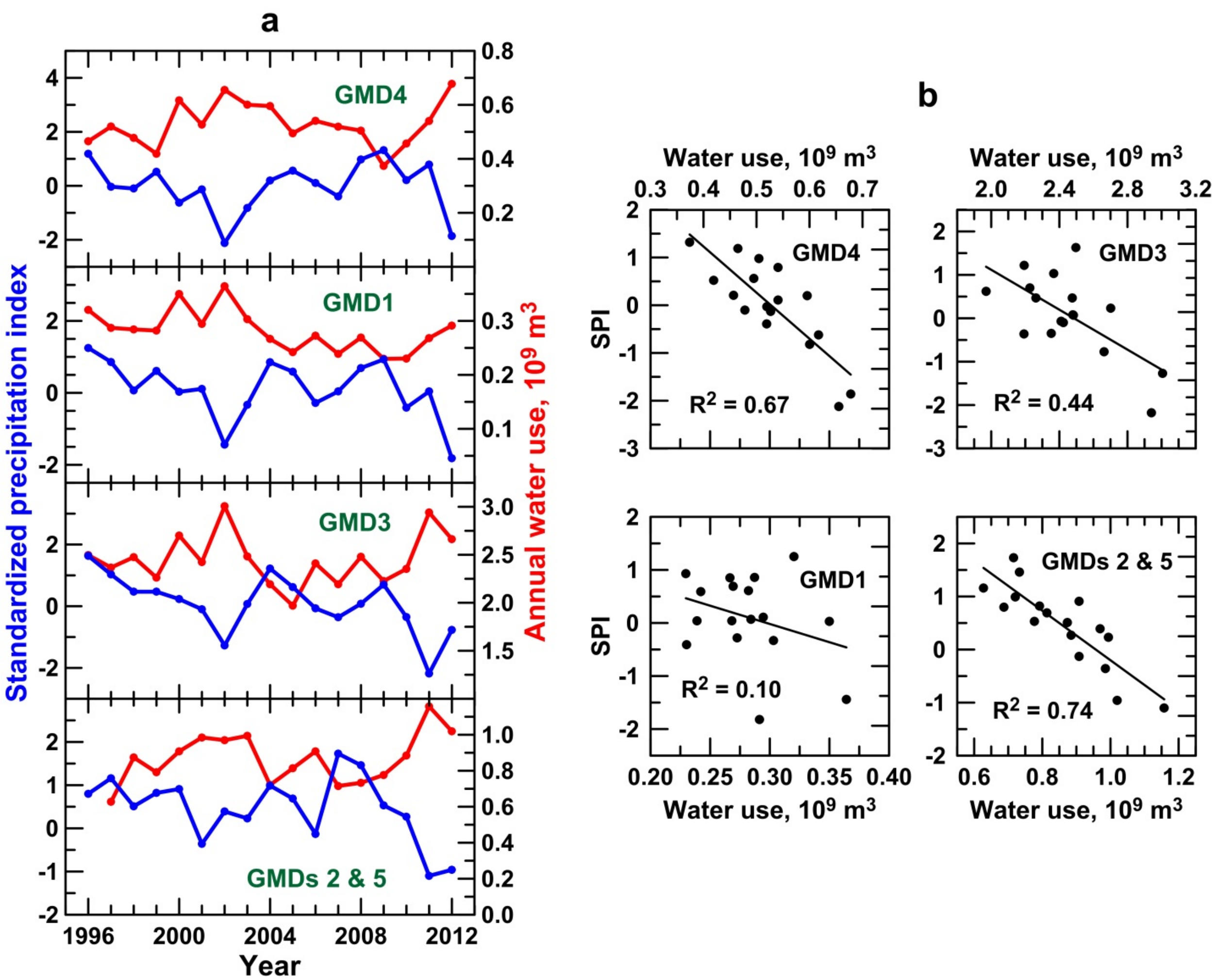

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Table 1. Optimum[a] and utilized[b] (bolded) correlations of mean annual water-level changes for GMDs with climatic indices for coinciding climatic divisions during 1996-2012.

Climatic index	GMD and Climatic Division	R^2
PDSI, August	GMD4 – Div. 1	0.739
Palmer Z, mean Jun.-Sep.	GMD4 – Div. 1	0.822
SPI, 9-month, December	GMD4 – Div. 1	0.831
SPI, 9-month, October[c]	**GMD4 – Div. 1**	**0.781**
Water-level change (m) = 0.1409 x SPI - 0.182		
PDSI, mean Aug.-Nov.	GMD1 – Div. 4	0.463
Palmer Z, mean Jun.-Nov.	GMD1 – Div. 4	0.656
SPI, 9-month, October[c]	**GMD1 – Div. 4**	**0.709**
Water-level change (m) = 0.1524 x SPI - 0.171		
PDSI, mean Jun.-Dec.	GMD3 – Div. 7	0.833
Palmer Z, mean Apr.-Nov.	GMD3 – Div. 7	0.830
SPI, 9-month, November	GMD3 – Div. 7	0.800
SPI, 9-month, October[c]	**GMD3 – Div. 7**	**0.776**
Water-level change (m) = 0.3166 x SPI - 0.584		
PDSI, mean Jul.-Oct.	GMD 2&5 – Div. 8	0.744
Palmer Z, mean Jan.-Dec.	GMD 2&5 – Div. 8	0.794
SPI, 12-month, December[d]	**GMD 2&5 – Div. 8**	**0.782**
Water-level change (m) = 0.4528 x SPI - 0.283		

[a]Optimum correlation determined for each of the climatic indices (PDSI, Palmer Z, and SPI).
[b]Linear regression equations are listed for the utilized correlations. All R^2 (coefficient of determination) values are significant at P = 0.001 except that for GMD1 water-level change versus PDSI division 4, which is significant at P = 0.01.
[c]Index based on 9-month period ending with October.
[d]Index based on 12-month period ending with December.

Table 2. Coefficients of determination (R^2) and linear regression equations for correlation of mean annual water-level changes with reported water use during 1996-2012 for the GMD areas[a].

GMD	R^2	Equation
GMD4	0.732	Water-level change (m) = -1.60×10^{-9} x water use (m^3) + 0.664
GMD1	0.068	Water-level change (m) = -1.01×10^{-9} x water use (m^3) + 0.131
GMD3	0.318	Water-level change (m) = -0.706×10^{-9} x water use (m^3) + 1.17
GMDs 2&5	0.765	Water-level change (m) = -2.44×10^{-9} x water use (m^3) + 2.02

[a]Correlations for GMD4 and GMDs 2&5 are statistically significant at P = 0.001 and for GMD3 at P = 0.02; the correlation is not statistically significant for GMD1.

Table 3. SPI values for given year and predicted water-level declines calculated using the regression equations in Table 1 for a drought of the same length and intensity of that of the 1950s.

	GMD4		GMD1		GMD3		GMDs 2&5	
Year	SPI 9-month October	Predicted decline, m	SPI 9-month October	Predicted decline, m	SPI 9-month October	Predicted decline, m	SPI 12-month December	Predicted decline, m
1952	-1.62	-0.41	-1.70	-0.43	-1.92	-1.19	-1.46	-0.94
1953	-0.53	-0.26	-1.02	-0.33	-1.14	-0.94	-1.36	-0.90
1954	-1.47	-0.39	-1.46	-0.39	-1.26	-0.98	-2.16	-1.26
1955	-1.66	-0.42	-0.78	-0.29	-0.01	-0.59	-0.62	-0.56
1956	-2.49	-0.53	-2.87	-0.61	-2.44	-1.36	-2.47	-1.40
Total		-2.01		-2.05		-5.06		-5.07

Table 4. Steps for calculating pumping reduction to obtain stable water levels (water-level change of zero) for GMD4 and GMDs 2&5 during 1996-2012 using water-level and water-use regression equations in Table 2.

Percent reduction in water use required for stable water levels under observed climatic conditions

GMD4: Water-level change (m) = 0 = -1.60×10^{-9} x water use (m^3) + 0.664

Water use = $-0.664/(-1.60 \times 10^{-9}) = 4.14 \times 10^8$ m^3

Average annual reported water use for 1996-2012 = 5.38×10^8 m^3

Percent reduction in water use = ((5.28-4.14)/5.28) x 100 = 21.7%

GMDs 2&5: Water-level change (m) = 0 = -2.44×10^{-9} x water use (m^3) + 2.02

Water use = $-2.02/(-2.44 \times 10^{-9}) = 8.27 \times 10^8$ m^3

Average annual reported water use for 1996-2012 = 8.57×10^8 m^3

Percent reduction in water use = ((8.57-8.27)/8.57) x 100 = 3.4%

Table 5. Steps for calculating average annual water-level decline for 21.7% reduction in pumping in GMD1 based on SPI change for this reduction in GMD4 for 1996-2012.

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a. SPI change corresponding to 21.7% pumping reduction in GMD4
Insert water-level change of zero for reduced pumping into regression equation in Table 1
    Water-level change (m) = 0 = 0.141 x SPI - 0.182
    SPI = 0.182/0.141 = 1.29
Average SPI (9-month October) for 1996-2012 = -0.011
SPI change corresponding to pumping reduction = 1.29 – (-0.011) = 1.30

b. Compute average annual water-level change for GMD1 for SPI change of 1.30
Use regression equation in Table 1 for GMD1
    Water-level change (m) = 0.152 x SPI - 0.171
    Average SPI (9-month, October) for climatic division 4 (GMD1) = 0.105
    SPI for change of 1.303 = 0.105 + 1.303 = 1.408
Water-level change (m) = 0.152 x 1.41 – 0.171 = 0.044 m
    Average annual water-level change observed for 1996-2012 = -0.155 m
    Reduction in average annual water-level decline = 0.044- (-0.155) = 0.199 m

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